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Experiences with Mine Closure in the European Coal Mining Industry: An Overview of the Situation in Germany and Adjacent Regions

In recent decades, the mining industry in Europe has been characterised by a very high rate of mine closure. One of the affected branches is the underground hard coal mining industry. There is substantial demand for environmentally compatible mine closure programs, especially in light of the implementation of the new EU Water Framework Directive. Hence, acid mine drainage is a specific challenge.

By 2018, the last remaining active coal mines in Germany's largest hard coal mining area, the Ruhr industrial region, will be closed. With a maximum population density of 2,800 people per km^2, the Ruhr district is the largest urban agglomeration in Germany and one of the most densely populated coal mining areas worldwide. Early coal mining activities date back to the twelfth century. Since then, a total of about 10 billion tonnes of coal has been produced. The maximum depth of the mining process is 1,500 m below the surface, and the maximum subsidence ranges up to 25 m.

It is necessary to sustain the drainage system to prevent built-up areas from being flooded or impacted by mine water. Hence, water management measures will continue in perpetuity after coal mining has ceased: about 70 million m^3/a of mine water and an additional 900 million m^3/a of water in the polder areas have to be pumped permanently.

Numerous shafts, deep cavities and shallow openings call for remedial activities in order to prevent damage, stabilise new structures or restore former geomorphology. For these reasons, risk management was established a couple of years ago. A special challenge will be the protection of subsurface groundwater horizons, especially drinking water horizons, against infiltration of mine water.

The paper also summarises the results of a study that compiles numerous European hard coal mining areas' experiences with mine closures. In particular, the investigation compares the effects of rising mine water level, impacts on the ground surface resulting from mine subsidence/uplift and effects of the mine water hydrochemistry at the different sites.
On this basis, advice is given to reduce closure risks and optimise closure operations. The purpose is to achieve lasting safety for the ground surface, the population and the water bodies at a reasonable cost.

1 Introduction

The mining industry has played an important part in the economic and social development of Europe. In the nineteenth century, the extraction of coal and lignite provided the basis for the industrialisation of many European regions. However, the production of mineral raw materials in Europe has permanently decreased in recent decades. Between 1992 and 2012, a total decrease of 300 million tonnes took place (Reichl et al., 2014). The metal ore and hard coal mining industries have been particularly affected by this trend. The main reasons for this include reservoir conditions, production costs, popular resistance and environmental regulations. The European hard coal mining industry has therefore had to cope with a massive reduction in production from more than 350 million tonnes in 1990 to 110 million tonnes in 2012 (European Association for Coal and Lignite , 2013). The current annual production of hard coal in the European Union comprises 100 million tonnes. As a result, the past 50 years have seen a significant reduction in the number of active mines, so that in Germany alone more than 250 mines have been shut down. Approximately 20 % of this total relates to metal ore mines, and more than 50 % to underground hard coal mines. For comparison, in 1960, around 140 million tonnes of hard coal were extracted in Germany. After the mine closures in 2012, the last remaining three operating collieries produce a com-

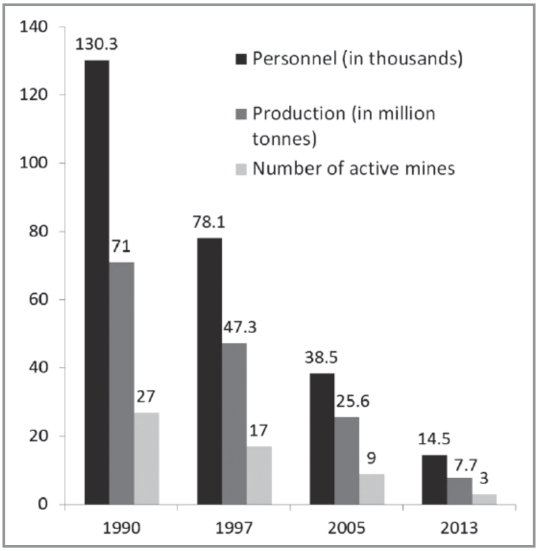

Figure 1 / Developments in the German hard coal industry — reduction of production corresponds with decline in employment (GVST, 2014).

bined total of barely 7.5 million tonnes a year. Corresponding to the decline in production, the number of personnel decreased from 130.3 thousand in 1990 to 14.5 thousand in 2013 (Figure 1). The drop in production during recent decades was primarily caused by sales-related problems and reduction of government subsidies. In 2007, in agreement with the European commission, the federal government of Germany and RAG AG, the last remaining German hard coal mining company, decided that subsidised hard coal production would be phased out by 31 December 2018 (Steinkohlefinanzierungsgesetz, 2007; GVST, 2014). Similar agreements have been made for the other coal-producing states of the EU.

