Detection of iron-rich groundwater "hot spots" entering streams in Lusatia

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Abstract

In the German Lusatian Lignite Mining Region, high iron concentrations occur in the groundwater, which discharges to natural streams and brings about unfavourable conditions. It was suspected that the iron load to streams varies greatly in space, and that the contamination originates from discrete point sources (hot spots). Water quality analyses of the few local monitoring wells were found to be insufficient to characterise the problem. A direct push technique for exploring iron hot spots was therefore developed to better identify the areas of high priority for remediation. The developed method was tested at a 700-m-long section of the stream "Kleine Spree", where the presence of hot spots was expected and the planning of remedial measures is already underway. Along that section several samples have been taken from the stream bank and a large spatial variation of iron concentrations was found. While the highest detected dissolved iron concentration in the groundwater beneath the stream bank was about 400 mg/L, 50 m downstream the concentration was only about 240 mg/L and 100 m further it decreased to 50 mg/L. Temperature measurements were conducted to qualitatively characterize the groundwater influxes along the studied section of the stream.

Key words: river, groundwater, iron, hot spots, Kleine Spree

Introduction

In the German Lusatian Lignite Mining Region, acid mine drainage causes high iron and sulphate concentration in the groundwater. With the rising groundwater table that follows closure of open pit mines the iron-rich water discharges into natural streams, oxidizes and settles into a thick layer of iron sludge, bringing about unfavourable conditions for organisms and for commercial and recreational use.

Areas of iron-rich water discharge can be roughly located using flow measurements and water sampling in the stream. Explorations of shallow groundwater quality in these areas have shown that the local iron concentrations differ greatly. This implies that high concentrations appear in the form of so-called "hot spots" (IWB 2012). Due to their linear structure and high cost, remedial measures such as subterranean barriers, injection of oxidizing agents or pump-and-treat should be limited only to areas of high priority. It is therefore imperative to locate these hot spots as accurately as possible.

The use of existing observation wells is not suitable for this purpose, because the information they provide about the spatially differentiated groundwater conditions is limited due to their low spatial density, permanently fixed locations and the positions and lengths of their filter sections. It is difficult to make sure that the water sampled is the same as the water entering the stream, and thus difficult to reliably quantify the iron load to the stream. To understand the interactions between groundwater and surface water and to identify contamination caused by mining leachate or natural hot spots, a characterization of geochemical characteristics at high spatial resolution is essential (Cirmo and McDonell 1997, Nimick and von Guerard 1998). In several studies, the direct push water sampling method was used to gain depth-specific groundwater quality results (Pitkin et al. 1999, Edge and Cordry 1989). Schulmeister et al. (2003) discovered that this method is suitable for the measurement of inorganic parameters like iron. The simplified direct push technique offers the benefits of no drill cuttings, minimal purge water generation and efficient sampling for a large number of points.

To explore the hot spots in the study area, a direct push method for water sampling was developed and tested. An abstraction element is rammed into the stream bed or bank to the desired depth and the water abstracted using a hand vacuum pump. This technique requires only two people and results can be gained fast and flexibly while on site. Challenges included the thick sludge deposit of iron hydroxide in the stream and fine soil material in the aquifer, which can clog the filter of the abstraction element and lead to turbid water samples and falsified lab results.

The method was tested along a section of a stream in Lusatia. In designing the sampling device and conducting all measurements simplicity and efficiency had the highest priority after the quality of data. In this way this method can be easily applied at any similar sites to obtain good results in a short period of time.

Study area

The “Kleine Spree” is a tributary of the Spree River with a total length of 40 km and a catchment area of 175 km² within the German state of Saxony. The long-term mean discharge of the Kleine Spree is 2,500 L/s. In previous investigations areas of significant interaction with iron-rich groundwater were detected by using flow measurements and water sampling at intervals of several kilometres along the river. Furthermore, a groundwater inflow rate of 200 - 300 L/s with a total iron concentration of 60 - 80 mg/L was determined. Explorations of shallow groundwater quality within these areas have shown that the local iron concentrations vary greatly (IWB 2012).

