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Hidden groundwater inflows from the Slovenský kras Mts. to the Slaná River identified by thermometric and resistivimetric measurements

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Abstract: Longitudinal profile measurement of specific electric conductivity (resistivimetry) and water temperature (thermometry) along the watercourse of a surface stream, if performed in sufficient density of measuring points, can reveal position of hidden groundwater inflows in a surprisingly detailed scale. Contrary to flow accretion survey, i.e. discharge measurements on appropriately distanced locations of streams that are able to quantitatively define hidden surpluses or losses of discharge, but their evaluator can attribute these to stream segments only, outputs of thermometry and resistivimetry have potential of precise location identification of groundwater outlets. The best season for such measurements is culminating summer or winter with naturally highlighted contrast in surface water and groundwater temperatures. In our case, thermometric and resistivimetric measurements were performed on the watercourse of the Slaná River (SE Slovakia), segment between Brzotín and Gombasek municipalities, where the river is cutting two major karstic plateaus (Silická planina and Plešivská planina) in a form of several hundred meters wide and several hundred meters deep canyon. Three major karstic springs are found in this area, but hidden dewatering of karst water resources directly into the Slaná River remained unknown. Measurements were performed within 5 summer days from 21/06/2016 until 25/06/2016 on an 8300 meters long rivercourse section. The basic footage step of measurements was 1.0 meter. Mesurements were performed in the streamline of active flow and also along its left and right side, 20 cm aside the stream-bank. Both parameters – water temperature and specific electric conductivity – were measured near the streambed, ~5 cm above the bottom, in the ~20 to 40 cm distance from the left or right bank, and also in the main streamline. No major karstic groundwater inlets were found here, but small-scale inflows were mostly found on the left bank pointing to groundwater flow from the east – from the Silická planina Plateau. It seems that at least on the Brzotín-Gombasek watercourse segment of the Slaná River, Plešivská planina Plateau is dewatered only through already registered karstic springs west from the river.

Key words: hidden groundwater surpluses, Slaná River surface stream, longitudinal profile measurements, water electric conductivity, resistivimetry, thermometry

Graphical abstract

Highlights

- Hidden groundwater inflows to the river were verified by water temperature and electric conductivity measurements.
- Major karst groundwater inputs were not registered.
- River section between Brzotín and Gombasek had low incidence of right-sided anomalies, more inflows were from the left bank from the Silická planina Plateau.
- Hidden dewatering of the Plešivská planina Plateau was not verified.

Introduction

The use of longitudinal profile measurements of temperature and specific electrical conductivity (EC, also described as electrolytic conductivity, which is a reciprocal value of specific electrical resistance) in the investigation of quantitative-qualitative relationships between groundwater and surface waters has long been considered a proven geophysical method in Slovak hydrogeological practice. This simple, less costly but very effective method has been applied initially to surface streams in karst areas since the early 1980s (Husák and Lizoň, 1980; Lizoň, 1980; Foltán, 1983; Kullman et al., 1985). Later, it was also successfully applied in hydrogeological surveys for mineral water sources (e.g. Ferenc et al., 1986). Resistivimetric and thermometric measurements were used to locate hidden groundwater inflows into surface streams (Filo and Švastová, 1994; Švastová in Malík et al., 2000;

Vojtková and Malík, 2005). These measurements utilize the temperature and conductivity contrast between surface water and groundwater, when the groundwater is considerably colder in summer time and considerably warmer in winter time than surface water. Therefore, periods of extreme air temperatures (culminating winter or summer) are usually most preferable for such measurements. The EC contrast depends on the differences in the geochemical nature of the rocks in the whole source watershed of the surface stream and in the immediate surroundings of the measurements, where groundwater is supposed to originate. In this (EC) case, one should also consider possible presence of anthropogenic influences (usually contaminants). The groundwater inflow rate is reflected over the surface streamflow course in the range of temperature and specific electric conductivity anomalies, taking into account the total flow discharge of the investigated stream/river. Correlation of both data (temperature/EC) allows qualitative identification of hidden groundwater surpluses as anomalies caused by inflowing groundwater and excludes possible false anomalies caused by other factors.

Resistivimetric and thermometric measurements were also applied to detect hidden water increments inside cave spaces, respectively in underground hydrological systems of caves (Malík et al., 2010a, 2010b, 2011; Gregor et al., 2017). In karst hydrogeology, such methods are even more effective in the cases of combination of surface and underground parts of streams in karst areas (Auxt et al., 2012; Malík et al., 2013; Malík et al., 2016). Performing resistivimetric and thermometric measurements inside the cave, the thermal contrast rate is usually suppressed due to the constant temperature inside the underground spaces, and the detection of inflows relies on EC anomalies unless a significant inflow from the ground surface enters the underground hydrological system. If in this case there is limited time for temperature equalisation, water temperature measurements can be helpful as well. From a speleological point of view, lateral, hydraulically active branches of the karst systems can be inspected for in hidden water inflows from unknown places. For karst hydrologists and hydrogeologists, these results are important in assessment of hydraulic and hydrodynamic conditions of water flow in open karst conduits. Great importance of such a knowledge is valuable especially in the design and refinement of caves' protection zones or recharge areas/protection zones of (exploited) karstic springs.

Another interesting contribution of the longitudinal profile measurements of water temperature and EC may also be their indirect impact on the water balance calculation as it was in the case of Kopa karstic hydrogeological structure (NW part of the Veľká Fatra Mts., northern Slovakia). Balance closure of this hydrogeological structure was verified by thermometric and resistivimetric measurements carried out directly from the boat to reveal signs of hidden groundwater inflows into the surface water of the Krpeľany Reservoir (Švasta and Malík, 2006). Identification of places of hidden groundwater inflows remains the main goal of resistivimetric and thermometric measurements, however, their quantification, i.e. the determination of the hidden groundwater amounts must already be done by other methods – mostly by hydrometric measurements. On the other hand, interval (sectional) hydrometric measurements are usually performed by measuring stream cross-section in profiles distanced each from other in the order of hundreds of meters, if not more. For this reason, only combination of both methodologies is currently able to reliably determine both – the size and location of hidden groundwater inflows existing in the form of streamflow surpluses.

In the current paper, we present the results of measurements of temperature and specific electrical conductivity of surface water carried out along both banks of the surface stream of the Slaná River in its section between Brzotín and Gombasek, in the Slovenský kras Mts. (Fig. 1). In this section, Slaná River preserves relatively low total dissolved solids (TDS) content characteristic for phyllites, sandstones and metarhyolites of the low-grade metamorphic Gemeric sequences (Hanzel in Bajaník et al., 1983). TDS of natural waters here is usually in the range between 100 and 200 $mg.l^{-1}$ while in karstic waters of Silická planina Plateau it is ranging from 400 to 700 $mg.l^{-1}$ (Haviarová et al., 2010; Fľaková et al., 2018). In the past, a geophysical thermometric survey was carried out here (Džuppa and Husák, 1976), but measurements applied shallow probes of 0.5 to 1.0 m depth in a regular network of 4 × 4 m in the surroundings of major karstic springs of Gyepű/Brzotínska vyvieračka, Pisztráng/Pstruhová vyvieračka and Vyvieračka pod Veľkou skalou springs. In total, 503 measurements were carried out here in February 1976, focusing only on the immediate surroundings of the aforementioned three karstic springs, and leaving the surface flow of the Slaná River without measurements. The presence of such karst water outflows in this area encouraged also our measurements, aiming to verify the existence of possible hidden groundwater inflows to the Slaná River. The Slaná River in the Brzotín area enters a deep but also wide canyon, where both canyon slopes are formed by light-grey Wetterstein limestones of the Silica unit (Mello – ed., 1996, 1997). The obtained and interpreted results contributed to the better understanding of water communication between Slaná River as the main surface recipient in the area and the karstic groundwater accumulated in the extensive karstic plateaus of the Silická planina and Plešivská planina plateaus.

Data acquisition methodology

The suitability of resistivity measurements usage is based on the assumed differences in TDS of surface water

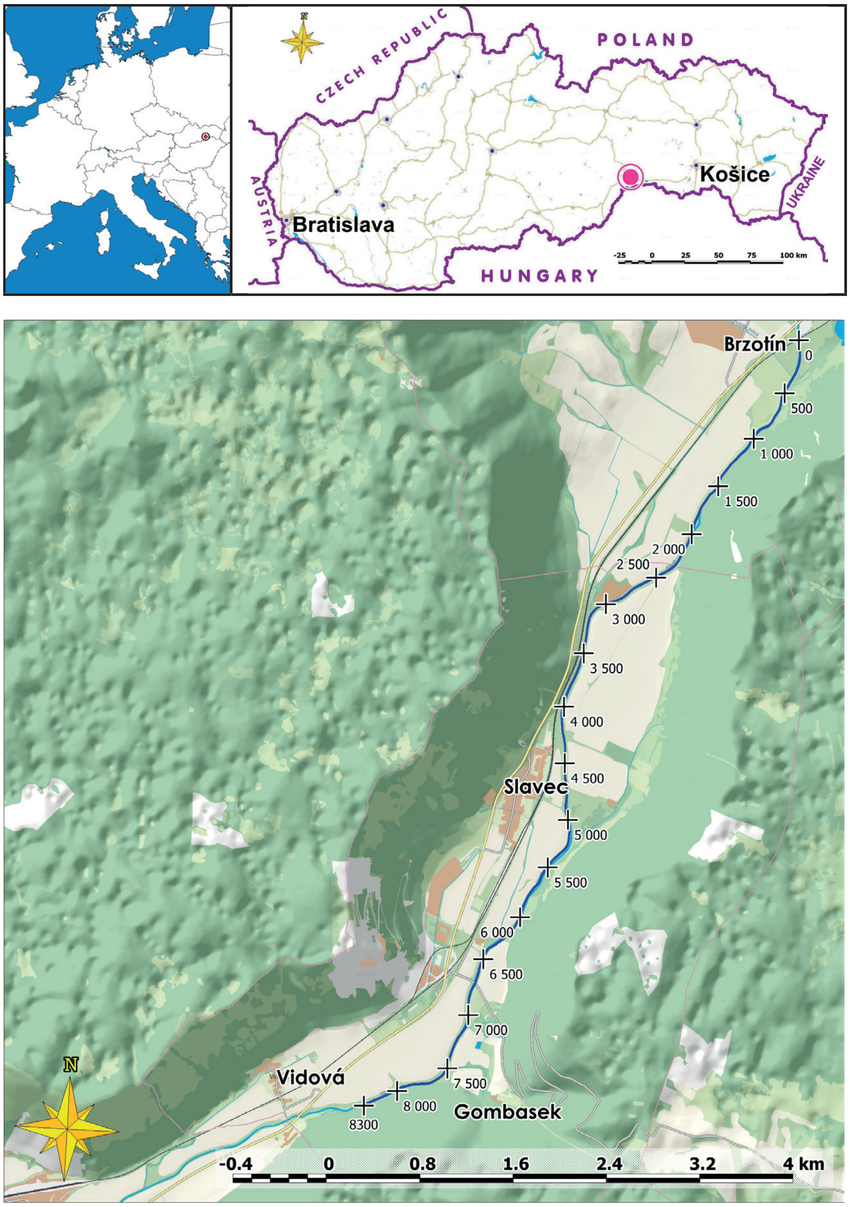

Fig. 1. Location of the investigated area on the territory of Slovak Republic and location of thermometric and resistivimetric measurements performed in the period between 21/06/2016 – 25/06/2016 on the Slaná River on the Brzotín – Gombasek section.

and groundwater and thus the places of hidden groundwater inflows are manifested by local change of specific electric conductivity (in our case, the entry of groundwater into the surface water should be signalised by its increase). The inflow rate (its discharge) is reflected in the course and range of temperature and conductivity anomalies, taking into account the total discharge of the investigated river watercourse. Correlation of both (temperature and EC anomalies) allows qualitative interpretation of hidden tributaries and enables exclusion of false anomalies caused by other phenomena like sewage or drainage channels. To obtain appropriate dataset for the Slaná River between Brzotín and Gombasek, side measurement of the stream electrolytic conductivity and water temperature were performed near the river bottom, about 5 cm above its level and in the distance of 20 to 40 cm from the bank on both sides of the river. EC and water temperature values were also taken from the streamline (flow nozzle) at the same footage, where measuring point was also some 5 cm above the river bottom (Fig. 2a, b). The measurement step was set to 1.0 m, and before taking, a footage path was drawn up using the measuring tape following the streamline (Fig. 2c). All the measurement records, present in the detailed documentation for both river banks, are then related to this uniform footage of river axis/streamline.