As it is not just Germany or Europe that is affected by mine closures, the subject is of global significance, posing a challenge for cities, regions and governments all over the world. Structural change in mining districts is a complex process comprising social, ecological, economic and cultural aspects. Therefore, the demand for environmentally compatible concepts for the back filling and plugging of mines, shafts and caverns is continuously increasing. These concepts apply to both active production plants and mines that are already closed. The handling of mine water in active mining as well as in post-mining areas yields specific challenges. Directive 2000/60/EC from the European Parliament and the Council from 23 October 2000 established a framework for community action in the field of water policy. This EU water framework directive commits EU member states to achieve good qualitative and quantitative status for all water bodies by 2027 (EC Directive, 2000). Unfortunately, in numerous cases it is still not clear how to achieve this objective. The following chapters reveal the current and prospective situation of the German coalfield regions and summarise the main research activities of the Research Institute of Post-Minin at the TH Georg Agricola in Bochum (Germany) concerning mine closure and post-mining in Europe.

Figure 2 / Map of Central Europe; the German coalfield regions under discussion are highlighted in black.

2 German coalfield regions

In Germany, three coalfields are currently in the transition phase between production and closure. The largest of these is the Ruhr-area, followed by the Saarland and the coalfield around Ibbenbüren (Figure 2). Production in the Saar coalfield ceased in 2012. The last remaining collieries are the Auguste Victoria mine in Marl (Ruhr-area), which will be closed by the end of 2015, and the Anthrazit Ibbenbüren colliery in Ibbenbüren and the Prosper-Haniel colliery in Bottrop (Ruhr-area), which will both shut down by the end of 2018.

2.1 Ruhr-area

The Ruhr-area, named after the Ruhr River, covers parts of the Federal State of North-Rhine Westphalia (NRW). According to the Ruhr Regional Association (Regionalverband Ruhr), an administrative association of cities and districts, the Ruhr metropolitan region covers an area of about 4,400 km^2 and is populated by more than five million people living in 11 cities and four districts. It is the largest urban agglomeration in Germany and the third largest in the European Union after Paris and London. The average population density is 1,161 people per km^2. In the five largest cities – Duisburg, Essen, Gelsenkirchen, Bochum and Dortmund – the highest population density is 2,800 people per km^2 (Figure 3) (Regionalverband Ruhr, 2012).

The beginning of the retreat of the mining industry 50 years ago triggered a crucial structural change in the region. Today, the overall economy is dominated by service industries, high-tech operations, logistics sites and research and educational institutions. In the course of this industrialisation, the population of the Ruhr-area increased very quickly. The infrastructure of the whole region is therefore very well developed.

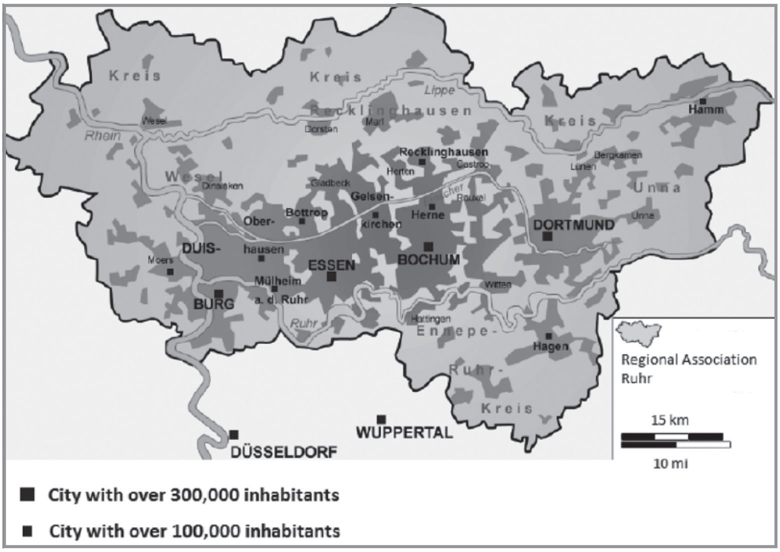

Figure 3 / Settlement structure of the Ruhr-area; all named cities have more than 50,000 inhabitants, and the settlement areas are marked in dark grey (after Regionalverband Ruhr, 2012)

