Quantification of diffuse iron discharge into surface waters in the Lusatian lignite mining district

Wilfried Uhlmann[1], Yvonne Lindig[1], Thomas Claus[1], Sven Radigk[2],
Volkmar Zarach[2]

[1]Institut für Wasser und Boden Dr. Uhlmann, Lungkwitzer Str. 12, 01259 Dresden, Germany, info@iwb-dresden.de
[2]Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH, Knappenstr. 1, 01968 Senftenberg, Germany

Abstract Lignite mining affects the water balance and the water quality of surface water and groundwater on a large scale. The interactions between surface water and groundwater play an important role in the different stages of active mining, remediation mining and post-mining. A current problem of the remediation mining is the diffuse discharge of contaminated groundwater into surface water. This results in acidification and iron hydroxide precipitation in the surface water.
This paper shows two case studies where it was possible to quantify diffuse discharges of groundwater into surface waters in a reliable way and with an appropriate measurement effort.

Key words: diffuse discharge, iron hydroxide precipitation, streams

Introduction

Lignite mining affects the water balance as well as the water quality of surface and groundwater on a large scale. The interactions between surface water and groundwater play an important and changing role in the different stages of active mining, remediation mining and post-mining. A current problem of the remediation mining are diffuse discharges of contaminated groundwater into surface water in the regions of groundwater rising. This results in acidification and iron hydroxide precipitation in the surface water (Benthaus et al. 2015).

Knowledge of discharge volumes, concentrations and loads are necessary to plan suitable measures to prevent the inflow of iron rich groundwater into surface water. A methodological problem to localize groundwater inflow is that discharge volume and loads are not directly measurable. The determination of discharge volume of groundwater inflow by differential measurement of discharge in watercourses does not provide the required accuracy and spatial resolution. Observation wells nearby surface waters only provide point information about hydraulic potentials and hydrochemistry. Geohydraulic models are often limited in their accuracy (Uhlmann et al. 2014).

The present paper shows two case studies where it was possible to quantify diffuse discharges of groundwater into surface waters in a reliable way and with an appropriate measurement effort. Essential prerequisites were a good knowledge of the investigation area, synthesis of measurement and evaluation concept as well as the reasonable using of a geohydraulic model.

Case Study 1: River Spree between the weir Ruhlmühle and the village Spreewitz

Introduction

Since 2011 the river Spree had been polluted by iron on a section of about 7 km between the weir Ruhlmühle and the village Spreewitz due to groundwater rise (Figure 1). The iron input occurs locally by point sources (ps) like trenches (Altarm, Graben Neustadt) and partly as diffuse source (ds) from groundwater. Due to point sources and diffuse source, the iron concentration in the river Spree increases from 1 mg/L at the weir Ruhlmühle to 7 mg/L at Spreewitz. The german surface water regulation (OGewV 2016) provides an assessment value of 1.8 mg/L for total iron and 0.15 mg/L for dissolved ferrous iron.

The discharge volume of groundwater inflow is small in relation to the flow rate in the river Spree. The aim was to localize and quantify the iron input locally differentiated. Different methods were applied, such as reference date measurements, groundwater investigations nearby the river and geohydraulic modelling.

Methodology

Groundwater inflow may be quantified by hydrochemical balancing methods. In case of assymetric discharge volumes (watercourse >> diffuse inflow) two conditions must be complied for this purpose: (1) the chemical compounds should be conservative und (2) there should be a high difference in concentrations between surface water and groundwater. In the specific case, the condition (1) for iron und the condition (2) for sulphate were not given.

For iron and the relevant iron species (ferrous iron Fe(II), total iron Fe_{tot},) the following material flows between the balancing sections have to be taken into account:

iron input: R_{input} ,

oxidation of iron: R_{ox} , and

sedimentation of iron: R_{sed} .

For total iron, the iron load balance in the river sections is calculated by:

$$\frac{d[Fe_{tot}]}{dx} = R_{input} - R_{sed}$$

For Fe(II), the iron load balance in the river sections is considered:

$$\frac{d[Fe(II)]}{dx} = R_{input} - R_{ox}$$

The iron input was determined using a statistical approach. For this, water samples were taken and analysed at five sampling stations (Figure 1) three times a week over a period of six months. Flow rates were not determined in the river Spree, only the data of the gauging stations Spreewitz and Sprey were used. Flow rates at point sources were measured by a current meter.