Measurements were performed by two WTW ProfiLine Cond 197i field conductivitymeters (Fig. 2b), allowing the water temperature measurement accuracy of 0.1 °C and the accuracy of EC measurements of 0.1 μS.cm^{-1}. In the second case, 1.0 μS.cm^{-1} resolution of EC data records was applied. Thermometric and resistivimetric measurements on the Slaná River were carried out from 21/06/2016 to 25/06/2016. The measurements were performed by two closely cooperating measuring groups moving independently but in coordination along both banks of the river (Fig. 2d) following the footage measuring tape. Each measuring group consisted of a data recording person equipped with waterproof notebook, and a surveyor, equipped with a conductivitymeter. Conductivitymeter probe was placed on the measuring rod to keep the probe constantly submerged in the water and to avoid fluctuations in the probe measurements caused by its transfer through the air. It was verified by practical experience that each probe emergence above the water level caused time-consuming stabilization of measured parameters. There were two measuring groups, each for the left resp. right bank, and one "geometer" group equipped with measuring tape and GPS device following the river streamline and thus marking the footage of measurements. Garmin 60 CSx GPS instruments were used here to measure the position of the endpoints of the band, i.e. to mark the measured section by point of every 50 m (Fig. 2c). The measured section had a total length of 8300 m and consisted of the

Fig. 2a. Measurements of water temperature and specific electric conductivity performed along the Slaná River left bank on 23/06/2016.

Fig. 2b. Measurements of water temperature and specific electric conductivity performed along the Slaná River left bank on 25/06/2016.

Fig. 2c. Fixing of the measuring tape for positioning of thermometric and resistivimetric measurements of the Slaná River on 25/06/2016.

Fig. 2d. Thermometric and resistivimetric measurements of the Slaná River on 24/06/2016 – coordination of measuring groups on both right and left river bank.

same number of footage measurements (8300) along the left bank and right bank of the river. Taking into account the river width, EC and water temperature measurements for the streamline were separately measured by each measuring group. Therefore the group moving along the right bank marked its streamline measurements as center-right and a group moving along the left bank referred respective measurements as center-left.

Obtained data and discussion

The first measurement on the footage of 0 m in the area under the railway bridge over the Slaná River near Brzotín was carried out on 21/06/2016 at 10 : 10, the last measurement in the alluvium in the middle of fields under the Gombasek municipality, respectively in between Slavec-Vidová and Plešivec municipalities took place on 25/06/2016 at 15 : 10. During each day of measurements, systematic daily changes in water temperature were observed – a gradual increase by 2.3 to 4.3 °C (3.2 °C in average) depending on the weather conditions. Systematic daily increase in the specific electric conductivity values was not as significant, ranging from 1 to 8 μS.cm^{-1} (4.2 μS.cm^{-1} in average), but in the meantime a slight decrease in conductivity was observed, associated with a noticeable increase in discharge in the afternoons, which was possibly related to the water manipulation at the upstream hydro-power plant in Dobšiná. Data on water temperatures and EC at the beginning and at the end of the day are summarized in Table 1. An overview presentation of the thermometric and resistivimetric measurement results of the Slaná River in the section between Brzotín and Gombasek, along with the footage indication of individual measured sections is shown in Figs. 4 and 5. Course of water temperatures and EC values measured on both river banks as well as in the middle of the river (streamline), indicating some important anomalies, are depicted here.

A detailed description of the results of water temperature and EC measurements in the Slaná River streamline and its right and left banks by both measurement groups is presented in the following text from the beginning to the end of measurements, thus from the footage 0 to 8300 m. After the start of measurements on the "zero point" located under the railway bridge south of Brzotín, an anomaly of a hidden tributary from

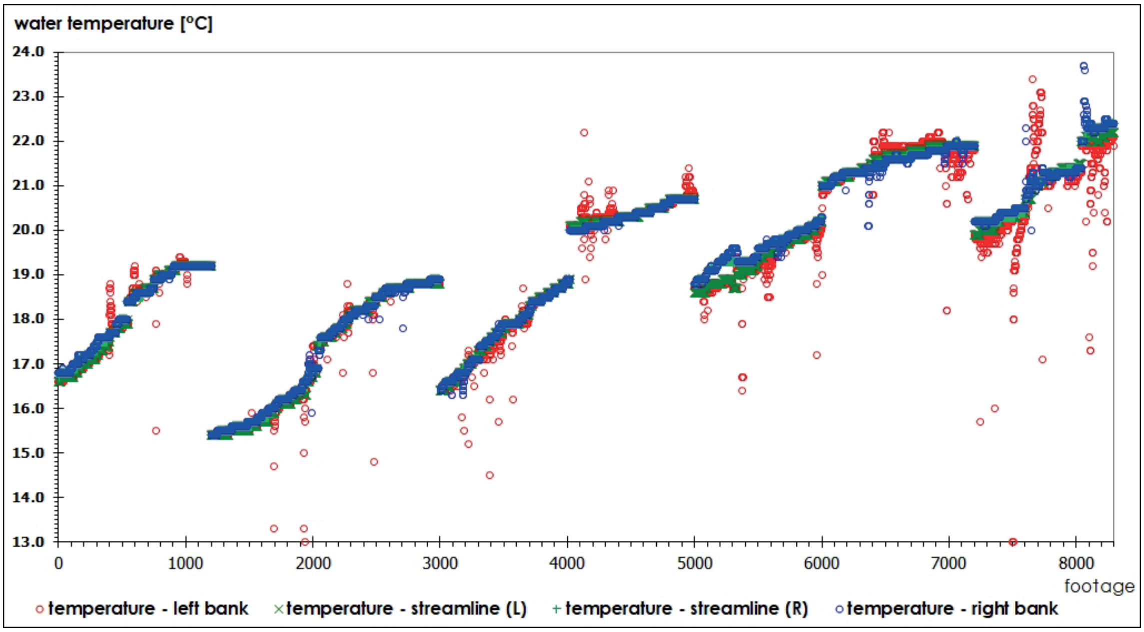

Fig. 3. Graphical representation of the water temperatures observed at both – right and left banks of the Slaná River and in the middle of the river ("left middle – L" or "right middle – P" according to the measuring working group) during thermometric and resistivimetric measurements in the section between Brzotín and Gombasek during 21/06/2016 – 25/06/2016.

the right side was observed on the 95 m footage. This anomaly is not shown in temperature response, but significantly affects the EC for a few meters on the right bank of the Slaná River. The recorded EC increase was from 299 to 335 μS.cm^{-1}. On the left bank, a decrease of temperature and an EC increase between the 388 and 395 m footage reflects a hidden groundwater inflow into the surface water flow of Slaná River (decrease of temperature by 0.2 resp. 0.3 °C, increase of EC by 20 resp. 29 μS.cm^{-1}). We assume that this is groundwater circulating in the alluvium of the Čremošná stream, which enters into the Slaná River on the footage of 405 m. Here, surface water of the Čremošná stream had a conductivity of 409 μS.cm^{-1} and a water temperature of 18.9 °C (Slaná River: 302 μS.cm^{-1} and 17.7 °C). Although Čremošná stream is considerably warmer (probably the effect of water storage in the Brzotín ponds), groundwater in its alluvium accompanying its surface stream maintains a lower (more stable) temperature, and shows a higher conductivity than Slaná River. A display of an interpretation graph of measurements on the footages 0 to 500 m is shown in Fig. 5.

Tab. 1

Data on the initial and final values of water temperatures and EC during the individual measurement days and the corresponding values of the measured footage in the Slaná River.

Date	Measured footage	Streamflow temperature at the beginning of daily measurements [°C]	Streamflow temperature at the end of daily measurements [°C]	Streamflow EC at the beginning of daily measurements [μS.cm^{-1}]	Streamflow EC at the end of daily measurements [μS.cm^{-1}]
21/06/2016	0–1200 m	16.6	19.2	299	300
22/06/2016	1200–3000 m	15.4	18.8	300	303
23/06/2016	3000–5000 m	16.4	20.7	314	320
24/06/2016	5000–7200 m	18.6	21.9	334	342
25/06/2016	7200–8300 m	19.9	22.2	326	331

On 614 m footage, there is a smaller hidden anomaly on the left bank, manifested by an isolated temperature drop of 0.2 °C and an increase in conductivity of 4 μS.cm^{-1}. The already visible spring on the left bank on 765 m footage causes a high increase in EC, from 305 to 388 μS.cm^{-1} and a drop in temperature from 18.9 to 15.5 °C, but its influence on these values on the left bank quickly resembles. In 29 meters downstream (footage of 794 m) there is a smaller left-bank anomaly of the hidden inflow (temperature decrease by 0.4 °C, increase of EC by 7 μS.cm^{-1}), also without significant influence on the surrounding water flow. Similarly, there is an anomaly on the right bank (footage 871 m) with a temperature drop of 0.1 °C and an increase in EC of 6 μS.cm^{-1}. The hidden groundwater surplus from the left bank is then manifested by a minor anomaly at 1006 m footage (temperature drop of 0.4 °C from 19.2 to 18.8 °C, EC increase of 7 μS.cm^{-1} from 303 to 310 μS.cm^{-1}). Another, almost 500 m long section of Slaná River is without any significant sudden changes in temperature or specific electric conductivity. A smaller visible spring, manifested also by an increase in water temperature of 0.3 °C and an EC of 8 μS.cm^{-1}, is found on footage 1515 m on the left. An overview of the measurement results on the 0 to 2000 m meter is shown in Fig. 6.

As very pronounced there can be then considered the manifestation of a visible spring on the Slaná River left bank of on the footage of 1687 m (values measured directly in the spring were 10.3 °C and 555 μS.cm^{-1}, which is in 5.9 °C less and in 260 μS.cm^{-1} more than the respective values in the stream). This spring, named Hradná vyvieračka/Várforrás (Castle Spring), leaves a significant mixing track along the left bank on a stretch of more than 25 m. Smaller visible springs on the left side of the river on footages 1826 and 1871 m are manifested by an increase of EC values by 12 resp. 14 µS.cm^{-1} and by increasing the water temperature by 0.1 °C without significantly affecting the properties of the river water. These are probably parts of larger drainage area of already

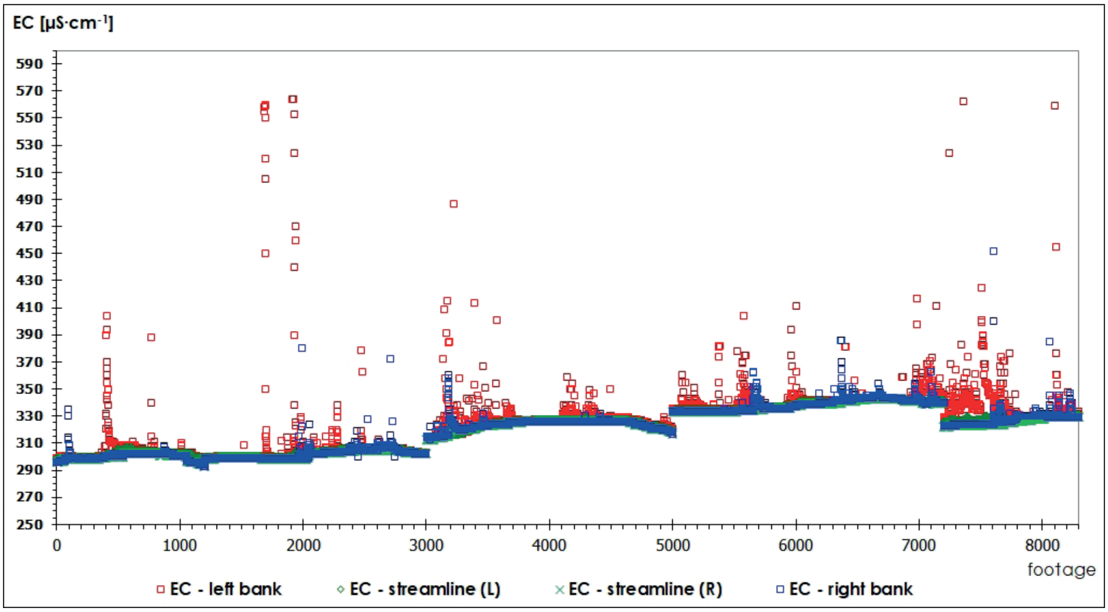

Fig. 4. Graphical representation of the specific electric conductivity observed at both – right and left banks of the Slaná River and in the middle of the river ("left middle – L" or "right middle – P" according to the measuring working group) during thermometric and resistivimetric measurements in the section between Brzotín and Gombasek during 21/06/2016 – 25/06/2016.