A 700-m-long section of the Kleine Spree was selected to test the developed direct push method. The section is about 2 km upstream from the confluence with the Spree River and lies to the south of the village Spreewitz (Fig. 1). It stretches from the Railway Bridge (St. 1+000) in the Southwest over the area of the Old Cloth Factory (St. 1+200) to the bottleneck to the Spree (St. 1+700) in the Northeast. The closed and flooded open pit mine “Burghammer” and its overburden stockpile are located to the south of the study area, which affect the groundwater dynamics and chemistry and therefore the Kleine Spree. In addition to the closed pit mine Burghammer the most significant source of pollution (75 %) is supposed to be in the Pleistocene aquifer of the “Spreewitzer Rinne”, caused by pyrite oxidation (acid mine drainage) (IWB 2012).

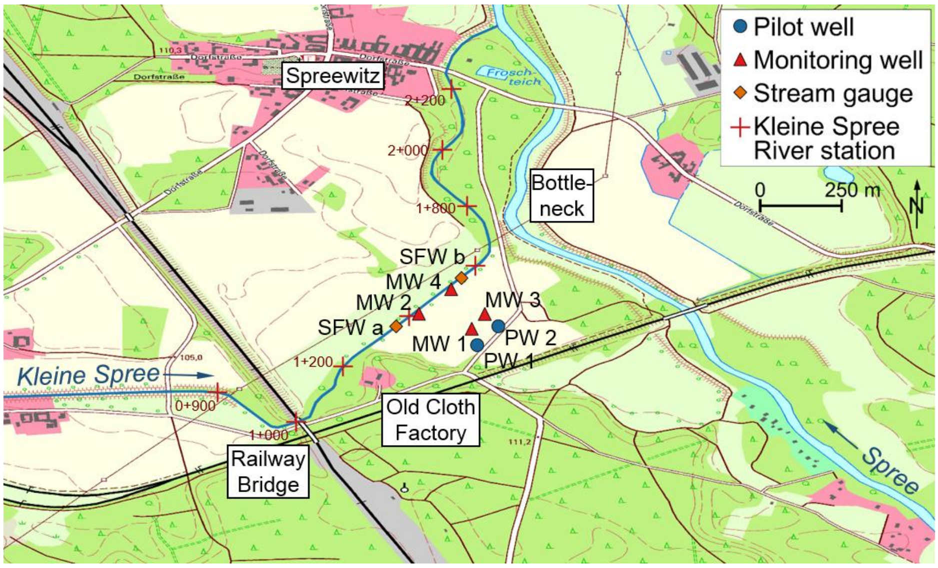

Figure 1 *Overview map of the study area.*

Downstream of the Railway Bridge the Kleine Spree gently meanders for 300 m with deciduous forest on the right and agricultural fields on the left, before running straight down to the bottleneck. The stream has a natural bed and gradient and the banks are host to dense vegetation. As the groundwater generally flows in a northwesterly direction with a shallow groundwater table, the right stream bank of the Kleine Spree was the focus of the investigations.

Planning and construction of remedial measures in the study area are already underway. A gallery of remediation wells is intended to capture the iron-rich water, which needs to be treated after abstraction. Two pilot wells were already constructed and tested. Four monitoring wells and two additional gauges in the stream were used to observe the groundwater and surface water levels and to determine the flow direction.

Materials and Methods

Water sampling probe

For testing purposes a water sampling probe (WaSP) was designed and manufactured with tool steel. The total length of the WaSP is about 200 mm, consisting of a 30-mm-diameter drive point (Fig. 2) and the 75-mm-long abstraction unit, which is reduced to a diameter of 25 mm. A total of 64 inlet ports with an opening width of 3 mm were placed all around the abstraction unit, to enable the groundwater to enter. A Prestolok® Push-In fitting is used to allow a quick and air tight connection to the polyethylene (PE) tubing (d= 4 mm). The WaSP screws into regular drill rods (d= 36 mm) to extend the tool as needed.