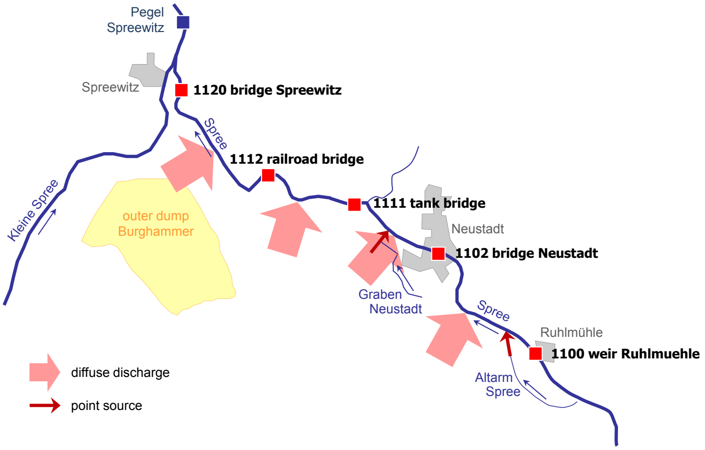

Figure 1 *Sampling stations and locations of discharge from point sources (ps) and schematic areas with diffuse inflow (ds) at the river Spree*

Results and Discussion

At the point sources discharge flow and hydrochemistry were measured directly. The discharge flow at point source Spree-Altarm is on average 110 l/s. It is characterized by an iron concentration of 160 mg/L. The point source Graben Neustadt has a discharge volume of about 20 l/s and an iron concentration of 320 mg/L.

The boxplots of hydrochemical parameters (Figure 2) show an increase in the total iron concentration in the first three sections ($R_{input}>R_{sed}$) and a stagnation in the fourth section ($R_{input}\approx R_{sed}$). Thus, the iron input in the fourth section corresponds to the losses caused by oxidation and sedimentation. Dissolved iron concentration increases in the first three sections ($R_{input}>R_{ox}$)) and decreases in the fourth section ($R_{input}<R_{ox}$). Thus, in the fourth section iron oxidation is higher than iron input. The boxplots of the pH-value show a slight decrease in direction of flow due to the hydrolysis of ferric iron.

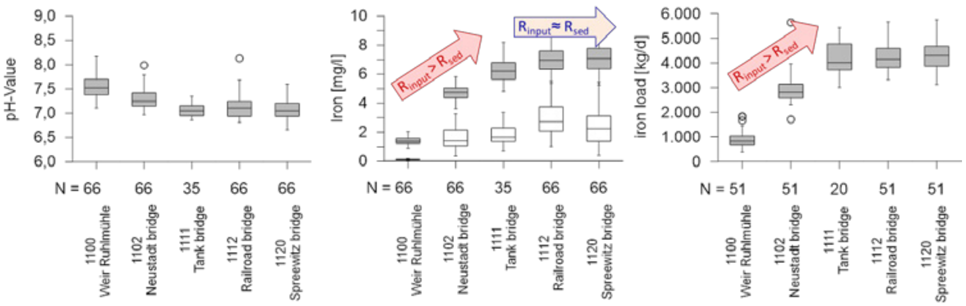

Figure 2 *Boxplots of the pH-value (left), iron concentration (centre: filled – total iron, blank – dissolved iron) and iron load (right) at the sampling stations of the river Spree*

Based on the reference date measurements, a mean iron load balance was established for the investigation section of river Spree (Figure 3, Table 1). With this approach, losses caused by sedimentation of iron hydroxide cannot be quantified. Diffuse inputs into the river Spree were underestimated by these losses.