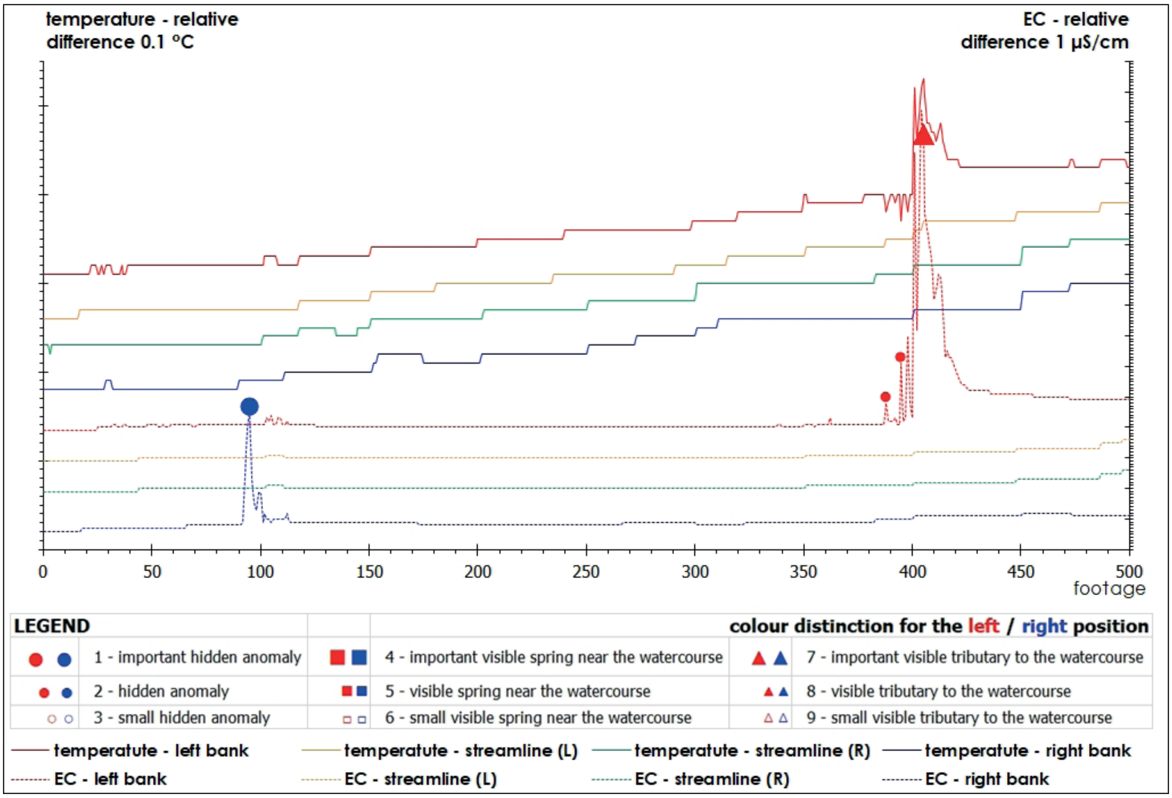

Fig. 5. Relative changes in the course of the water temperature of the Slaná River [°C] and its specific electric conductivity [µS.cm^{-1}] at both right and left banks, and in the middle of the river ("left middle – L" or "right middle – P" according to the measuring working group) in the footage 0–500 meters based on measurements from 21/06/2016.

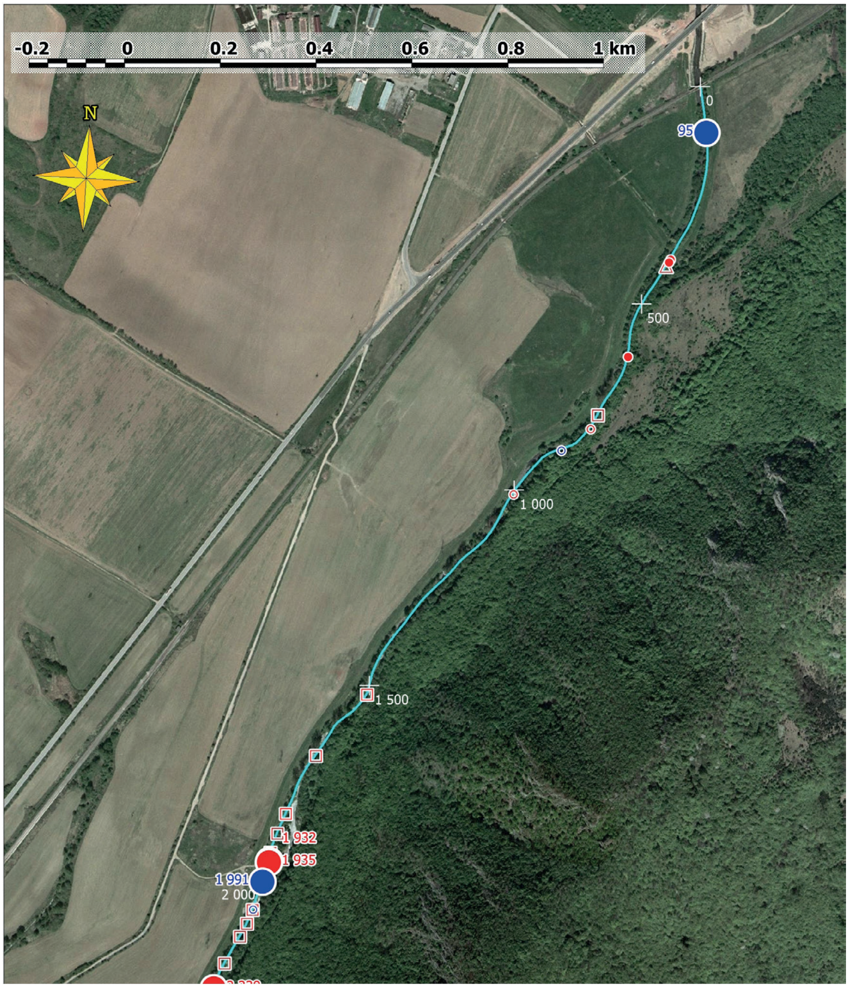

Fig. 6. Location of anomalies detected by thermometric and resistivimetric measurements on the Slaná River in the Brzotín – Gombasek section, 0 to 2000 m footage. For explanation of symbols see Fig. 5.

mentioned Hradná vyvieračka/Várforrás spring system, which itself also appears on the ground surface in the form of three seemingly independent spring outlets. In the past in this area, pretty productive hydrogeological exploration boreholes were drilled, of which the 507.6 m deep RC-12C borehole (Orvan, 1992) is currently exploited for a drinking water supply. In addition, there are also other unexploited boreholes in the same area – HR-1 (419 m deep) on the right and R-29 (25 m deep) on the left side of the Slaná River. Significant manifestation of the main Hradná vyvieračka/Várforrás spring, discharging approximately 5 l.s^{-1} at the time of measurements, was visible on the left bank on the 1915 m footage by reducing the water temperature by 6.5 to 9.9 °C and increasing the specific electric conductivity in 264 to 564 µS.cm^{-1}. Significant persistence of this signal along the left bank and a decrease in water temperature of 0.1 °C even in the river streamline was registered here. Behind this place, two significant anomalies were found on the left bank in 1932 and 1935 m footages (drop in water temperature by 6.4 and 3.8 °C respectively; increase in EC by 253 and 166 µS.cm^{-1}, respectively). On this site, a steel waterworks pipeline is crossing the river bed, and it is not possible to exclude the influence of possible water leaks from this pipeline on the water properties in the river. Slightly lower, on the 1963 m footage, two smaller right-side anomalies were detected, probably originating in a hidden surface inflow (increase in water temperature by 0.3 and 0.5 °C, increasing of EC values by 17 and 8 µS.cm^{-1} respectively). Similarly, anomalies of elevated water temperature (rise of 0.4 °C in water temperature and of 26 µS.cm^{-1} in EC values) were also detected on the left bank on the footage from 1980 to 1982 m, originating in visible water leakage from the left bank. On the right bank, a significant anomaly appeared on the 1991 m footage with a drop in water temperature of 0.9 °C and a rise in conductivity of 82 µS.cm^{-1} (here, a visible water inflow of 13.9 °C and 512 µS.cm^{-1} was recorded). Slightly warmer water (by 0.3 °C) with slightly increased conductivity (by 7 µS.cm^{-1}) was spotted on the opposite bank (footage 1998 m). At the same place, dry tributary outlet was found with already abandoned gauging by Thomson weir. At the time of measurements, it was without any runoff and stagnant water was found in the small pools along the river bank. So far (i.e. from the footage 1687 m to the footage of 1998 m), we can observe both visible and hidden large drainage area around the group of springs Hradná vyvieračka/Várforrás, where karstic groundwater of the Silická planina Plateau is feeding the surface flow of the Slaná River.

An overview of the measurement results on the footage interval 2000–4000 m is shown in Fig. 7. On the 2052 m footage, a hidden anomaly was identified on the right bank (water temperature in 0.2 °C lower and EC in 22 µS.cm^{-1} higher than surface water in the river), whereas on the opposite left bank a small groundwater inflow was also recognized, responsible for a 0.2 °C drop in the water temperature. This was followed by a number of minor anomalies along the left bank of the river. A small groundwater outflow on the 2083 m footage causing a local 10 µS.cm^{-1} EC increase on the left river bank was registered, and on the 2113 m footage a similar visible flow caused not only an increase in EC of 6 µS.cm^{-1}, but also a drop in water tem-perature of 0.5 °C. On the 2181 m footage, a visible groundwater outlet on the left bank caused an increase of EC in 10 µS.cm^{-1} and a drop in the water temperature of 0.1 °C. The hidden anomaly was identified in the deep pool of the river water course at 2239 m footage, this caused a more intense change in the properties of the Slaná River water on the left bank – decrease in water temperature by 1.1 °C and an increase in specific electrical conductivity by 15 µS.cm^{-1}. This clearly recognizable feature was accompanied by smaller anomalies in 5 to 7 meters upstream. Down-stream, in the distance of 35 to 40 m, another two anomalies signalizing hidden inflows to Slaná River from its left bank were found: on footage 2275 m with water temperature drop by 0.2 °C and EC increase by 33 µS.cm^{-1}; on footage 2281 m with water temperature drop by 0.2 °C and increase of EC by 23 µS.cm^{-1}.

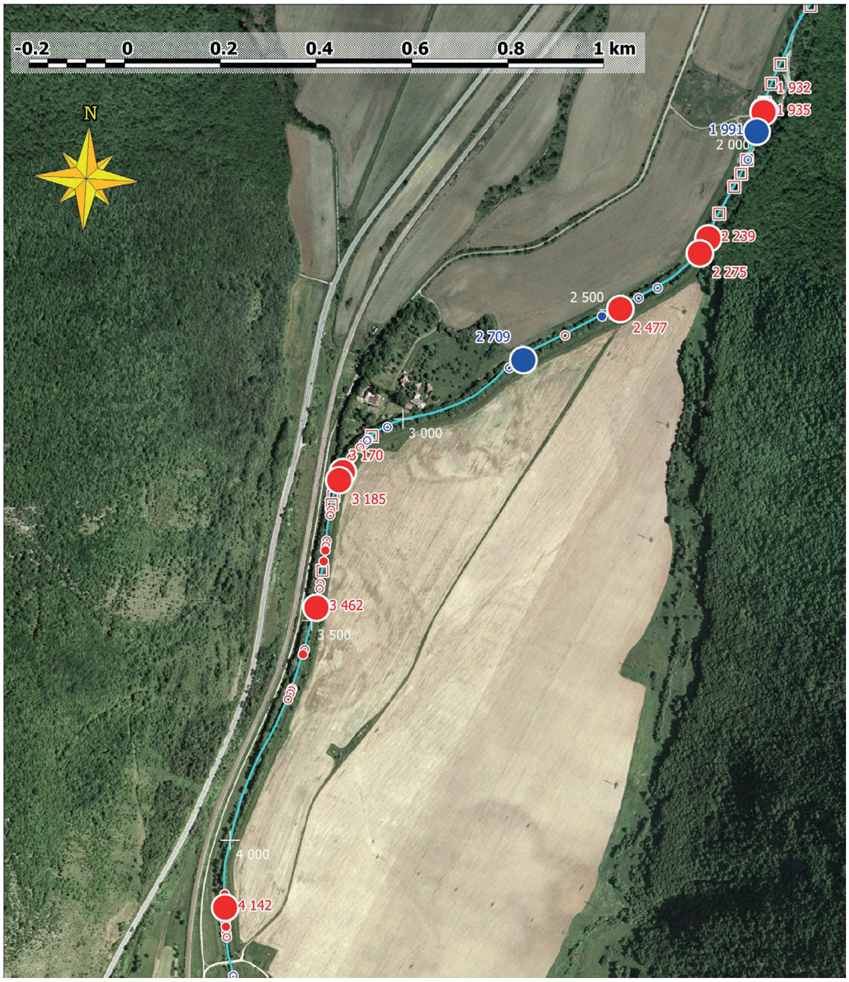

Fig. 7. Location of anomalies detected by thermometric and resistivimetric measurements on the Slaná River in the Brzotín – Gombasek section, footage of 2000–4000 m. For explanation of symbols see Fig. 5.