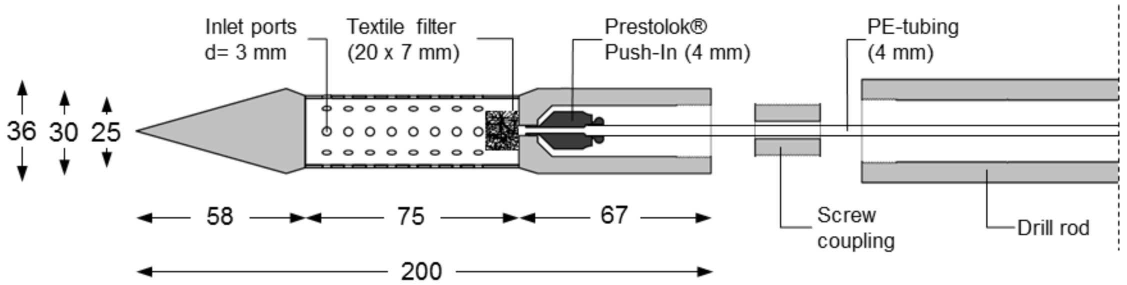

Figure 2 *Drawing of the WaSP and its components (not to scale).*

Initially a fine-mesh stainless steel screen was installed behind the inlet ports to prevent fine-grained sediment from entering to reduce the turbidity of the water sample. During the first tests, the screen became clogged by the thick sludge deposit of iron hydroxide in the stream. Furthermore the screen was damaged after just a few uses and needed to be changed out. Therefore the stainless steel screen was replaced by a modified geotextile filter, which can be easily installed inside the abstraction unit. Fine-grained sediment entering through the inlet ports now settled to the bottom of the abstraction unit after installation of the WaSP or was held back by the geotextile filter. After use, the abstraction unit can be purged by reverse flow.

In the design and operation of the WaSP there are three main criteria that need to be fulfilled to ensure a high-quality sample:

- Do not clog the WaSP with fine sediment or sludge,
- Do not contaminate or falsify the sample through unwanted influence from the soil layers above, for instance the sludge layer on the river bank, and
- Minimize destruction of the soil matrix and the consequent risk of adsorption of dissolved iron in the groundwater to be sampled.

Between August and December 2015, five sampling campaigns were carried out using the WaSP. To obtain as many samples as possible using comparable methods and detect variations in iron concentrations along the river, groundwater quality on the right-hand bank of the Kleine Spree was the primary measurement focus. Initially, two sampling points were envisioned for every cross-section to be investigated, one in the centre of the river (a) and one on the bank (b) (Fig. 3). The ground entry point for sampling at location (b) was chosen at a horizontal distance less than 0.5 m above the water line at the bank (Fig. 4). This ensured that no short-circuit flow occurred along the WaSP's drill rod between the surface water and the sampling point. For this reason, sampling point (b) was ultimately preferred, and only a smaller number of comparison measurements were taken at sampling point (a) for the cross-sections visited.

Iron hydroxide sludge deposits up to 0.3 m thick can be found along the banks of the Kleine Spree. As these posed a threat through contamination of water samples or clogging of the WaSP, a 0.5 to 1-m-deep hole was first created using a percussion core sampler (d_{outer} = 360 mm). The WaSP was lowered to the bottom of the hole and rammed in 0.2 to 0.4 m further using a sledge hammer. Prior to the design improvement using the geotextile filter, the WaSP was repeatedly clogged by fine-grained sediment. To combat this, 50 to 100 mL of bottled tap water was infiltrated through the WaSP's PE tubing using a sealed 100-mL laboratory syringe.

Upon reaching the desired sampling depth, at least twice the volume of water infiltrated in this way was pumped out before the actual sample was taken. The entire sampling apparatus including the syringe can be seen in Fig. 5.

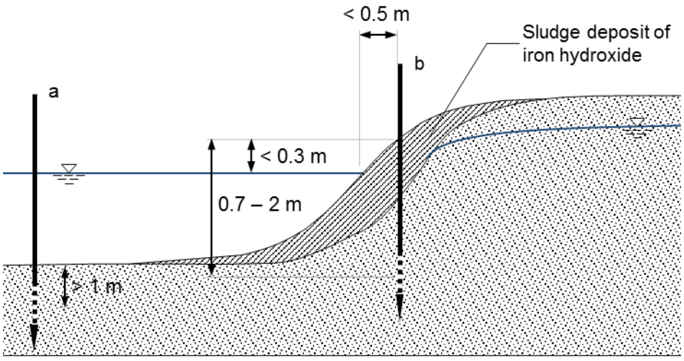

Figure 3 *Typical cross-section of the Kleine Spree with two planned measuring points.*