The extraction of hard coal in the Ruhr coalfield region dates back to the twelfth century. It started in the south, where the coal seams crop out directly at the surface or underneath thin overlying quaternary sediments (Pfläging, 1999). The coal-bearing Carboniferous strata was extensively folded during the Variscan orogeny and reshaped by syn- to post-Variscan break tectonics. North to the river Ruhr, the thickness of the caprock increases continuously, and the carboniferous rocks are unconformably overlain by massive post-Variscan deposits of Permian to Quaternary age. According to its extensive distribution, the Upper Cretaceous strata comprises the most important caprock unit. In the stratigraphical sequence, massive, fissured and local karstified limestones of Cenomanian and Turonian age are overlain by the Emscher Mergel, Coniacian to lower Santonian clay marlstones.

The active mining sites operate further in the north, where the target depth reaches up to 1,500 m. The mines in the southern part of the area were closed gradually in recent decades (Figure 4). In total, about 10 billion tonnes of coal have been exploited from the Ruhr deposit (personal communication with T. Kalisch (GVST), 2015). The exploitable areas influence a zone of more than 3,000 km2 at the surface, and the mining-induced subsidence reaches an absolute number of 25 m locally (Harnischmacher, 2010). The last remaining coal mine will shut down by the end of 2018.

2.2 Saarland

As the Saar coalfield was formed under limnic conditions, the waters draining from this deposit are less enriched in chlorides than those of the Ruhr coal basin. The hard coal min-

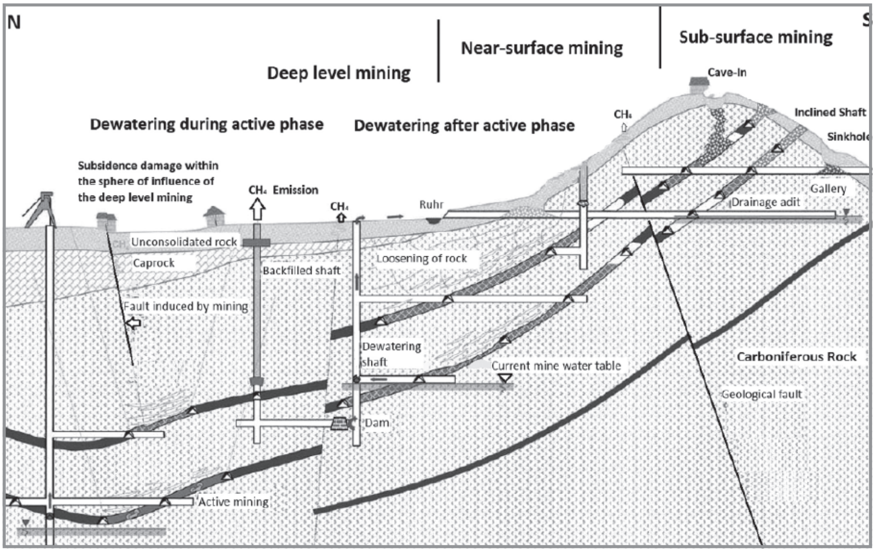

Figure 4 / Schematic cross-section through the hard coal deposit of the Ruhr (after Kaiser, 2002)

ing in the Saar region dates back to the fifteenth century. In the first half of the twentieth century, 60,000 people worked in 18 hard coal mines. The annual production in the year 1960 accounted for 17 million tonnes of hard coal (Slotta, 2011). As a reaction to a number of mining-induced seismic events (the strongest of which, in 2008, had a maximal vibration velocity of 93.5 mm/s), the production of hard coal ceased in 2012 (Preusse et al., 2010). Since last year, the mine water level has been rising.

2.3 Ibbenbüren

The hard coal deposit Ibbenbüren, located in the northwest of Germany, is characterised by a horst-structure. As a result of the upturning underground, the caprock is missing, and the coal layers strike out at the surface. The colliery is situated on a hill that overtops the surrounding area by more than 100 m. The extraction of anthracite coal began in the fifteenth century and currently reaches a depth of 1,600 m. The production of hard coal will be phased out by the end of 2018. The production in the western part of the 90 km coalfield ceased in 1979, and the underground mine workings were subsequently flooded (Goerke-Mallet, 2000; Goerke-Mallet and Drobniewski, 2013; Rudakov et al., 2014).

