Process oriented quantification of mine dump pollutant inventories on the large scale—The case of the lignite mining district Lusatia, Germany

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ABSTRACT

The release of various contaminants from mining dumps can have a severe and long-lasting effect on groundwater quality and affect the whole watershed. While the status of the present groundwater quality is often closely monitored, little is known about the size and the geochemical composition especially of older mining dumps. However, the geochemical inventory of the mining dumps is an important control for the future development of groundwater quality. A process oriented methodology is presented to determine the geochemical composition of dump bodies on the base of geological and geochemical data from pre-mining exploration. The method is applied to the Lusatian lignite mining district in Germany (2500 km^2). The content of sulphur species and carbon species, i.e., the main acid-releasing and acid-buffering components, was determined individually for more than 40 dump bodies. In total about 100 Mt of sulphur were estimated to be stored within the study area, whereby 66% prevails as pyrite sulphur. Pyrite oxidation during past mining activities released about 4.6 Mt of sulphate within the research area. A comparison of predicted results with measured sulphur concentrations indicates the suitability of the approach. The impact of data quality and resolution on the derived inventory was investigated by varying the size of the considered subset of geological and geochemical data. It was shown that geological data resolution is less significant compared to geochemical data. Furthermore the usage of average geochemical properties seems to be insufficient if the methodology is applied to large mining districts.

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1. Introduction

Mining dumps are usually the most important sources of pollutants like sulphate, iron and aluminium in former open pit coal or lignite mining districts. The pore water emitting from the mining dumps is highly mineralised acid mine drainage (AMD) and its release has a major effect on downstream groundwater quality (Mayes et al., 2009; Wolkersdorfer and Bowell, 2005; Younger, 2001). Discharge is often expected to occur over decades and typically affects areas that are considerably larger than the area occupied by the dumps.

While the impact of AMD on groundwater quality in the past and present can be characterised by monitoring data, its future development depends, among other aspects, strongly on the size and specifically the geochemical composition of the mining dumps. Thus, the prediction of the long-term water pollution in mining areas requires a detailed characterisation of the pollutant sources, as for example

requested by the EU Mining Waste Directive (EU-MWD, 2006). However, especially in regions with a long mining history detailed data that allow to characterise the composition of the mining dumps are typically not available and appropriate approaches and information to predict the overall emission potential from the whole mining district are absent. This lack of information prevents robust predictions of both the time-scale as well as the spatial extent and severity of the future mining-related groundwater impact that are needed for implementing regulatory frameworks such as the EU Water Framework Directive (EU-WFD, 2000).

AMD-related problems and processes on local scale and AMD remediation techniques were intensively examined and reported during the last decades, for example by Banks et al. (1997); Blodau (2006); Evangelou (1995); Herbert (1999); Johnson and Hallberg (2005); Wolkersdorfer and Bowell (2005). Their and other studies investigated in detail the mineral composition of mining dumps and of the resulting AMD, together with possible treatment schemes. While short-term predictions of the effects of mining dumps on the surrounding groundwater quality can possibly be based on monitored data under the assumption of a constant source composition, longer-term predictions are mostly not feasible in the absence of a

more comprehensive characterisation and quantification of the pollutant sources. However, especially for older mining dumps it is difficult to reliably quantify their composition because the existing data are generally incomplete and often also difficult to locate.

Efforts to characterise open pit lignite mining dumps with respect to proxies for pollutants such as sulphate and iron have been made by several authors. For example, Kohfahl and Pekdeger (2004); Kohfahl and Pekdeger (2006); Schöpke et al. (2001) estimated the potential of pollutants and acidification in dump material from the results of column tests. The authors provide a detailed description of the dump material on the base of a limited number of sampling locations within the dump. The suitability of the up-scaling process to predict the composition of large mining dump bodies based on few point data remains questionable, especially since open pit lignite mining dumps in lignite mining areas are known to be highly heterogeneous (Buczko and Gerke, 2005; Gerke et al., 1998; Knappe et al., 2004).

Oehmig (2003) tried to overcome the problem of heterogeneity by considering an increased number of sampling locations. The dump composition was determined by analysing 22 cored boreholes from two mining dumps. However, it remained unclear to what extent the cores and associated data, which are expensive to gather, are representative for their surroundings and what data-density would eventually be required for a precise quantification of the pollutant inventory.

A different approach was used by several other authors, who described the geological composition of the mining dumps based on pre-mining geological information together with geochemical properties of the geological layers. For example, Berger (2000) and Rolland et al. (2001) reported an application of this approach to the operating Welzow mine (Lusatia) and Jänschwalde mine (Lusatia), respectively while Hoth (2002) described the application for the operating Espenhain mine (Lignite mining district Central Germany).