Approximately at the 2300 m footage, the Slaná River watercourse changes its position from the foot of the Silická planina Plateau towards the foot of the Plešivská planina Plateau (the transition watercourse segment is up to the footage of approximately 3100 m). At these places then the Slaná River crosses its own alluvium from northeast to southwest. If we suppose the groundwater flow in the Quaternary alluvial sediments to be parallel with the general course of river alluvia, one should expect anomalies pointing to groundwater inflows mostly (if not only) on the right bank of the Slaná River in this section. This assumption has been fulfilled by two small hidden anomalies on the 2388 m footage (local water temperature drop of 0.1 °C and EC increase of 4 μS.cm^{-1}) and on the 2436 m footage (here the water temperature on the right bank was by 0.3 °C less and EC by 14 μS.cm^{-1} more than the water in the main stream). Very surprising was then the discovery of a 1.6 °C drop in the water temperature on the left bank and an increase of EC by 72 μS.cm^{-1} (footage 2471 m), and of a water temperature drop of up to 3.6 °C and an EC increase in 50 μS.cm^{-1} (footage 2478 m, also on the left bank). The temperature and the specific electrical conductivity on the left bank of the river in these places of the left bank were significantly affected on a larger section. The origin of this anomalies can only be explained by the entry of groundwater directed from the foot of the Silická planina Plateau towards the west – but such an assumption can only be verified by otherwise conceived field work. Right-side anomalies of different levels were then registered along the footage 2520 m (local temperature drop by 0.5 °C and EC increase of 23 μS.cm^{-1} on the most significant anomaly). Signs of groundwater inflow from the left-bank were again discovered at a footage of 2607 m – by a presence of minor anomaly indicated by temperature drop of 0.2 °C an EC increase of 6 μS.cm^{-1}. Further downstream there are four anomalies on the right bank – on the footages 2709 m, 2714 m, 2727 m and 2742 m. On the first, the highest one (footage 2709 m), water temperature compared to the main river flow was in 0.9 °C less and the EC there was in 67 μS.cm^{-1} higher. On the next anomalies below, the water temperature was found identically to be only in 0.1 °C lower, and the difference in the specific electrical conductivity was found to be in 6 or 21 μS.cm^{-1}. Only after the change of the direction of the Slaná River watercourse to the south, along the edge of the Plešivská planina Plateau (footage of 3176 m with visible inflow of the tributary from the Gyepü/Brzotínska vyvieračka karstic spring), two smaller right-side anomalies (3035 m and 3088 m footages) were identified. The lower anomaly influenced also the surface flow temperature by 0.3 °C (the EC values has been increased, compared to the main flow, in both anomalies – by 8 and 9 μS.cm^{-1} respectively). Significant visible inflow of water from the Gyepü/Brzotínska vyvieračka karstic springs, where the water temperature 13.6 °C and EC 516 μS.cm^{-1} were directly measured at the footage of 3176 m, was influencing the water temperature along the right side of the Slaná River watercourse at a section of about 40 m and EC values even at a section of about 60 m long. The right bank was then found to be without any major changes in measured values up to footage of 3460 m.

Much more varied data have been registered along the left bank of the Slaná River since its approach to the foot of the Plešivská planina Plateau, approximately from the footage of 3070 m. A small visible spring was found on the left bank (footage 3073 m), which influenced only difference in EC by 3 μS.cm^{-1}. Downstream, three smaller anomalies without visible inflow were identified at footages of 3084 m, 3099 m and 3110 m. In all three cases, the temperature difference (drop) was only up to 0.2 °C and EC rise up to 11 μS.cm^{-1}. Further on, on footages 3137 and 3142 m, the EC was raised in 55 and 99 μS.cm^{-1} (at equally small temperature differences), and several significant EC fluctuations were also recorded on footages 3150 m, 3164 m and 3170 m. At the latter point (footage 3170 m), a water temperature drop of 1.0 °C (EC increase in 97 μS.cm^{-1}) was also registered. This place on footage 3170 m therefore represents a more significant left-side anomaly, together with an analogous point on the footage of 3185 m (water temperature decrease by 1.3 °C and EC increase by 67 μS.cm^{-1}), also found along the left bank. A visible groundwater outlet on the left bank (15.2 °C; 487 μS.cm^{-1}) was then found on the 3225 m footage, a smaller one also on the 3246 m footage (16.7 °C; 338 μS.cm^{-1}). The left-side anomalies at footage points of 3195 m, 3258 m, 3270 m, 3327 m, 3339 m, 3349 m and 3371 m are likely to belong to the same groundwater flow that is invisibly drained by the surface flow of the Slaná River. Later, this is also evidently reflected in the 3390 m footage visible spring (14.5 °C, 414 μS.cm^{-1}) and by minor hidden anomalies at 3416 m and 3427 m footages (temperature drops of 0.4 and 0.2 °C, respectively, and an EC increase in 27 and 20 μS.cm^{-1}, respectively). Also a significant anomaly was detected on the 3462 m footage (water temperature drop by 1.9 °C and EC was found higher by 44 μS.cm^{-1}). The whole left-bank groundwater transfer front probably ends with small anomalies on footages 3476 m and 3479 m (local temperature drops of 0.3 °C and increase of EC by 10 μS.cm^{-1} and 26 μS.cm^{-1} respectively). There is also a small right-bank anomaly in this area (3460 m footage, water temperature increase in 0.2 °C and conductivity increase 9 μS.cm^{-1}).

Despite the fact that the watercourse of the Slaná River is in direct contact with the important compact karst area of Plešivská planina Plateu foothills in these places, no sign of visible or hidden groundwater inflow into the river was noticed on its right bank. Only the left river bank was active, where there was a minor hidden anomaly on the 3560 m footage (0.5 °C water temperature drop, EC increase of 29 μS.cm^{-1}), followed by a larger 3571 m footage anomaly (temperature drop of 1.7 °C with EC increase of 75 μS.cm^{-1}). A series of minor detected anomalies between footages of 3647 and 3673 m (3647 m, 3651 m, 3658 m and 3673 m) was associated with an increase of water temperature on the left bank (0.2 and 0.5 °C, later a 0.2 respectively 0.1 °C decrease) associated with a slight increase in EC from 5 to 13 μS.cm^{-1}, which, however, was still recognizable along the left bank up to the footage of 3700 m. From this section, water of the Slaná River showed a uniform temperature increase within the usual daily variation without records of significant temperature and conductivity anomalies up to approximately 4100 m footage. The difference (increase) of water temperature by 1.1 °C on footage 4021 m was recorded during approximately hour-long lunch break, and the specific electric conductivity values remained unchanged. Fig. 8 shows the overall situation of measurement results on the footage from 4000 to 6000 m.

In the immediate area of the Slavec municipality, the first major anomaly was found on the 4118 m footage, where the 0.9 °C drop of water temperature and the local EC value increase by 8 μS.cm^{-1} was detected on the left river bank. The following section of the river, more than 100 m wide up to 4230 m footage, is characterized by an intensive variation in water temperature (decreases, but also significant increases) on the left bank of the Slaná River. However, elevated temperatures were recorded in the shallow water by the river bank, possibly heated by the sun, while the decreases were as high as 1.6 °C (4142 m footage). This significant temperature anomaly was also accompanied by an increase in conductivity of 29 μS.cm^{-1}, which is also the largest measured difference in this section. Other left-bank anomalies were located on footages of 4131 m, 4171 m (change in EC with rising temperature), 4177 m (drop in water temperature by 0.6 °C, increase in EC by 18 μS.cm^{-1}), and 4187 m (drop in water temperature by 0.5 °C, EC increase of 22 μS.cm^{-1}); partly also on footages of 4201 m and 4210 m (lowering of temperature in 0.4 °C and increasing EC by 16 μS.cm^{-1}). It should be stated that the values in the streamflow remained unchanged, however, a slight decrease of 0.1 °C was registered in the section between footages 4251 m and 4217 m. The values along the right bank of the Slaná River remained unchanged for the whole described section (water temperature 20.0 to 20.1 °C; EC value 326 μS.cm^{-1}). The river section up to the 4290 m footage was then found without any changes of both parameters along the both river banks.

After an approximately 80 m long section without manifestations of anomalies in EC and water temperature, another section with signs of hidden groundwater inflows begins in footages approx. 4290 to 4400 m, starting in the area of the cart-road bridge across the Slaná River (the cart-road leads to the captured spring Pisztráng/Pstruhová vyvieračka). This section starts with a slight increase in conductivity at the right bank (from 326 to 330 μS.cm^{-1}) and a decrease in water temperature (from 20.2 to 20.0 °C) on the 4292 m footage. Then, a series of slightly more pronounced anomalies, but only at the left bank, follows. On the 4300 m footage the temperature drop by 0.5 °C and the EC increase by 7 μS.cm^{-1} were recorded, on the 4314 m by 0.3 °C and 9 μS.cm^{-1}, on footages of 4325 and 4358 m EC was increased by 18 resp. 17 μS.cm^{-1}, but also the temperature was increased by 0.6 resp. 0.5 °C, what points to shallow water circulation in these places. The whole series of aforementioned anomalies is then terminated again on the right bank and again only by slightly increasing conductivity on the right bank (by 3 μS.cm^{-1}, from 326 to 329 μS.cm^{-1}) and by lowering the water temperature (by 0.2 °C, from 20.3 to 20.1 °C) on 4404 m footage. The left-bank change in EC value of 21 μS.cm^{-1} on 4489 m footage did not have a temperature changing effect and was caused by a visible inflow of low yield (from behind a stone).

By following river course section, about 800 m long, the Slaná River gradually returns from the foothills of the Plešivská planina Plateau back to the foothills of the Silická planina Plateau, again crossing the entire width of its alluvium. However, up to 5000 m footage, this section is significantly hydraulically passive – for more than 500 m, no sudden drop in the water temperature of the surface stream has been recorded, either in the middle of the stream or at its edge. On the footage around 4930 m, there was a slight increase in the EC values at the left bank by 6 resp. 4 μS.cm^{-1} (from 323 to 329 and from 322 to 326 μS.cm^{-1} respectively), but these were accompanied by an increase in the water temperature (by 0.5 and 0.6 °C respectively). These increased temperature anomalies had some persistence along the river bank but did not occur in the middle of the stream. Measurement on 23/06/2016 was completed on footage of 5000 m at air temperature of 27 °C and water temperature in the river of 20.7 °C.

The next day of measurement (24/06/2016) began with 18.7 °C at the main flow (2.0 °C lower than at the end of the previous day measurement), but specific electric conductivity changed even more significantly – it was 334 μS.cm^{-1} compared to 320 μS.cm^{-1} measured at the end of the previous day. Stable values of water parameters, similarly as in the previous section, continued up to the 5070 m footage. Then there were five left-bank anomalies on the 110 m long section, two of which more significant. These can be found on footages 5074 and

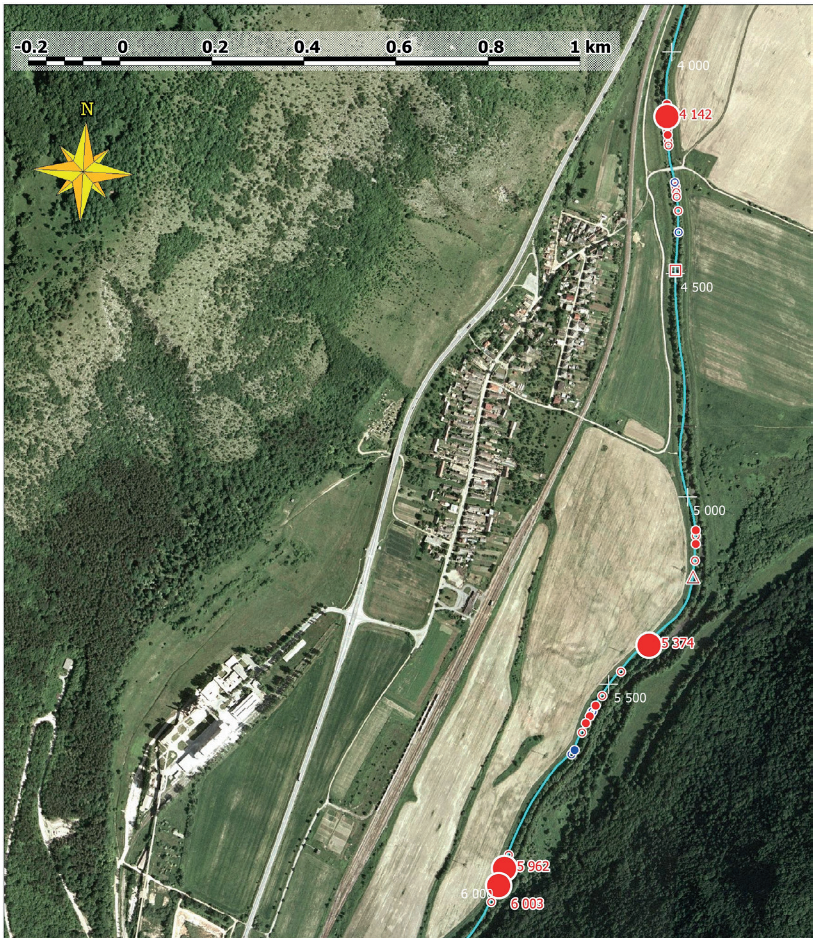

Fig. 8. Location of anomalies detected by thermometric and resistivimetric measurements on the river Slaná in the Brzotín – Gombasek section, 4000 to 6000 m footages. For explanation of symbols see Fig. 5.