3 Perpetual obligations in the Ruhr-area

The perpetual mine management obligations (also referred to as "inherited liabilities with unlimited duration") are water management measures that will continue in perpetuity even after coal mining has ceased. In order to reduce the costs for the public sector and

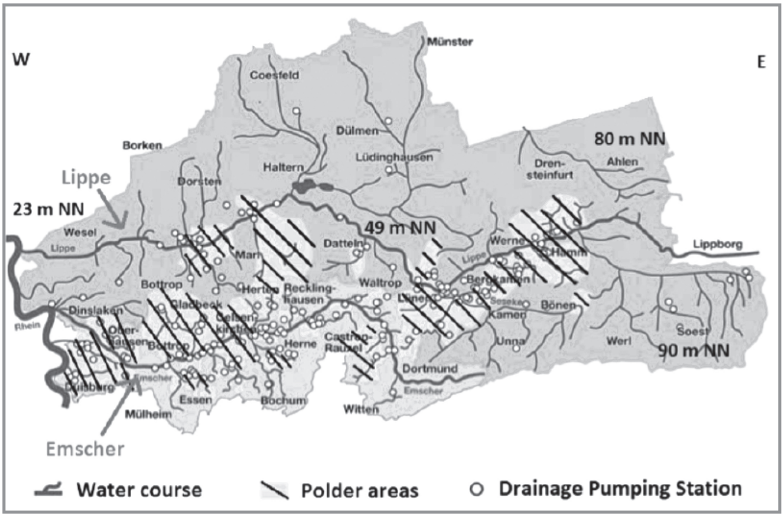

Figure 5 / Polder areas in the zone of influence of the rivers Emscher and Lippe (after EGLV, n.d.)

thus for the taxpayers, RAG-Stiftung has committed itself to funding perpetual management measures for the coalfields of the Ruhr-area, Saarland and Ibbenbüren. The foundation will obtain the funds for these tasks by selling its shares in Evonik Industries AG and through income from its holdings and diversified financial assets. Past and future incomes from the sale of shares, as well as the annual Evonik dividends, supply a large part of the funds the foundation needs to perform its tasks. At the end of 2013, the foundations' shares in Evonik and in the real estate firm Vivawest had a total value of around € 10 billion. It is estimated that starting in 2019, around € 220 million will have to be invested annually to finance the perpetual mine management (RAG-Stiftung, 2014). It should be noted that the correction of mining-related damage is not a perpetual management measure. The financing of mining-induced damage to buildings, properties and roads is and will be covered by the financial reserves of the RAG Corporation. This will also be the case after 2018 (Fischer, 2014).

3.1 Polder measures

Over the centuries, mining has also caused changes to landscapes. Entire regions have subsided – in extreme cases, by up to 25 metres (Harnischmacher, 2010). As a result, 30 % of the morphological plane region between the rivers Emscher and Lippe is made up of polder areas – potential flooding areas – with no outlet (Figure 5). Diking and deepening of water bodies resulted in a hydrological system with a dominant anthropogenic character. The surface water will always have to be actively regulated in these areas in order to prevent it from collecting in the depressions. More than 200 special pumping facilities are currently operating in order to ensure that the water is properly drained (EGLV, 2013).

3.2 Emscher conversion

The installation of an underground channel system for wastewaters was not possible because of sustained mining-induced ground motion. This is why the mining industry and the associated rising population density turned the untamed river Emscher into a man-made system of open waste waterways. In order to handle the wastewater and to ecologically transform the watercourse, the Emschergenossenschaft and Lippeverband (EGLV), supported by the NRW state and the EU, initiated a huge project called the Emscher conversion. In future, the wastewater will be channelled through closed conduits, and the river and its tributaries will be converted into natural waterways. Converting a river system this size is a project extending across several generations and involves far more than turning former open areas used to absorb water in the event of flooding into attractive recreation areas. The objective is to upgrade the Emscher region decisively through projects extending well beyond the river. The processing has been developed in continuous dialogue with neighbouring cities and districts, industry and business, the relevant government authorities and many other organisations and institutions. The Emscher conversion serves as a model project for numerous regions in the world (EGLV, 2013).