Figure 4 *Typical ramming installation of the WaSP on the bank at sampling point (b), using a hammer.*

Ramming the WaSP partially destroyed the soil matrix, which led to a visible increase in turbidity of the water sample. This can lead to the undesired effect that dissolved iron is adsorbed to the exposed grains of the freshly destroyed soil matrix or reversely, adsorbed or deposited iron is released from destroyed surfaces and conglomerates (Grischek et al. 2005). The turbid water was pumped out using a hand-vacuum pump at the lowest possible suction pressure and collected in a collection bottle (Fig. 5). The extraction flow rate ranged from 50 to 100 mL/min. Between 150 and 900 mL (300 mL on average) was pumped out before taking the sample.

The air-tight collection bottle was attached to the sampling tube, separated by a three-way valve with the Luer-Lock Connection System. A sampling syringe (V = 50 mL/ 100 mL) was attached to the last remaining valve port. The water sample was collected by closing off the tube to the collection bottle and drawing the water out of the ground under slight suction pressure. In this way, it was ensured that the water samples at no point came into contact with oxygen, until they were deposited into the sample bottles prepared with nitric acid. Syringe filters with a pore size of 0.45 µm were used to filter the samples before entering the sample bottles. At each sampling point a total of 5 sample bottles were filled (V_{tot} = 135 mL).

Water quality analysis

Field parameters electrical conductivity and pH were measured in a glass beaker using a MultiLine® Multi 3430 (WTW). To gain first information in the field, two field test kits from Merck (MColortest and MQuant) to determine iron have been used. The analysis of total iron (Fe_{tot}), dissolved iron and major cations and anions was performed parallel in two independent laboratories (HTW and ERGO). Cations were determined by ICP-OES (Spektrometer Optima 4300 DV, Perkin Elmer). Anions were determined using ion chromatography (ICS 900, Dionex).

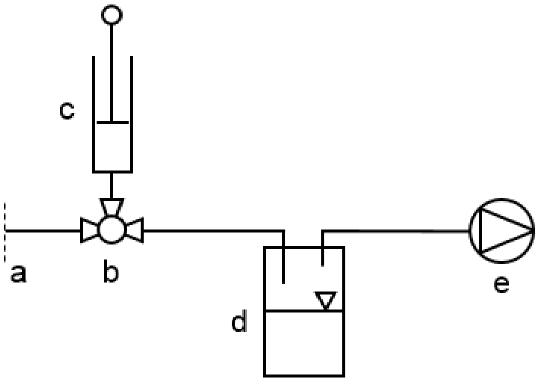

***Figure 5** Sampling equipment with the tube from the WaSP (a), a three-way valve (b), the connection to the sampling syringe (c) and the air-tight collection bottle (d) with the vacuum pump (e).*

Temperature measurements

Temperature measurements were conducted in the Kleine Spree to gain qualitative results in December 2015. The temperature in the river bed was measured at a depth of about 15 cm using a probe thermometer (FLUKE 561). Each cross-section was measured at 5 points in the river bed and one in the river water, at intervals of about 10 m along the river. The background groundwater temperature was measured in the 2 monitoring wells close to the river.

Results

During the site visits along the river it was possible to visually identify points of groundwater inflow, especially when the river water level was low. These were especially apparent near the Old Cloth Factory (St. 1+200), on the right side of the river. They were identifiable through a very wet bank with terraced pools and recognizable runoff channels in the sludge layer (Fig. 6).