5104 m, where the water temperature drops by 0.6 and 0.5 °C respectively and EC increases in 25 and 19 μS.cm^{-1} respectively. On footages 5086 and 5137 m, without water temperature change, only the specific electric conductivity is increased by 10, resp. 7 μS.cm^{-1}. On the footage 5174 m, the EC increase of 15 μS.cm^{-1} was registered as a manifestation of the visible water inflow into the stream, tributary from the 0.5 km distanced Pisztráng/Pstruhová vyvieračka karstic spring. It is interesting that the water temperature on the left bank reacts only in a drop by 0.1 °C. The left-side anomaly found on the footage 5374 m is more pronounced, where the water temperature has dropped by 2.6 from 19.0 to 16.4 °C and the conductivity has risen from 336 to 381 μS.cm^{-1} (by 45 μS.cm^{-1}). After this significant fluctuation of water properties of the Slaná River, the measured values up to 5520 m footage showed then only a stable course of values, with the exception of a small anomaly (again left-side) on footage 5452 m (water temperature drop by 0.1 °C, EC increase by 7 μS.cm^{-1}).

Between the 5525 and 5646 m footages, there is a frequent manifestation of temperature and specific electric conductivity anomalies on the appro-ximately 120 m long section on the Slaná River left bank. This situation is also illustrated in the interpretative graph of measurements on footages 5500–6000 m in Fig. 9. Its effect can be observed on this relatively long section for both variables along the shore, but the main streamflow remains unaffected. Anomalies in footages 5526 m, 5565 m and 5609 m are manifested only by a significant increase in EC – by 42, 30 and 10 μS.cm^{-1} – without sufficient parallel decrease in water temperature (or only by 0.1, 0.3 and 0.2 °C). Therefore, anomalies detected here are classified as minor hidden anomalies, compared to the more pronounced anomalies in footages 5550 m, 5573 m and 5588 m. The anomaly on footage 5550 m is characterized by a drop in the water temperature by 0.5 °C (from 19.4 to 18.9 °C) and increase of EC value by 25 μS.cm^{-1} (from 336 to 361 μS.cm^{-1}). On the footage 5573 m, the water temperature dropped by 0.5 °C and the EC increased by 64 μS.cm^{-1}, on the footage 5588 m by 0.7 °C and 29 μS.cm^{-1}. Interestingly, as soon as the above-described occurrence of anomalies on the left bank diminishes approximately on footage 5646 m, similar changes in water properties appear on the right river bank on approximately 55 to 60 m long section roughly between footage of 5651 and 5706 m. Influence of the lowered water temperature and increased EC can be observed here in the whole aforementioned section, but the most significant is the anomaly on 5655 m footage, where the temperature difference was found in 0.4 °C (decrease from 19.8 to 19.4 °C) and conductivity difference of 29 μS.cm^{-1} (increase from 334 to 363 μS.cm^{-1}). A less contrasting, but long-lasting anomaly was found on footage 5672 m (temperature drop by 0.1 °C and increase in EC by 17 μS.cm^{-1}). There were no phenomena documented by the hydrogeological mapping (Malík et al., 2013) to which the hidden inflows could be related.

After weakening of right-side anomalies approximately from the 5707 m footage, the stable water temperature of 20.0 °C and its EC value of 337 μS.cm^{-1} are maintained in the stream and along the banks of the Slaná River for approx. 230 m long section up to footage 5934 m. This state is eventually interrupted by fluctuations of values in small anomaly on 5934 m footage on the left bank (water temperature drop by 0.2 °C and increase in EC by 6 μS.cm^{-1}). Behind it, about 20 m long stone paved bottom stretches along the right bank of the river, and downstream a small left-bank anomaly on footage of 5954 m (water temperature drop of 0.5 °C and EC increase by 5 μS.cm^{-1}) signalizes the onset of very significant change of water properties at the left bank on the 5962 m footage. At this significant anomaly, a drop in water temperature of 2.4 °C and a rise in EC of 56 μS.cm^{-1} were measured, followed by a smaller anomaly on footage 5968 m (0.4 °C/20 μS.cm^{-1}). Manifestations of lowered temperature and increased EC are then following the left bank on approximately 80 to 90 m long section and can be considered to completely diminish on the 6050 m footage. Surface water properties of the Slaná River remained unchanged in EC but its temperature has increased from 20.2 to 21.0 °C (by 0.8 °C) during one-hour lasting lunch break (13 : 40 – 14 : 40). On the left bank, on 6003 m footage, another significant anomaly was then detected

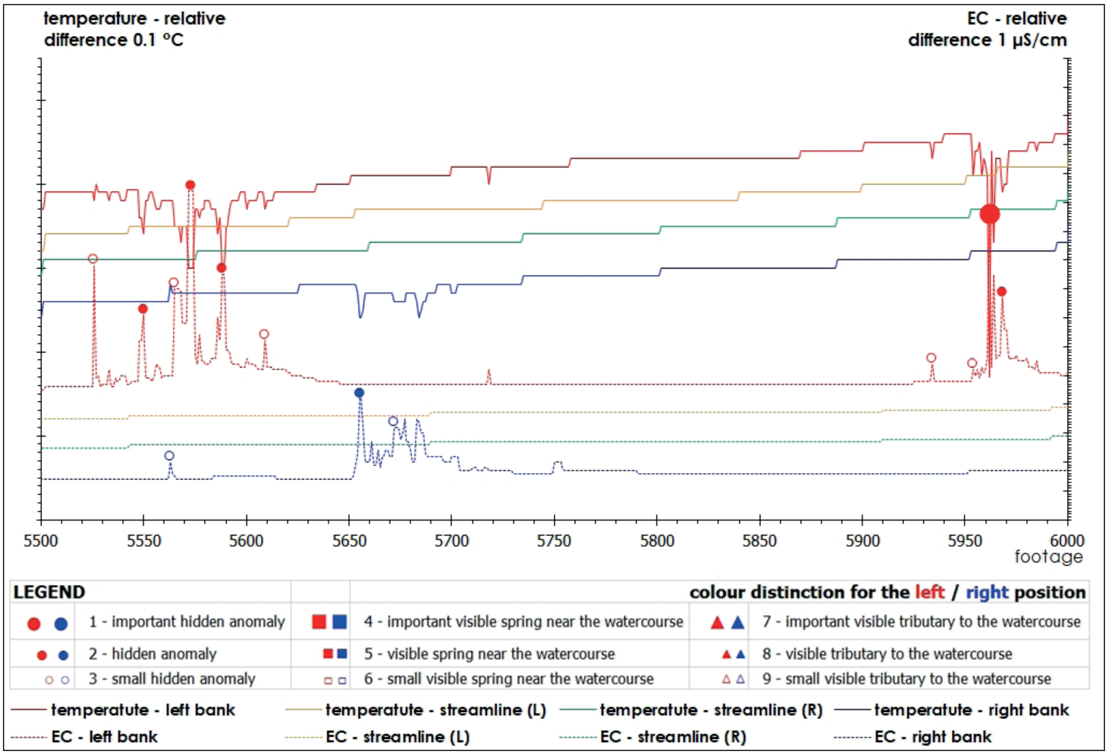

Fig. 9. Relative changes in the course of the water temperature of the Slaná River [°C] and its specific electric conductivity [μS.cm⁻¹] at both right and left banks, and in the middle of the river ("left middle – L" or "right middle – P" according to the measuring working group) in the footage 5500–6000 meters based on measurements from 24/06/2016.

by water temperature decreased in 1.8 °C and EC increase by 57 μS.cm^{-1}. This was followed by another minor anomaly 5 meters downstream (footage 6008 m; water temperature drop by 0.5 °C, conductivity increase by 20 μS.cm^{-1}). The whole section of left-side anomalies (in the 5950–6050 m footages) was then finally terminated by a small left-side anomaly at 6047 m (water temperature drop of 0.1 °C, EC increase of 6 μS.cm^{-1}). This part of the Slaná River watercourse can be considered as affected by the most significant manifestations of hidden groundwater inflows to the surface flow in the area south of the Slavec municipality, and here too, previous hydrogeological investigations on the ground surface did not document any phenomena pointing to groundwater – surface water interaction in these places.

An overview of the measurement results of the Slaná River on the footages from 6000 to 8300 m is shown in Fig. 10. After the smooth section of the stable water temperature and its specific electrical conductivity both in the streamflow and on the river banks, which follows from 6050 m footage and reaches approximately to 6360 m footage and is interrupted by only one small right-side anomaly on 6188 m footage (isolated drop of water temperature by 0.4 °C and increase of EC by 8 μS.cm^{-1}), the first significant right-side anomaly was detected on the 6367 m footage. It is situated approximately at the previously existing, in the meantime dry outflow intermittent stream from Slavec municipality between the Slaná River and the railroad, bringing water from the occasional karst spring Pri cintoríne ("Near the cemetery"), active only during higher water levels. The tributary riverbed is on the bank of the Slaná River terminated by a concrete building with a shut-off valve. At the time of measurement, this bed was dry, but a visible flow of surface water was observed on the bank of Slaná River. This was manifested by the above-mentioned anomaly on the 6367 m footage by decreasing the water temperature by 1.3 °C and increasing the EC by 46 μS.cm^{-1}. It is likely that there is still a hidden drainage of groundwater in the area from the right side, from the Plešivská planina Plateau (Pri cintoríne spring), although in small quantities. Low flow conditions at that time of measurements let this anomaly to resolve relatively quickly, after about 20 m. Continuation of thermometric and resistivimetric measurements revealed a visible water flow on the left bank on the 6402 m footage, in a small pool close to the streamflow. This visible inflow resulted in a decrease in the water temperature of 0.7 °C and an increase in its specific electrical conductivity by 39 μS.cm^{-1}. Several minor anomalies were found on the right bank, successively on footages of 6432 m, 6440 m, 6462 m and 6480 m where changes in 0.3 °C/11 μS.cm^{-1}; 0.1 °C/2 μS.cm^{-1}; 0.3 °C/9 μS.cm^{-1} resp. 0.1 °C/7 μS.cm^{-1} were detected, all for water temperature drop and EC increase. Shallow water exposed to the sun on the left bank contributed to the increase of the water temperature between footages of 6406 to 6494 m, while the EC value on the left bank in this section as well as the water temperature in the streamflow remained unchanged.

The following nearly 500 meters of the watercourse remain without significant anomalies. At the 6533 m footage, there was a small visible spring on the left bank, which was manifested by an increase in water temperature of 0.3 °C and an increase in EC of 5 μS.cm^{-1}, which was then accompanied by two smaller hidden anomalies on 6521 and 6536 m footages (EC increase by 2 and 5 μS.cm^{-1} respectively, water temperature decreased by 0.1 °C in both cases). On the 6673 m footage, a right-side anomaly was detected, indicated by a decrease in water temperature by 0.1 °C and an increase in its specific electrical conductivity by 9 μS.cm^{-1}. In the area of anomaly there is also a water management object on the right bank, a flood damper signalizing surface water communication, and perhaps also hidden groundwater communication, which may also lead to appearance of a hidden anomaly on the 6673 m footage. Between 6415 and 6720 m footages, there is a road bridge for the road leading to the Gombasecká jaskyňa Cave and the village of Silica. Another anomaly (left-bank) was detected on footage 6865 m and is characterized by a 0.3 °C drop in water temperature (from 22.1 to 21.8 °C) and an increase in EC value of 18 μS.cm^{-1} (from 341 to 359 μS.cm^{-1}).