3.3 Long-term water management

To avoid flooding or pollution around and in urbanised areas, it will be necessary to maintain water management for an unforeseeable period beyond the production phase. Annually, around 70 million m^3 of mine water and about 900 million m^3 (RAG Aktiengesellschaft, 2014) of ground- and rainwater in polder areas have to be pumped and drained (EGLV, n.d.; LINEG, 2014). Fifteen pit water management facilities currently operate in NRW and five in Saarland. These facilities are located at the deepest points of the shafts, often more than 1,000 metres underground. A complex system of pump stations collects the pit water from the underground excavations and adits and transports it to the main water management facilities, where it is pumped to the surface through metre-wide pipes. The pump system has a redundant arrangement so that if a pump fails it can be quickly replaced by another (RAG-Stiftung, 2014). Beyond that, contaminated water (e.g. around former coking plants) has to be collected and cleaned to prevent it from mixing with drinking water reservoirs.

As water management represents a high expense factor, thought should be given to how to reduce costs of water drainage measures by partially or completely flooding open underground mine workings. Thus, after active mining has ceased by the end of 2018, the task is to extensively flood the mine workings in the whole Ruhr-area. The rising mine water level may lead to various impacts on the caprock groundwater reservoir and on the ground surface. The protection of important drinking water reservoirs against infiltration of mine water will be a special challenge in this context (Terwelp, 2014). Therefore, potential risks and the level of mine water recovery have to be assessed at an early stage in the process in order to minimise these risks.

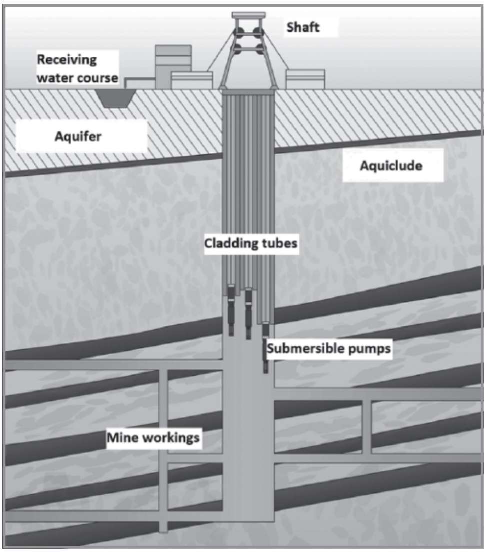

Figure 6 / Schematic image of a well water management facility (after RAG Aktiengesellschaft, 2014)

In the long term, the flooding concept provides an average mine water level between 250 m below zero in the south and 600 m in the west. This will keep the mine water level far below the lowermost boundary of sub-surface groundwater horizons in order to avoid any risk of mixing. After the mine water table has reached the predicted level, which is expected to be in 2035, it is planned to operate six main water management facilities in the Ruhr region (RAG Aktiengesellschaft, 2014). At these localities, well water management facilities (Brunnenwasserhaltungen) will be installed within the existing shafts (Figure 6). With the help of powerful submersible pumps, the water will be discharged to the surface and then pumped into the receiving watercourse.

4 Abandoned mines and near-surface openings

To date, Germany has been characterised by extensive abandoned surface and underground mine workings. Around 60,000 abandoned shafts and adits are expected in NRW alone, with 28,000 of these being registered at the mining authority NRW. According to Welz (2014), 52% of the total land surface of NRW is affected by abandoned mining. In addition, a huge number of the presumed 60,000 openings to the surface have to be classified as not or inadequately secured. On the basis of the present evaluation of the available documentation (e.g. mine maps and authority documents) on the mining activities of the past centuries, the mining authority NRW identified approx. 11,500 abandoned openings to the surface in the Ruhr region (Welz, 2014). If the mine workings are flooded after active mining has ceased, in the worst case scenario, an estimated 5,300 abandoned openings to the surface (including 4,000 shafts and 600 adits) will be affected by the rising mine water (Welz and Weissbeck, 2006). Therefore, numerous shafts and near-surface openings

Figure 7 / Sinkhole in the city of Witten, southern Ruhr-area (photo by DMT GmbH & CO KG, Essen, 2014)

require long-term securing measures in order to avoid any damage to the surface in order to enable subsequent use of the area or to reconstruct the former morphology.

A few spectacular sinkholes brought the maintenance required to secure the surface was brought to the public's attention (Figure 7).