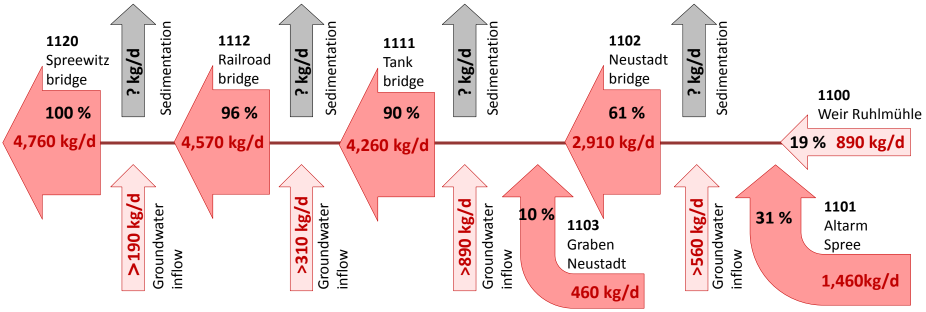

Figure 3 *Average cumulative iron load in the river Spree and its inflow*

The average iron load at the balancing point Spreewitz was about 4,760 kg/d (100%) in the investigation period. Pre-load of the river Spree at weir Ruhlmühle had a portion of about 19 %. The section between the weir Ruhlmühle and the tank bridge was localized as the main iron input (71 %). Thereby, a significant portion of the iron input is applied to the point sources Altarm (31 %) and the Graben Neustadt (10 %). Diffuse groundwater inflow causes the remaining iron input (30 %).

Table 1 *Balance of iron load from diffuse and point sources into the river Spree in the section between Ruhlmühle und Spreewitz (March to August 2015)*

Section	Code	discharge	L/s	iron	mg/L	iron load	kg/d
		Spree	Inflow	Spree	Inflow	Spree	Inflow
Spree weir Ruhlmühle	1100	7,400		1.4		890	
Altarm Spree	ps1		110		160		+1,460
groundwater	ds1		≥ 15		430		≥+560
Spree – Neustadt	1102	7,500		4.5		2,910	
trench Neustadt	ps2		20		320		+460
groundwater	ds2		≥ 40		250		≥+890
Spree – tank bridge	1111	7,600		6.5		4,260	
groundwater	ds3		≥ 15		230		≥+310
Spree – railroad bridge	1112	7,600		7.1		4,570	
groundwater	ds4		≥ 10		230		≥+190
Spree – Spreewitz	1120	7,800		7.1		4,760	

Groundwater sampling from 11 observation wells nearby the river complements the investigations and confirmed the existence of hot spots with local iron concentrations up to over 400 mg/L. Based on the results of groundwater modelling, groundwater investigations and measurement campaigns, the iron load could be quantified as shown in Table 1. The balance shows that the capture and treatment of the point sources can substantially reduce the iron input. Treatment measures of diffuse inputs are only economical in sections between weir Ruhlmühle and the tank bridge (ds1, ds2).

Case Study 2: Lower course of the river Kleine Spree

Introduction

Since 2008 the river Kleine Spree is contaminated by iron on a section of about 4.5 km between the outlet of the Burghammer reservoir and the mouth of the river Spree (Figure 4). The reason for this is also the exfiltration of iron-rich groundwater as a result of the groundwater rising. Between 0.2 and 75 mg/L iron were measured in the river Kleine Spree (Uhlmann et al. 2012). The aim of the investigations was to localize and quantify the iron input.

The investigation area of the river Kleine Spree is characterized by a special feature. Upstream of the input area, the reservoir Burghammer discharges into the river. Burghammer is a post-mining lake. It is acidified and has to be chemically neutralized regularly. Discharge from the reservoir Burghammer occurs discontinuously. In the reservoir Burghammer, the sulphate concentration is also increased. Since the discharge in the river Kleine Spree is naturally low ($MQ \approx 1\ m^3/s$), the periods with a discharge from the reservoir Burghammer can be used as a tracer signal.

Methodology

Between Burg and Spreewitz seven measuring points were installed in the river Kleine Spree to localize hot spots of iron input (Figure 4). At the sampling stations, measurements of the flow rate and hydrochemistry were conducted. Due to the predominantly low flow rates in the river, the discharge of the groundwater inflow could be estimated by difference measurements. However, the measurement error is too high for planning technical measures.

Observation wells nearby the river Kleine Spree were sampled. The range of the hydrochemical parameters is widely spread. It can only be characterized statistically. Based on the flow rates and investigations of the water chemistry the groundwater inflow and the groundwater chemistry were estimated using a mass balance model. Thereby, especially the tracer signal of the outlet from the reservoir Burghammer was useful.