The focus of most previous investigations was to determine the effects of single dumps on downstream groundwater and surface water quality. However, mining activities are generally concentrated within specific mining districts, resulting in a high density of mining dumps of different ages. Controlled by the dewatering activities of the operating mines the groundwater flow within these areas is highly transient. While the studies targeting single mining dumps are important for an improved understanding of geochemical mechanisms, additional approaches are needed to understand the interactions of a system of pollutant sources within a whole mining district.

The current study presents (i) the development of a process oriented grid-based mass-balance approach that predicts the pollutant inventory of mining dumps and (ii) its application to a whole lignite mining district which extends over thousands of square kilometers. The major objective of this work was to provide a contribution towards improved predictive capabilities for large-scale and long-term mining-related impacts on groundwater quality.
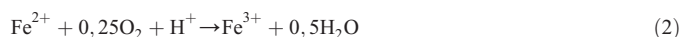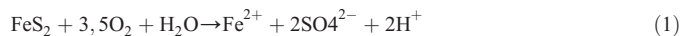
2. Study site

2.1. Site description

The site selected for this study, the lignite mine district Lusatia, is located in the eastern part of Germany, about 100 km south of Berlin (Fig. 1). During the Tertiary period the geochemical characteristics of the Lusatian mining district were controlled by marine conditions in the north and brackish conditions in the south. However, conditions were altered during the Quaternary period by glacial erosion (Brause et al., 1989; Darbinjan, 1989; Nowel, 1982; Seifert et al., 1993), whereby the lateral continuity of the lignite seams was interrupted by post-depositional valleys, which divided the district into mining fields. In total 5 coal seams were found in the district and lignite mining occurred for more than a century. Conveyer bridge technology was predominantly used for the open pit mines to excavate lignite. The second Lusatian seam is the main lignite source of the district

with an average thickness of between 8 and 12 m. Fig. 2 shows the Quaternary and Tertiary geological layers of the Lusatian mining district, including the second Lusatian lignite seam. For the stratigraphical description a lignite classification system (EMB, 1985) is used within the Lusatian mining district, where ID numbers are applied for identification. The average overburden thickness was about 44 ± 20 m. A more detailed description of the Lusatian lignite mining district can be found, e.g., in Seifert et al. (1993). Most of the mines were closed after Germany's reunification in 1990 and currently only four mines remain operating. Overall more than 40 mining dumps of different sizes are located within an area of about 2500 km². They were mined mainly between 1920 and 1990, with a climax in the 1980s. The mine sites encompass about 19% of the area. Dewatering of the mines resulted in a substantial groundwater drawdown that affected an area of about 1350 km² in the 1980s, leading to a groundwater deficit of about 7 billion m³ (LMBV, 2001). In the meantime rising groundwater levels have eliminated half of the groundwater deficit since 1990.

Mining induced contact with atmospheric oxygen during excavation and deposition of top layers has induced pyrite oxidation within the dumps (see Eqs. (1)–(4)), i.e.:

$$FeS_2 + 3,5O_2 + H_2O \rightarrow Fe^{2+} + 2SO4^{2-} + 2H^+ \tag{1}$$

$$Fe^{2+} + 0,25O_2 + H^+ \rightarrow Fe^{3+} + 0,5H_2O \tag{2}$$

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ \tag{3}$$

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2+} + 16H^+ \tag{4}$$

Iron, sulphate and protons were produced and the affected groundwater became highly mineralised. Today aqueous sulphate concentrations can reach between 2000 and 4000 mg/l and the corresponding typical iron concentrations range between 100 and 1000 mg/l. To distinguish between the different types of sulphur we use the term *sulphate sulphur* for oxidised sulphur (e.g. as $CaSO_4$), *pyrite sulphur* represents all reduced sulphur species such as FeS or FeS_2, *organic sulphur* describes the sulphur contained within organic matter and *total sulphur* stands for the sum of all sulphur species.

Typically observed pH values in the groundwater of the Lusatian lignite mining district currently range between 5 and 6. Despite a high acidification potential that originates from the substantial concentrations of ferrous iron (Blodau, 2006), conditions to date are only moderately acidic because the proton release was largely buffered by both cation exchange and calcite dissolution, i.e.,

$$CaCO_3(s) + 2.H^+ \rightarrow Ca^{2+} + H_2O + CO \tag{5}$$

So far the formation of extensive groundwater depression cones prevented or limited pollutant discharge from mining dumps. However, with rising groundwater levels pollutant reservoirs are now transforming into pollutant sources and a substantial and successively increasing number of AMD plumes have started to evolve over the last decade.

2.2. Data

2.2.1. Geological data

To characterise the geological conditions within each of the potential mining zones several thousand boreholes were drilled in the Lusatian mining district during the pre-mining exploration campaigns. For the present study a subset of 600 of these boreholes was selected to develop a large-scale geological model. This selection