In order to establish the long-term stability of insufficient backfilled shafts and near-surface extraction fields, high-performance technologies have been developed to be flexibly tailored to the specific requirements in each case. In this context, it should be noted that according to the court decisions of recent years and the German mining law (Bundesrepublik Deutschland, 1980) the last mining operator is obliged to deal with the legacies and consequences resulting from all mining activities within the respected excavation site in the case of potential endangerments. For the reasons mentioned above, the mining authority NRW and numerous mining companies established a risk-management program (Sikorski and Reinersmann, 2010).

5 Research Institute of Post-Mining at the TH Georg Agricola

Recognising the significance of securing the surface and optimising the long-term water management in the Ruhr-area, the RAG-Foundation funded a chair for the new academic course "Geotechnical Engineering and Post Mining Management" at TH Georg Agricola. In this masters program, the students obtain the competence to support industrial companies, consulting engineers and administrative bodies in the field of post-mining.

In addition to organising the new masters program, the holder of the endowed chair and his team are entrusted with establishing the Post-Mining Research Institute. One of the basic research projects is the development of an organised process for the perpetual

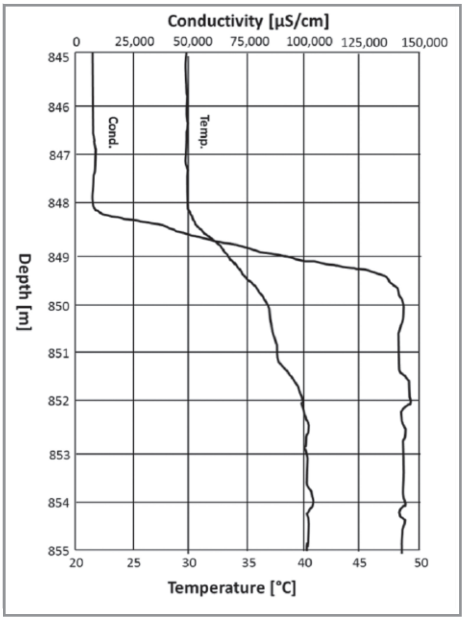

Figure 8 / Temperature/conductivity log of shaft Hermann 1, southern Ruhr-area (Melchers et al., 2014)

obligations in the Ruhr-area. In this context, the institute is dealing with the retention of specific know-how in the mining industry, with the processing of the key research areas and the establishment of collaborations. Some of the current research projects are:

- acquisition of density stratification in flooded mine workings;
- monitoring of underground flooding processes;
- analysis of water-bearing adits or drainage adits;
- analysis of terminated flooding processes of mines in Germany, Europe and worldwide.

5.1 Acquisition of density stratification in flooded mine workings

In flooded shafts of the Ruhr-area, distinct boundaries between differently mineralised water bodies have been observed at diverse localities. The influx of higher mineralised water from the rock mass and from the mine workings on the one hand, and the penetrating less mineralised surface water on the other hand causes significant density differences in the water column. The formation of a stable stratification can be proven by measurements of temperature and conductivity. These measurements confirm that columns of water in flooded shafts display stratification with distinct boundaries between individual, homogeneous layers. The stable conditions are driven by convection currents generated from the influx of higher tempered and mineralised mine water. Therefore, the observed density stratification can be considered the result of a complex flow pattern governed by the mineralisation and temperature of the water in the shafts. There is substantial evidence that density stratification exists in other mining regions as well. There are also indications of missing convection cells in other localities. Figure 8 shows the temperature and conductivity profile logged in a shaft located in the southern Ruhr-area. The jump of the measured values for conductivity and temperature at a depth of between 848 and 850 m displays the boundary layer.

Density stratification is an important criterion for the flooding process of mine workings after closure. Considering the significance of this phenomenon for the flooding of different mines, proceeding site investigations are required; they are the subject of a current research project (Melchers et al., 2014).

5.2 Monitoring of underground flooding processes

The flooding of a hard coal mine in the Ruhr region will be attended by intensive monitoring underground and above ground within the context of a research project. With the help of distinct sensors, the observation of the rising mine water is carried out via telemetering. The measurement parameters are mainly water pressure, salinity, temperature, flow velocity, flow rate and methane content. Among other measurements, the reaction of the surface to the rising mine water will be controlled by satellite geodesy.

For the first time in Germany, the flooding of the Saar coalfield will be accompanied by the implementation of an environmental impact study. In this context, the uplift of the surface connected to the rising mine water table and the flooding-induced seismic events will attract public attention.