The section between footage 6935 and 7166 m is accompanied by a series of minor anomalies on the left bank, part of which (footages 6935 m, 6948 m and 6983 m) is a manifestation of visible groundwater outflows on the left bank of the Slaná River (temperature decrease by 0.6, 0.1 and 3.5 °C and an increase in the EC of 7 μS.cm^{-1}, 3 μS.cm^{-1} and 67 μS.cm^{-1}). Anomalies representing possible hidden groundwater inflows to the surface stream were indicated on footages of 6962 m, 6,973 m and 6978 m. Here, a temperature decrease of 0.3 °C, 0.5 °C and 0.6 °C and an increase in the specific electrical conductivity of 8 μS.cm^{-1}, 19 μS.cm^{-1} and 21 μS.cm^{-1} were recorded. Nearby, a karstic spring of Biela vyvieračka ("White Spring")/ Margitin prameň ("Margita's spring") is lo-cated, and it is possible that the water in anomalies is coming from this source, moving in the underground in the alluvium of an old, no longer existing trough. The currently existing inflow from the Biela vyvieračka/Margitin prameň spring was recorded on footage of 7143 m. Its estimated discharge rate at the mouth was approximately 4 l.s^{-1}; the measured EC value directly in the inflow was 572 μS.cm^{-1} and the inlet water temperature was 15.2 °C. Directly at the mouth of the tributary, it was possible to observe the formation of recent travertines and travertine mass connecting gravel pebbles in the river alluvium. However, between this visible tributary and 7000 m footage there were even more anomalies indicating hidden groundwater inflows to the surface stream from its left side: on 7008 m footage there was a minor anomaly (water temperature drop of 0.4 °C and EC increase of 14 μS.cm^{-1}), bigger anomaly was on footage of 7023 m (water temperature drop by 0.6 °C and EC increase by 16 μS.cm^{-1}), and finally a smaller anomaly on the footage 7040 m (water temperature drop by 0.2 °C and EC increase by 13 μS.cm^{-1}). Still on the left bank, these were followed by three major anomalies on footages of 7064 m, 7087 m and 7107 m. On these temperature decreases of 0.5 °C, 0.6 °C and 0.4 °C were recorded with an increase in EC of 18 μS.cm^{-1}, 19 μS.cm^{-1} and 24 μS.cm^{-1}. In the case of the last of these anomalies, there was a visible groundwater inflow from the gravel paved by travertine to the Slaná River. At the same time, anomalies were also indicated on the right bank of the river – on footages 7094 and 7109 m. The first was manifested by a decrease in water temperature by 0.1 °C and an increase in EC by 23 μS.cm^{-1}; in the second case the water temperature drop was more pronounced (by 0.4 °C) and EC increase was less (by 12 μS.cm^{-1}). In the case of a minor anomaly found on the left bank on the 7166 m footage of the Slaná River (already below the mouth of the Biela vyvieračka/Margitin prameň spring), a drop in water temperature of 0.3 °C and an increase in EC by 12 μS.cm^{-1} was accompanied by a visible spring on the river bank.

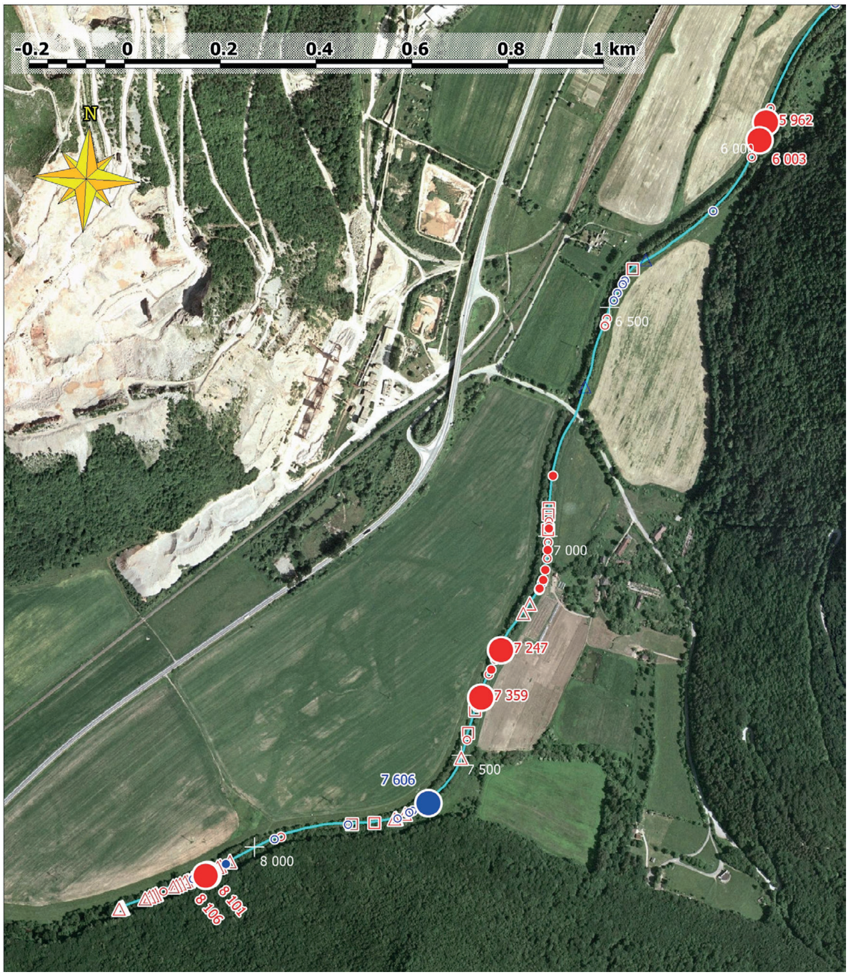

Fig. 10. Location of anomalies detected by thermometric and resistivimetric measurements on the river Slaná in the Brzotín – Gombasek section, 6000 to 8300 m footages. For explanation of symbols see Fig. 5.

The measurement on 24/06/2016 was completed on 7200 m footage at a water temperature in the river of 21.9 °C and its specific electrical conductivity of 340 μS.cm^{-1}. At the onset of measurements the next day (25/06/2016), the main water temperature was 20.2 °C (in 1.7 °C lower), and EC was 322 μS.cm^{-1} (in 18 μS.cm^{-1} less than the value measured at the end of the previous day). On that day, two significant anomalies were detected in the section between 7200 and 7500 m footages: on 7247 m, where a significant hidden anomaly was indicated by the measurement, accompanied by a 4.2 °C drop in the water temperature and a 194 μS.cm^{-1} specific electrical conductivity rise, and on footage 7359 m, where the water temperature drop by 3.7 °C and the EC increase by 220 μS.cm^{-1} were also accompanied by a visible manifestation of water output from the left bank of the Slaná River. In the meantime, both these significant anomalies were (always on the left bank) accompanied by several minor anomalies – in the section that recorded their onset were footages 7236 and 7244 m, which preceded the above-mentioned more significant hidden inflow on the 7247 m footage. In the case of 7236 m footage only EC increased by 7 μS.cm^{-1}, in the case of 7244 m footage, in addition to an EC increase of 20 μS.cm^{-1}, a temperature drop of 0.3 °C was also observed. This significant anomaly (footage 7247 m) was followed by indications of hidden groundwater inflows on footages 7254 m, 7259 m, 7270 m, 7275 m, 7299 m and 7311 m. Water temperature decreases of 0.3 °C/0.2 °C/0.2 °C/0.3 °C/0.4 °C and 0.3 °C were recorded there, as well as an increase in the EC values of 26 μS.cm^{-1}/7 μS.cm^{-1}/17 μS.cm^{-1}/18 μS.cm^{-1}/32 μS.cm^{-1} and 20 μS.cm^{-1}. Significant anomaly on footage 7359 m with visible manifestation of groundwater output was preceded by smaller anomaly on footage 7345 m (water temperature drop by 0.2 °C and EC increase by 44 μS.cm^{-1}), followed by cloud of smaller left-bank anomalies on footages of 7372 m, 7389 m, 7399 m, 7446 m and 7460 m. Decreases in water temperature of 0.3 °C/0.2 °C/0.3 °C/0.0 °C and 0.1 °C, and an increase in the specific electrical conductivity of 20 μS.cm^{-1}/20 μS.cm^{-1}/29 μS.cm^{-1}/18 μS.cm^{-1} and 30 μS.cm^{-1}. Of the five anomalies, two (on footages 7399 and 7446 m) were accompanied by a smaller visible groundwater inlet to the Slaná River.

On the footage of 7502 m, a visible tributary of the flow from the karstic spring Čierna vyvieračka ("Black spring"), previously an underground flow through the Gombasecká jaskyňa Cave, enters the Slaná River from the left. Its temperature at the mouth was 13.0 °C and a specific electrical conductivity of 624 μS.cm^{-1} was recorded here. The flow rate of this inflow was estimated to be about 10 l.s^{-1}. Mixing of the spring water with the river water along the left bank was evident up to the footage of 7539 m, may last beyond in high water stages. The flow of the Slaná River is already influenced by the backwater of a small hydroelectric power plant, deep water in many places made the continuous measurements impossible. The footage 7600 m is then assigned to the dam body, which divides a part of the Slaná River into an upper artificial derivation channel supplying the turbines of the power plant, closer to the foot of the slope eastwards, and the original old riverbed. The measurements took place in the old riverbed, again along both its banks. An anomaly was reported on footage 7606 m, associated with an increase in water temperature of 1.6 °C and an increase in conductivity of 128 μS.cm^{-1}. Due to its temperature, we assume that this is a manifestation of surface water leakage. In the continuation of the old Slaná riverbed, several other minor anomalies were found on 7676 m, 7654 m and 7681 m footages at the right bank. Changes of 1.1 °C/5 μS.cm^{-1}; 0.1 °C/7 μS.cm^{-1} resp. 0.2 °C/5 μS.cm^{-1} were recorded here where there was a decrease in water temperature and an increase in its EC value. Along the left bank, anomalies are found on the opposite section (footages of 7657 m, 7663 m, 7684 m and 7687 m). The biggest anomaly found there (footage 7657 m) was associated with a 0.3 °C water drop in water temperature and an increase in the specific electrical conductivity by 34 μS.cm^{-1}. The other three have already been associated with a higher water temperature than in the surface stream and are therefore associated with water leaking through the embankment of the uppermost derivation channel, and in the last three cases these leaks were directly visible by the naked eye. The observed changes in EC in footages of 7663 m, 7684 m and 7687 m were 40 μS.cm^{-1}; 21 μS.cm^{-1} and 17 μS.cm^{-1}, with temperatures varying within the range of 2.4 from 21.0 to 23.4 °C (Slaná River streamline temperature was 21.0 °C). A small inflow with a discharge rate of about 0.04 l.s^{-1} was visually observed on footage 7733 m, but this caused an extremely strong drop of 5.1 °C on the left bank water temperature and an EC rise by 46 μS.cm^{-1}. On the continuing course of water temperature records on the left bank of the Slaná River downstream we find only minor anomalies on footages 7778 and 7932 m. On its right bank, up to footage 8000 m (nearby the AK-15 hydrogeological borehole) only smaller anomalies were found on footages of 7786 and 7948 m. Aforementioned left-bank anomalies (on 7778 and 7932 m footage) can be characterized by a drop in water temperature by 0.7 and 0.3 °C; as well as increasing the EC value by 16 and 4 μS.cm^{-1}. A smaller groundwater inflow was also visually observed on 7,778 m footage in connection with the registered anomaly. Concerning right-bank anomalies (footage 7786 and 7948 m), a drop in water temperature by 0.2 resp. 0.1 °C and an EC increase by 3 and 6 μS.cm^{-1} were recorded – these were really small anomalies.