***Figure 6** Evidence of groundwater influx on the right bank..*

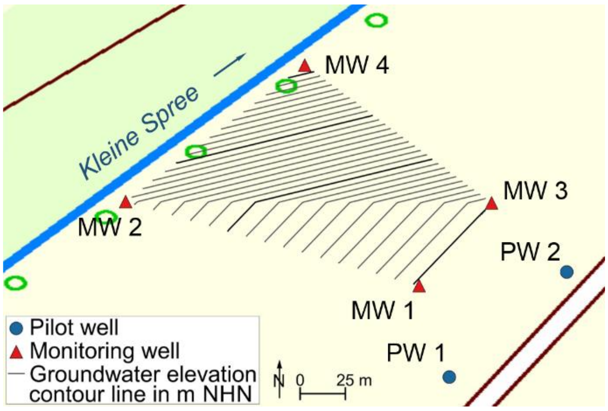

***Figure 7** Evaluation of the groundwater flow direction on the right side of the Kleine Spree.*

Water level measurements over the entire measurement period showed a groundwater flow direction uniformly towards the river. The water level in the river was always lower than the groundwater level in the two riverside monitoring wells, with a steadily rising gradient up to the two monitoring wells closest to the pilot remediation wells. As it can be assumed that there is a hydraulic connection between the groundwater and surface water, the section of the Kleine Spree studied acted as a gaining river during the entire measurement period, being fed by the groundwater from at least the right side (Fig. 7).

In total, 24 water samples were collected from the groundwater aquifer along the right-hand bank between St. 0+870 and St. 1+510, and several areas were sampled multiple times (Fig. 8).

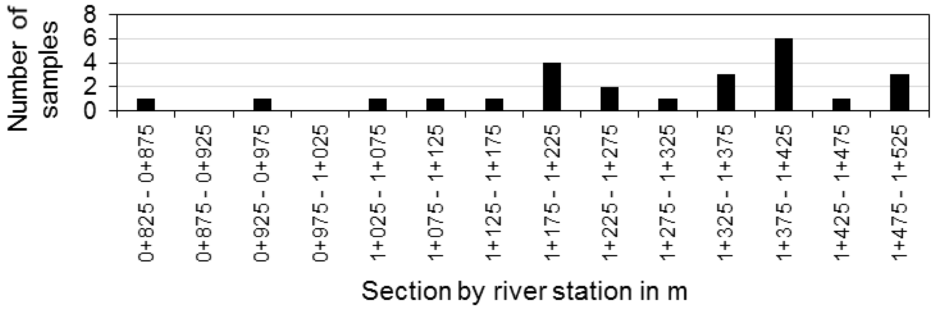

Figure 8 *Overview of samples taken and their locations.*

Within the study area, a large spatial variation of iron concentrations was found (Fig. 9). The independent analyses of the HTW and ERGO showed similar results, with an average difference of 11 %. The results from the different sampling days showed a consistent tendency at each location.

The highest detected dissolved iron concentration in the groundwater beneath the stream bank was about 400 mg/L at the Station 1+250 close to the Old Cloth Factory. Just 50 m further downstream the concentration was only about 240 mg/L and 100 m further still it decreased to 50 mg/L. In the actual area of influence of the pilot remediation wells the concentration of dissolved iron in the shallow groundwater is less than 40 mg/L. Upstream of the Old Cloth Factory, the progression of iron concentrations was less dramatic. At the Railway Bridge the concentration was about 200 mg/L and 100 mg/L was still measured 120 m upstream of the bridge.

Between St. 1+375 and St. 1+425 a total of 6 samples were taken, some on different days. The results from the different sampling dates showed a good agreement for specific stations and fit well within the overall progression of iron concentrations along the investigated section of river. Between St. +175 and St. 1+225 a total of 4 samples were taken. The result from Dec. 4th is likely an outlier, as all other results confirm the high iron concentrations along that part of the river (Fig. 9).

In general, the results from different days reflect the same overall pattern of iron concentrations along the 700-m-long section of the Kleine Spree. This could indicate the likelihood of a long-term stable condition, resulting from the fixed locations of hot spots in this area.