Results

Since the measurement campaigns were carried out at different discharge conditions, the range of hydrochemical findings is very large. On the basis of the median values of the iron and sulphate concentrations, however, a successive substance input with the groundwater can be detected in the longitudinal profile of the river Kleine Spree (Figure 5). Two hot spots of the substance input can be documented on the basis of the concentration change: (1)

before Burgneudorf, and (2) between the railroad bridge and the old cloth factory. The discharge measurements have shown that the groundwater inflow into the river Kleine Spree is very inhomogeneous. Sections with seepage were also found.

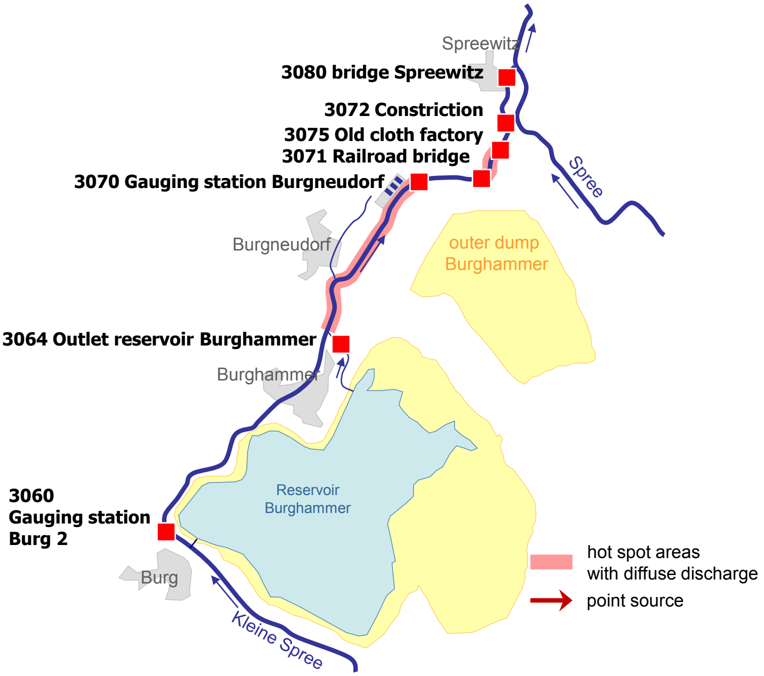

Figure 4 Sampling stations at the lower course of the river Kleine Spree

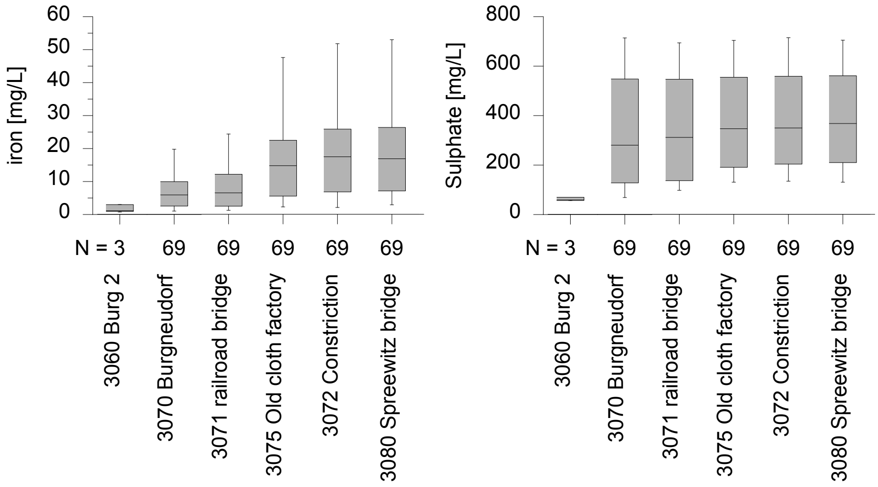

Figure 5 Hydrochemical findings for iron (left) and sulphate (right) at the sampling stations at the Kleine Spree (measurement period from September 2015 to January 2016)

The measured sulphate concentration in the longitudinal profile of the Kleine Spree was reproduced with the mass balance model. Figure 6 shows the result for the sampling station Spreewitz. For the calibration of the model, the periodic sulphate signal from the reservoir Burghammer was very helpful. Sulphate is particularly suitable for estimating the groundwater inflow because it doesn't react with other substances. For a groundwater inflow of about 100 l/s in the first hot spot and about 150 l/s in the second hot spot with a uniform sulphate concentration in the entire longitudinal section of the Kleine Spree of about 500 mg/L the model showed the best fit.