Along the left bank, a series of leaks from the more and more higher (with greater height difference between the levels) derivation channel of the power plant, whose step with turbines is located on the Slaná River near the Vidová-Rima osada area. The 8040 m footage shows a shift in water temperatures (an increase by 0.6 °C) during an approximately 1 hour lunch break while maintaining the specific electrical conductivity values. Visible leaks were observed in large quantities at the foot of the derivation channel. On 8051 m footage, leakage with EC parameters of 344 μS.cm^{-1}, temperature 18.6 °C and discharge rate of about 0.3 l.s^{-1} was manifested only by a small left-bank anomaly of EC increase by 1 μS.cm^{-1} and without change of water temperature. Much more pronounced was the hidden anomaly on the right bank on 8061 m footage (increase of water temperature by 1.7 °C and increase of EC by 56 μS.cm^{-1}). According to the water temperature, this is probably surface water input. From the leakages on footages of 8072 m, 8078 m and 8095 m (8072 m: EC 338 μS.cm^{-1}, water temperature 20.7 °C, discharge 0.5 l. s^{-1}; 8078 m: EC 342 μS.cm^{-1}, water temperature 20.2 °C, discharge approximately 0.5 l.s^{-1}; 8095 m: EC 352 μS.cm^{-1}, water temperature 21.1 °C, negligible discharge), only that from 8078 m footage can be considered as left-side groundwater inflow (water temperature drop by 1.7 °C, EC increase by 12 μS.cm^{-1}). However, the two adjacent left-hand anomalies on the footages 8101 and 8106 m were much more significant. They were characterized by a high temperature drop (by 4.4 and 4.6 °C) as well as by a steep change in conductivity (increase by 229 and 124 μS.cm^{-1}). In the area of the first anomaly, there was a small spring with a yield of about 0.05 l.s^{-1}, the spring in the area of the second anomaly had a discharge of up to about 1.0 l.s^{-1}, a conductivity of 592 μS.cm^{-1} and a water temperature of 11.0 °C. Given these parameters, it was obviously not a seepage water from the derivation channel, but a real manifestation of the transiting groundwater. Series of visible leaks from the derivation channel foot, with its position along the foot of the Silická planina Plateau slope continued also in the next sections. Leakage of approximately 0.1 l.s^{-1}

on footage 8126 m had the same EC as the river water, but the water temperature dropped by 2.3 °C. On footage 8132 m, there was a similar drop in water temperature of 2.0 °C, without conductivity change at the leak registered here. The leakage on the 8137 m had an EC value of 339 $\mu S.cm^{-1}$, the same as in the Slaná River stream, but its water temperature of 20.4 °C was in 1.1 °C decreased. In these places, finally a small anomaly of the hidden groundwater inflow was detected by lowering the water temperature by 1.0 °C and increasing the conductivity by 16 $\mu S.cm^{-1}$ at the right bank. Along the left bank, leaks from the dam were visually observed on footages of 8147 m, 8150 m and 8155 m, but they did not affect the water properties on the left bank of the old riverbed. Electric conductivity values measured here were 337 $\mu S.cm^{-1}$; 340 $\mu S.cm^{-1}$ and 395 $\mu S.cm^{-1}$, the water temperatures were 21.2 °C, 20.3 °C and 18.7 °C. The leak on meter 8150 m had an estimated discharge of 0.15 $l.s^{-1}$. Similarly, undetected in the river, was the impact of leaks from 8166 and 8182 m footages (although the first had a discharge of 0.1 $l.s^{-1}$, a temperature of 17.3 °C and an EC of 350 $\mu S.cm^{-1}$ and the second one, even discharge of approximately 0.8 $l.s^{-1}$, temperature 20.9 °C and EC of 338 $\mu S.cm^{-1}$). On the other hand, the leakage on the footage 8175 m between the aforementioned two, although at the surface of negligible yield, caused a decrease in water temperature of 0.9 °C and an increase in conductivity of 11 $\mu S.cm^{-1}$. On the footage 8205 m, an anomaly of a hidden groundwater inflow from the left bank, but without visible leaks from the derivation channel was detected by a decrease in water temperature of 1.0 °C and an increase in conductivity by 15 $\mu S.cm^{-1}$. The series of leaks from the channel above the left bank of the Slaná River old riverbed between footages of 8218 and 8240 m was manifested only by temperature drops, the difference in EC is (due to its similar source) only very slight. For the leakage on the footage 8218 m the EC value of 334 $\mu S.cm^{-1}$ and the water temperature of 21.7 °C were found, the large leakage on the footage 8220 m had 338 $\mu S.cm^{-1}$ and 21.0 °C and a discharge of about 0.2 $l.s^{-1}$, similar leakage on 8225 m had a discharge of approximately 0.4 $l.s^{-1}$, EC 338 $\mu S.cm^{-1}$ and a temperature of 20.5 °C. Between these two leakages, another water amount of approximately 1.0 $l.s^{-1}$ was seeping into the old riverbed. The leakage on the 8231 m footage had a temperature of 21.8 °C and a conductivity of 333 $\mu S.cm^{-1}$, and the last one in this section was the leakage on the 8240 m footage of about 0.2 $l.s^{-1}$, 20.2 °C and 340 $\mu S.cm^{-1}$. Temperature manifestations of these leakages in the Slaná River stream resulted in a significant decrease in water temperature by 1.5 °C on 8224 m footage and by 2.0 °C on 8242 m footage. Similarly to the section between 8140 and 8160 m footages, visually observed leaks from the derivation channel of the hydropower plant between footages 8290 and 8300 m did not affect the water properties on the left bank of the old riverbed. Gradually, a leakage of about 0.05 $l.s^{-1}$ of water at 18.9 °C with an EC value of 345 $\mu S.cm^{-1}$ was observed on footage 8290 m; 0.03 $l.s^{-1}$ of water with a temperature of 21.2 °C and an EC value of 338 $\mu S.cm^{-1}$ on the footage 8293 m and leakage with a water temperature of 21.9 °C and EC of 333 $\mu S.cm^{-1}$. On a footage of 8296 m it was about 0.4 $l.s^{-1}$ of water with a temperature of 21.3 °C and an EC value of 336 $\mu S.cm^{-1}$; on the 8298 m then there was a leak with a water temperature of 21.1 °C and an EC value of 339 $\mu S.cm^{-1}$. At that time, the temperature of the water stream in the Slaná River had a temperature of 22.2 °C and a specific electric conductivity of 331 $\mu S.cm^{-1}$. On the footage 8300 m, the measurements of 25/06/2016 as well as all measurements in the section between Brzotín and Gombasek were completed. The list and location of the most significant hidden anomalies

Tab. 2

List of the most important hidden anomalies detected by thermometric and resistivimetric measurements in the Brzotín – Gombasek section of the Slaná River within the 21/06/2016 – 25/06/2016 period and coordinates of their location (S-JTSK coordinate system).

Footage	Anomaly position	Date of detection	X – SJTSK coordinates	Y – SJTSK coordinates
95	right-hand	21/06/2016	–319 298.411	–1 247 663.155
1932	left-hand	22/06/2016	–320 210.395	–1 249 183.652
1935	left-hand	22/06/2016	–320 210.956	–1 249 185.734
1991	right-hand	22/06/2016	–320 225.100	–1 249 226.696
2239	left-hand	22/06/2016	–320 326.176	–1 249 449.714
2275	left-hand	22/06/2016	–320 344.190	–1 249 480.750
2477	left-hand	22/06/2016	–320 509.375	–1 249 596.989
2709	right-hand	22/06/2016	–320 712.472	–1 249 703.060
3170	left-hand	23/06/2016	–321 089.051	–1 249 936.888
3185	left-hand	23/06/2016	–321 096.591	–1 249 953.836
3462	left-hand	23/06/2016	–321 143.573	–1 250 219.787
4142	left-hand	23/06/2016	–321 334.789	–1 250 845.376
5374	left-hand	24/06/2016	–321 373.394	–1 251 993.740
5962	left-hand	24/06/2016	–321 687.469	–1 252 478.810
6003	left-hand	24/06/2016	–321 700.782	–1 252 516.582
7247	left-hand	25/06/2016	–322 240.598	–1 253 580.874
7359	left-hand	25/06/2016	–322 281.701	–1 253 679.324
7606	right-hand	25/06/2016	–322 392.022	–1 253 899.883
8101	left-hand	25/06/2016	–322 852.895	–1 254 049.285
8106	left-hand	25/06/2016	–322 857.149	–1 254 051.279

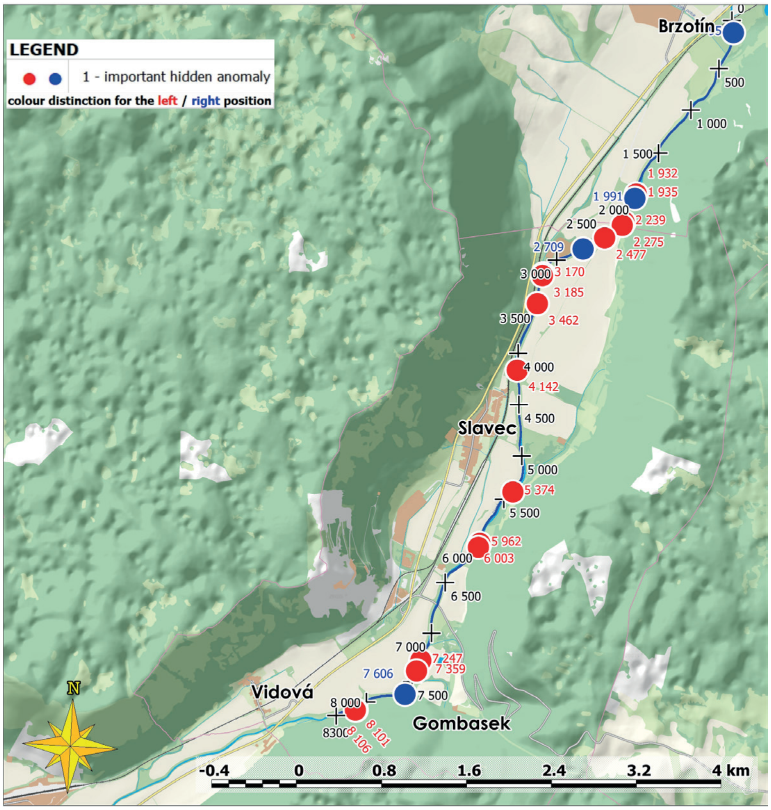

Fig. 11. Overview of the most important anomalies detected by thermometric and resistivimetric measurements performed within the period 21/06/2016 – 25/06/2016 in the Brzotín – Gombasek section of the Slaná River.

detected by thermometric and resistivimetric measurements in the Slaná River between Brzotín and Gombasek within the period 21/06/2016 – 25/06/2016 are shown in Tab. 2 and their overview in Fig. 11.

Conclusion

Results of longitudinal profile measurement of specific electric conductivity (resistivimetry) and water temperature (thermometry) along the watercourse of the Slaná River in its segment between Brzotín and Gombasek municipalities during 5 summer days from 21/06/2016 until 25/06/2016 enabled identification of hidden groundwater inflows position. Although many small anomalies were found, no major karstic groundwater inlets that would be able to influence water temperature and its specific electric conductivity were found here.

More pronounced hidden groundwater inflows to the Slaná River were found in several sections between the footages of 1900 and 8000 m. Detected hidden inflows mostly correspond to the position of already known important karstic springs rising from the foot of the western slopes of the Silická planina Plateau. Such significant left-side anomalies from the footages of 1932 and 1935 m correlate with their location to the visible springs of Hradná vyvieračka/Várforrás. Downstream, also left-side ano-malies of footages 2239 m, 2275 m and 2477 m are also interesting as these can point to hidden groundwater flow from the karstified Triassic limestones of the Silická planina Plateau towards Slaná River through gravels of Quaternary alluvia. However, right-hand anomalies from the footages of 1991 and 2709 m can be considered as also interesting, as quite distanced from the Plešivská planina Plateau and from the Brzotínska vyvieračka/Gyepü spring, the only karst water outlet is in these places. However, the highest right-hand anomaly on 95 m footage which does not manifest itself in temperature (only the value of specific electrical conductivity is increased), can be attributed to the passage of groundwater previously circulating in alluvium which could be partially affected by human polluting activity. Much more interesting is the origin of large left-side anomalies, which were registered along the left bank of the Slaná River on footages of 3170 m, 3185 m, 3462 m and 4142 m. Despite the fact that Slaná River watercourse in these places directly touches the foot of the Plešivská planina Plateau, any indication of visible or hidden groundwater inlet into the surface stream was recorded here. The presence of left-sided anomalies on these places suggests that groundwater flow here must cross a wide alluvium between the river and the foot of the Silická planina Plateau, while the side of Plešivská planina Plateau remains hydraulically inactive. The last of these anomalies (on the footage of 4142 m) could correspond by its location to the position of the karst spring Pod Veľkou skalou, which is known for strong variations in yield. It is possible that at minimum water stages these karstic waters are invisibly entering the alluvium and after passing this Quaternary gravely aquifer they feed the river. The point of their inlet can be marked by the anomaly found on footage 4142 m.