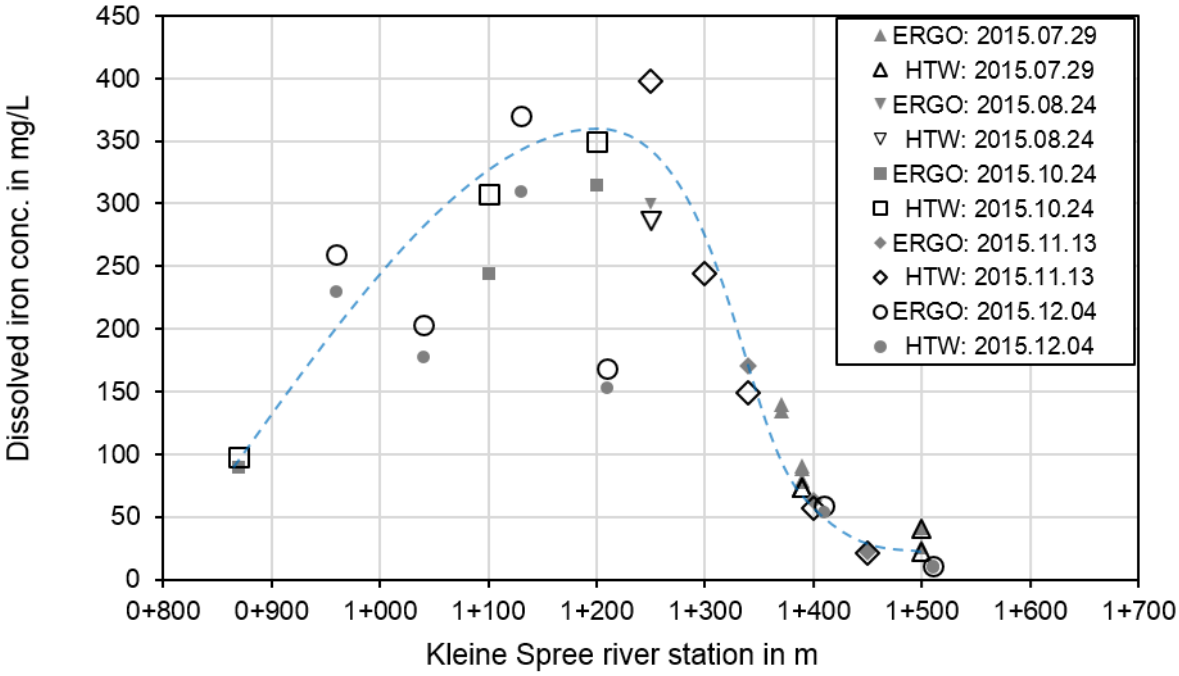

Figure 9 *Dissolved iron concentration in groundwater feeding the Kleine Spree.*

The investigated 700 m-long part of the stream has been classified into three classes with different ranges of iron concentrations in groundwater (Fig. 10): A – hot spot with highest iron concentration (> 300 mg/L), B – high iron concentration (100 – 300 mg/L), and C – lower iron concentration (< 100 mg/L).

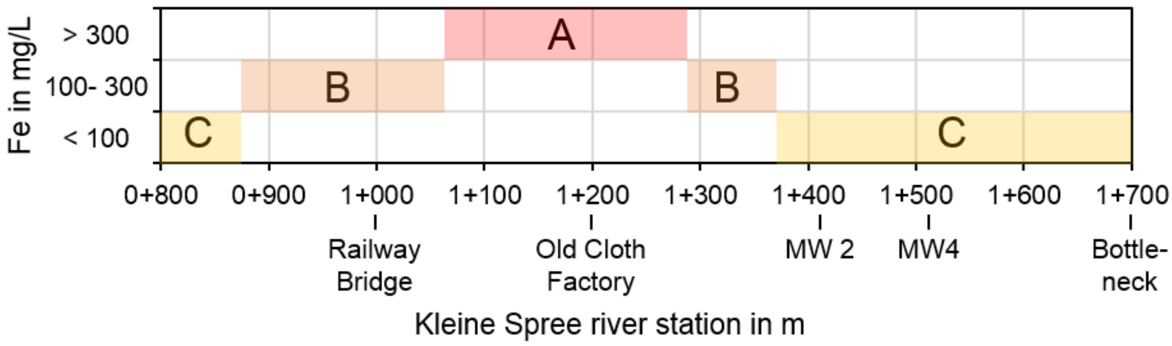

Figure 10 *Classification of the investigated river stretch.*

During the sampling period, the mean river water temperature was 6.4 °C and always lower than the temperatures measured in the river bed of the Kleine Spree ranging from 8 – 12 C (Fig. 11). This indicates that warmer groundwater was feeding the river. Along the investigated stretch of the river a change in temperature was observed downstream of St. 1+350. There, lower temperature in the river bed may be a result of lower discharge and flow velocity of groundwater entering the river. During hammer probing before application the WaSP at the right river bank, aquifer material was identified as medium to coarse sand, whereas downstream of St. 1+400 a higher portion of fine sand was found. Thus, a resulting lower hydraulic conductivity would support the assumption of lower discharge of groundwater into this river section. But different temperatures in the river bed may also be a result of entrance of groundwater from different depths of the aquifer.