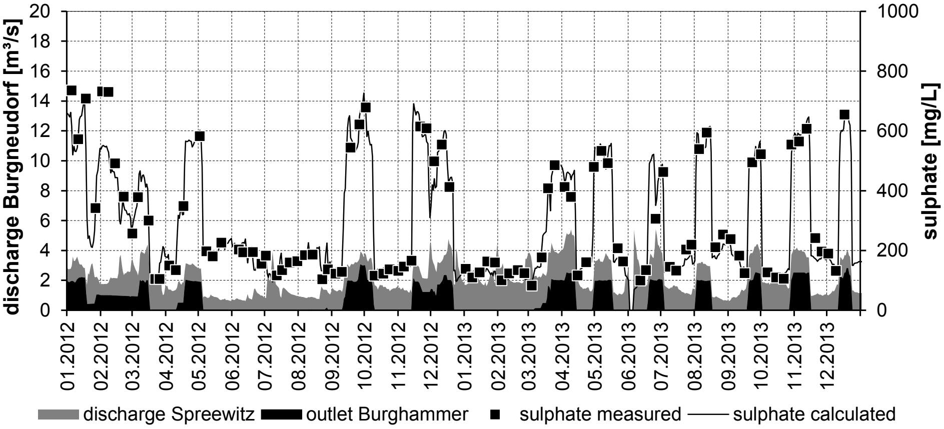

***Figure 6** Calculated and measured sulfate concentration at the sampling station Spreewitz (3080) in the context of the discharge*

Iron concentrations were also calculated with the calibrated model. Ferrous iron was used for this purpose. With the groundwater balance calibrated for sulphate, the best model fit could be achieved for an iron concentration of 100 mg/L in the first and second hot spot. Figure 7 shows the result for ferrous iron at the sampling station Spreewitz.

Higher calculated ferrous iron concentrations in summer can be explained by oxidation of ferrous iron to ferric iron-hydroxide. Due to higher water temperatures as well as to the lower discharge and therefore longer residence times, the oxidation of iron(II) to iron(III)-hydroxide is much faster in summer than in winter. However, the model used cannot reproduce the oxidation process.

With the measurement campaigns, the groundwater investigations and the processing of the measured data with a model, the hot spots of the groundwater inflow could be localized and the flow rates and the iron concentration of the groundwater could be quantified. The results of the investigations can be used to plan measures to prevent discharge of iron-rich groundwater.

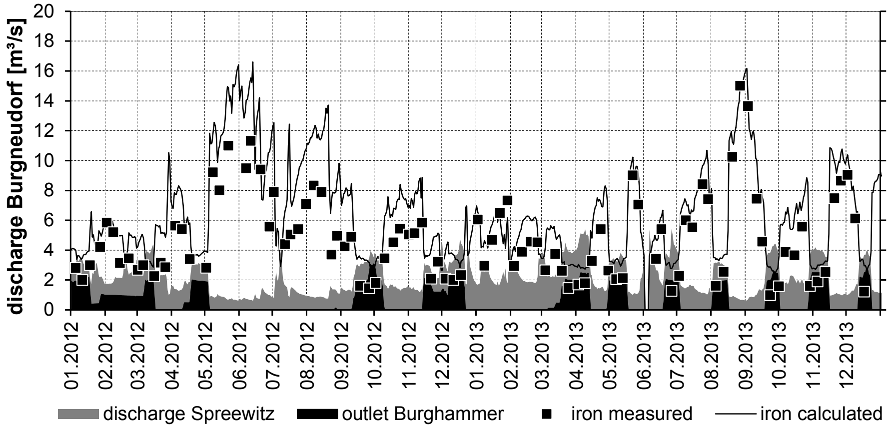

Figure 7 *Calculated and measured iron concentration at the sampling station Spreewitz (3080) in the context of the discharge*

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