Similarly to the Hradná vyvieračka/Várforrás spring near Brzotín situation, where anomalies were found several hundred meters below it, we can possibly attribute left-hand anomalies on footages 5374 m, 5962 m and 6003 m to residual karstic groundwater that are visible rise in the Pstruhová vyvieračka/Pisztráng spring. This is already captured and exploited drinking water source, but remains of uncaptured waters are possibly invisibly feeding alluvial gravels and only after flowing here in direction parallel to the Slaná River course, they finally appear on its left bank. In the area of Gombasek, along the left bank of the Slaná River on the stretch between footages 6850 to 7500 m, a series of small anomalies located between the springs Biela vyvieračka spring (also known as Margitin prameň spring) and Čierna vyvieračka spring (outflow from the underground hydrologic system of the Gombasecká jaskyňa Cave) is clearly visible. It is obvious that part of waters here either re-enters the Quaternary sediments from the short streams bellow the springs, or is directly fed in the underground by karstic groundwater of Triassic limestones, and later in groups of scattered inlets subsidize the Slaná River from its left bank. The most prominent points of these surpluses were indicated by anomalies on footages of 7247 and 7359 m. This makes the presence of a right-side anomaly at these places (footage 7606 m) even more interesting. The 7606 m footage anomaly is associated with an increase in water temperature (in 1.6 °C) with parallel EC increase in 128 μS.cm^{-1}, so we assume that this is a manifestation of surface water or the water that had previously been in contact with the ground surface.

During the measurements in the old riverbed of the Slaná River, numerous left-side inflows from the body of the supply channel embankment belonging to the small hydroelectric power plant were observed. The river step equipped with turbines is several hundred meters downwards around the Vidová-Rima osada site. These anomalies did not show any significant indication of groundwater inlets, but the presence of such a number of leaks is likely to jeopardize the stability of the embankment of this supply channel. However, this falls within the competence and responsibility of the Slovak Water Management Company to assess the seriousness of our findings. Karst groundwater outflows in these places were contrasting with the characteristics of the aforementioned seepages. These (karst groundwater outflows) were found in two adjacent left-hand anomalies (footages 8101 and 8106 m). Inlets of karstic groundwater was characterized by a high temperature drop (by 4.4 and 4.6 °C) as well as by a step change in EC (increase by 229 and 124 μS.cm^{-1}, respectively). In the area of the first mentioned anomaly, also a small spring with discharge rate of about 0.05 l.s^{-1} was registered, and the spring found in the area of the second anomaly had a discharge of nearly 1.0 l.s^{-1}, electric conductivity of 592 μS.cm^{-1} and water temperature 11.0 °C. In the vicinity of these groundwater inlets, there is no other natural karstic spring (visible groundwater outlet) at the foot of the Silická planina karstic Plateau, and the anomalies thus indicate the presence of an intense hidden surpluses of karst groundwater from limestones covered by alluvial gravels here.

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Skryté prestupy podzemných vôd Slovenského krasu do rieky Slaná medzi Brzotínom a Gombasekom identifikované termometrickými a rezistivimetrickými meraniami

Merania mernej elektrickej vodivosti (rezistivimetria) a teploty vody (termometria) pozdĺž povrchového vodného toku vykonávané v dostatočne zahustenej sieti meracích bodov dokážu identifikovať polohu skrytých prítokov podzemnej vody do povrchového toku v prekvapivo podrobnej miere detailu. Pri intervalových meraniach prietoku, t. j. meraní a vzájomnom porovnávaní prietoku na vhodne vzdialených miestach tokov, dokážeme kvantitatívne definovať skryté prestupy do toku alebo straty prietokového množstva, ale veľkosť prestupu môžeme priradiť iba k istému segmentu toku s dĺžkou rovnajúcou sa vzdialenosti meraní. Na rozdiel od toho, výstupy termometrie a rezistivimetrie majú potenciál presnej identifikácie polohy prestupov, a to aj bez ich kvantifikácie. Časovo najvhodnejšie obdobia na termometrické a rezistivimetrické merania sú vrcholiace leto alebo zima, ktoré prirodzene zvýrazňujú teplotný kontrast povrchovej a podzemnej vody. V našom prípade sa termometrické a rezistivimetrické merania uskutočnili na toku rieky Slaná v jeho úseku medzi obcami Brzotín a Slavec, časť Gombasek. Rieka sa tu vo forme kaňonu širokého aj hlbokého niekoľko sto metrov prerezáva pomedzi dve veľké krasové planiny (Silickú planinu a Plešivskú planinu). V tejto oblasti sú známe tri veľké krasové pramene, ale skryté odvodňovanie krasovej podzemnej vody priamo do rieky Slaná nebolo doteraz preskúmané. Merania na danom úseku rieky v dĺžke 8 300 m sa uskutočnili počas 5 letných dní od 21. do 25. 6. 2016. Základný krok meraní bol 1,0 m, jednotlivé zámery sa realizovali 20 cm od okraja toku pozdĺž ľavého a pravého brehu, ako aj v prúdnici aktívneho toku Slanej. Oba parametre, teplota vody a merná elektrická vodivosť, sa merali v blízkosti dna ~ 5 cm nad ním a vo vzdialenosti ~ 20 až 40 cm od brehu. Na celom úseku toku rieky Slaná medzi Brzotínom a Gombasekom dlhom 8 300 m sa však nezistili žiadne významné skryté prítoky krasovej podzemnej vody. Malé prítoky boli väčšinou situované na ľavom brehu a naznačovali smer prúdenia skryto prestupujúcej podzemnej vody z východu – od priestorov Silickej planiny. Zdá sa, že prinajmenšom v nami overovanom úseku sa Plešivská planina odvodňuje len cez známe krasové pramene, registrované západne od rieky Slaná.

Z celkového priebehu termometrických a rezistivimetrických meraní (teploty vody a jej mernej elektrickej vodivosti) realizovaných v dňoch 21. až 25. 6. 2016 na rieke Slanej v úseku medzi Brzotínom a Gombasekom možno určiť polohu významnejších anomálií, ktoré by mohli byť spôsobené skrytými prestupmi podzemnej vody do povrchového toku. Treba však konštatovať, že k skutočne výrazným prestupom veľkého množstva podzemnej vody, ktoré by ovplyvnilo aj teplotu vody a vodivosť celého toku meraného v prúdnici, tu nedochádza. Významnejšie prestupy sme zaznamenali na niekoľkých úsekoch medzi 1 900 a 8 000 m. V porovnaní s pomerne malým výskytom pravostranných anomálií boli v oveľa väčšej miere anomáliami indikované skryté prestupy podzemnej vody do ľavého brehu Slanej (v smere od Silickej planiny). Tie vo veľkej miere svojou polohou zodpovedajú polohe významných známych krasových prameňov vystupujúcich z úpätia západných svahov Silickej planiny. Významné ľavostranné anomálie z úsekov 1 932 a 1 935 m svojou polohou korelujú s viditeľnými vývermi prameňa Hradná vyvieračka/Várforrás. Zaujímavé sú aj ľavostranné anomálie nachádzajúce sa nižšie po toku z úsekov 2 239, 2 275 a 2 477 m, ktoré by mohli indikovať pohyb krasovej vody z vápencov budujúcich Silickú planinu do Slanej prostredníctvom aluviálnych náplavov, do ktorých skryto vstupujú z planiny. Zaujímavé sú ale aj pravostranné anomálie z úsekov 1 991 a 2 709 m, ktoré sú dosť vzdialené od Plešivskej planiny, resp. od Brzotínskej vyvieračky/Gyepü, ktorá ju v týchto miestach odvodňuje. Najvyššie sa nachádzajúcu pravostrannú anomáliu na úrovni 95 m, ktorá sa teplotne neprejavuje (stúpla len hodnota mernej elektrickej vodivosti), môžeme priradiť k prestupu vôd infiltrovaných a obiehajúcich v alúviu. Tie mohli byť čiastočne ovplyvnené (znečisťujúcou) činnosťou človeka. Oveľa zaujímavejší je pôvod veľkých ľavostranných anomálií, ktoré boli registrované popri ľavom brehu Slanej na úsekoch 3 170, 3 185, 3 462 a 4 142 m. Napriek tomu, že tok rieky Slanej sa v týchto miestach dotýka úpätia Plešivskej planiny, z jej strany nebol na pravom brehu toku Slanej zaznamenaný žiaden náznak viditeľného alebo skrytého vstupu podzemnej vody do povrchového toku. Prítomnosť ľavostranných anomálií naznačuje, že prúd podzemnej vody tu musí križovať široké alúvium smerom od úpätia Silickej planiny, kým zo strany Plešivskej planiny k jej odvodňovaniu nedochádza. Posledná z uvedených anomálií (na úseku 4 142 m) by svojou polohou mohla zodpovedať polohe krasového prameňa Pod Veľkou skalou, ktorý je známy silným rozkyvom výdatnosti (je možné, že pri minimálnych vodných stavoch voda vstupuje iba skryto do alúvia a až neskôr do rieky, čo môže byť signalizované anomáliou zistenou na úseku 4 142 m).

Podobne ako v prípade brzotínskej Hradnej vyvieračky (prameňa Várforrás) sa anomálie zistili aj niekoľko stoviek metrov pod ňou. Ľavostranné anomálie na úsekoch 5 374, 5 962 a 6 003 m môžeme pravdepodobne priradiť k zvyškovej krasovej vode, ktorá viditeľne nevystupuje v prameni Pstruhový/Pisztráng (tiež „Pstružia“ alebo „Vodovodná“ vyvieračka, ktorý je v súčasnosti vodárensky zachytený), ale pravdepodobne sa pod známou úrovňou výstupov skryto „vlieva“ do aluviálnych náplavov a až po pretečení (v prúde paralelnom s tokom rieky) skryto prestupuje do Slanej. V oblasti Gombaseka potom možno popri ľavom brehu Slanej zhruba na úseku medzi 6 850 až 7 500 m sledovať sériu malých anomálií, ktoré sa nachádzajú medzi prameňmi Biela vyvieračka (tiež Margitin prameň) a Čierna vyvieračka (vyústenie krasového podzemného toku pretekajúceho Gombaseckou jaskyňou). Je zjavné, že časť tu vyvierajúcich vôd buď spätne vstupuje do kvartérnych sedimentov, alebo do nich priamo vteká z prostredia skrasovatených vápencov a rozptýlene dotuje rieku Slanú z jej ľavého brehu. Najvýraznejšie miesta týchto prestupov boli indikované anomáliami na úsekoch 7 247 a 7 359 m. O to zaujímavejšia je prítomnosť pravostrannej anomálie v týchto miestach (7 606 m). Pretože je však táto anomália spojená so zvýšením teploty vody (o 1,6 °C) pri zvýšení jej vodivosti o 128 μS . cm^{-1}, predpokladáme, že ide o prejav povrchovej vody, resp. vody, ktorá už bola v predchádzajúcom čase v kontakte s povrchom terénu. Počas meraní na starom koryte Slanej sme pozorovali množstvo prítokov z telesa hrádze prívodného kanála malej vodnej elektrárne, ktorej stupeň (stavba s turbínami) sa nachádza na rieke Slanej v oblasti Vidovej, osady Rima. Vzhľadom na obeh podzemnej vody zväčša nemali významný indikačný význam, no prítomnosť takého množstva miest presakovania môže pravdepodobne ohrozovať stabilitu telesa hrádze tohto prívodného kanála. To však patrí do kompetencie Slovenského vodohospodárskeho podniku, ktorý by mal posúdiť reálnu závažnosť daných zistení. Vývery krasovej podzemnej vody v týchto miestach, ktorá je z hľadiska vlastností v kontraste so spomínanou presakujúcou vodou, sa zistili na dvoch susediacich ľavostranných anomáliách (úseky 8 101 a 8 106 m). Táto voda bola charakteristická vysokým poklesom teploty (o 4,4, resp. 4,6 °C), ako aj skokovou zmenou vodivosti (nárast o 229, resp. 124 μS . cm^{-1}). V oblasti prvej z nich sa navyše vyskytoval malý prameň s výdatnosťou zhruba 0,05 l . s^{-1}. Prameň v oblasti druhej anomálie mal výdatnosť až okolo 1,0 l . s^{-1}, vodivosť 592 μS . cm^{-1} a teplotu vody 11,0 °C. V blízkosti uvedených prestupov podzemnej vody sa na povrchu terénu (pri úpätí krasovej planiny) nevyskytuje žiaden viditeľný prirodzený vývер (prameň). Dané anomálie tak indikujú prítomnosť intenzívneho skrytého výstupu krasovej podzemnej vody z krasových priestorov prekrytých alúviom.

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