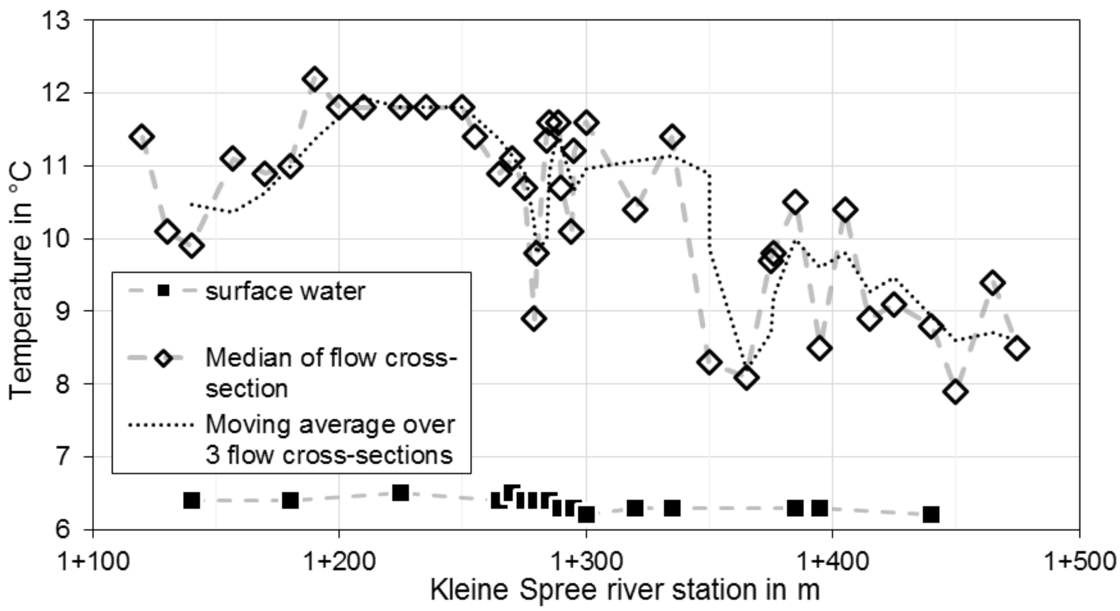

Figure 11 *Temperature of river water and within the river bed fed by groundwater.*

Conclusions

Based on experiences with direct push techniques for groundwater sampling, a method has been developed to investigate groundwater quality beneath rivers in mining regions, which are strongly affected by iron-rich groundwater and iron sludge deposits. Sampling campaigns to determine the iron concentration of groundwater entering the river by using the developed probe resulted in an acceptable agreement of the results from different dates.

Highly different iron concentrations can be found even along a 700 m-long river stretch. To determine the iron discharge rates, water quality data need to be combined with discharge measurements. As flow velocity and discharge measurements in the river itself will rarely allow to determine changes in the range of 0.1 – 1 L/s along a 100 m-long river section, other methods are required, e.g. temperature measurements to identify river sections of strong interaction with groundwater and higher groundwater entrance velocity. Therefor further investigations with have to be conducted. In future a multi-depth measurement of the stream bed temperature could be used to gain more accurate results of the groundwater influx rate.

The identification of hot spots of iron or classification of sections with different iron load is useful for the planning of remediation measures. For example, the highest effect will be achieved if groundwater inflow of class A would be treated or limited. On the other hand, injection techniques using air, oxygen or other oxidants to oxidise the iron in the subsurface as well as pump-and-treat techniques have specific limitations and may be not be applicable at such high iron concentrations as in class A.

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