5.3 Analysis of water-bearing adits or drainage adits

In the Ruhr-area, as well as in numerous other mining sites, mine water is discharged to the surface via adits. In many cases, the emerging mine water registers as reddish colour. This phenomenon can be attributed to increased iron contents due to the oxidation of pyrite. The precipitates may form inside the mine or several miles downstream. There are 50 drainage adits in the southern Ruhr district, some of which reach a total length of more than 10 km and may drain extensive mine workings and large areas at the surface. In cooperation with the responsible mining authority, these adits are currently analysed according to their water supply, hydrochemistry and possible effects on the surface.

There is evidence that coal mines and ore mines are affected by the oxidation of pyrite, resulting in acid mine drainage. As part of a research project, the deferrisation systems are to be optimised. In the caprock-free coalfield of Ibbenbüren the deferrisation system has been operating for many years, with mine water rates averaging around 6 m^3 and iron contents of currently approximately 200 mg/l (Goerke-Mallet, 2000). Similar conditions are prevailing in the abandoned ore mine of Meggen in the city of Lennestadt, district of Olpe, NRW. In both cases, the sulphate contents are approximately 2,000 mg/l. As the deferrisation is operating successfully, continuous process optimisation is required. For a similarly successful reduction of water-compatible sulphate contents, adjacent techniques have to be developed. The EU water framework calls for a profound analysis considering the overall topic of mine water purification.

5.4 Evaluation of the flooding process in flooded underground mines in Germany, Europe and worldwide

In the context of a research project, 21 European hard coal mining regions have been analysed according to the available information about mine closures. The evaluation concentrated mainly on the flooding process within the mine workings and the resulting effects. The different upward and downward movements of the surface and the specific prevailing hydrochemical conditions are compared. The study provides some interesting results regarding the implementation of the flooding process and the hydrochemistry of the mine water. For instance, in nearly all cases, there was no efficient monitoring, making it impossible to perform any further optimisation of the flooding processes. In some of the flooded underground mines, there are indications of the formation of density stratification. In none of the analysed cases is there evidence of any pollution of drinking water horizons by mineralised mine water. However, in many regions, the drain water adversely affects the water quality of the next receiving watercourse.

The rising mine water level has led to uplift of the surface in many mine regions worldwide. The maximum of the measured upward movement reaches 30 cm. It should be noted that this number is based on the available data. Higher upward movement might have taken place in regions where the monitoring did not have sufficient resolution. Massive mining-related damage to buildings in Germany to date is only known to have occurred in one German hard coal mining district, near Aachen. Here, the flooding mobilised a tectonic fault, unilaterally inducing the generation of a discontinuity (Melchers and Dogan, 2014).

5.5 Conclusions and implementation

Based on the previously performed and planned studies, suggestions can be given regarding the reduction of closure risks and the optimisation of processes related to mine management. The goal of the current research is to achieve sustainable safety for the ground surface, the population and the water bodies (ground- and surface waters) in combination with reasonable costs.

For not only the Ruhr deposit but also numerous other mining areas, the development and deepening of knowledge on the optimisation of closure processes is important for environmental and financial reasons. The projects of the research institute are designed to provide information about chances and risks in managing planned floodings of underground mine workings for different mines in the foreseeable future. This includes dealing with former extraction fields and proposing solutions for an environmentally compatible purification of mine water.

6 Summary

The current domestically sourced production of raw materials covers approximately 70 % of the total demand for resources in Germany. Germany remains a mining country with an extensive sector of old mining. In a region with such a high population density, the old mining sector creates special risks for the safety of the ground surface, the population and the environment. Unstable abandoned mine openings and sub-surface mine workings, uncontrolled methane emissions and acid mine drainage must be considered. One subject of the ongoing research at the Research Institute of the TH Georg Agricola is risk management for post-mining and the optimisation of closure processes in the mining industry. The conclusions to be drawn from the discussed and further studies will be used to design the processes for closure and safekeeping as optimally as possible.

Thus, the environmentally compatible flooding of the underground mines of the largest German hard coal region, the densely populated Ruhr-area, is to be planned and accompanied by an efficient monitoring program. Beyond pit water management, the so-called perpetual obligations include extensive polder measures and groundwater purification. The specific need for action in this context is also spurred by European regimentations.

There is a global need for environmentally compatible closure and safekeeping methods. The objective should be to enhance the transparency of communication on this subject in order to transfer specific pre-existing know-how across distinct mining regions all over the world. An important element is the international exchange of experiences.

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