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Hydraulics of Underground Mine Flooding – Optimization of Prediction and Monitoring Procedures

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Abstract

In 2018, the subsidized hard coal mining in Germany will end. Concurrently, this will terminate a shutdown process that lasted for decades and induced many tasks for the future. From 2019 onward, one of the foci in the Ruhr, Saarland and Ibbenbüren mining districts will be to establish a perpetual and eternal environmentally responsible mine drainage system. Controlled rebound of mine water is a complex process that can be linked to both risks and chances for the environment as well as the safety of the surface.

Many abandoned underground hard coal mines in Germany and Europe have already been flooded. During the flooding processes, important insights and experiences relating to the mine water rebound process per se and its environmental impacts have been gathered. Due to the site specific hydrogeological characteristics, some of these experiences are of local importance, while others can similarly be used at other mining areas.

Our study provides a systematic overview of selected European hard coal mine water rebound processes that already have or are about to be finished. The focus will be on the analysis of time and space-depended flooding processes. It will describe the flooding process from a hydrodynamical point of view and summarize the important parameters controlling and influencing the process.

Based on this analysis, the general properties and interdependencies of mine flooding are to be identified. In addition, the effects caused by the local conditions will be identified. Based on past mine flooding scenarios, and focusing on potential environmental effects, conclusions for optimising predictions and monitoring measures will be drawn. Finally, the project will provide a better understanding of the processes involved in mine water rebound which can be implemented in future mine closure plans. This will provide measures for transferring the experience-based knowledge to future mine water rebounds in other hard coal mining districts, thereunder the Ruhr, Saarland and Ibbenbüren mining districts.

1 Introduction

Germany has a long tradition in ore and coal mining. Annually, nearly 180 Mt of lignite are being mined in open pits and more than 500 Mt of ore, earth and stone minerals are being extracted (VRB 2016). Especially hard coal, salt and different ores have been mined for centuries in underground mines. In 2018, the last two hard coal collieries in Germany will close, both situated in North-Rhine Westphalia. With the closure of the mine "Prosper-Haniel" in the Ruhr District and the Ibbenbüren colliery situated at the northern border to Lower Saxony, the era of underground hard coal mining will come to an end. The closure of these two collieries, however, does not correspond to an end of the mining operator's responsibilities. It is the operator's legal responsibility to take care for a sustainable and environmentally acceptable post-mining management, especially regarding handling of mine water. In Germany, the term "perpetual tasks" underlines the timeframe of this responsibility, which includes the long-term regulation of the mine water table at an environmentally agreeable level, poldering measures for controlling the ground water table close to the surface and the treatment of ground water at old colliery sites, coking plants and spoil heaps. For many years, the mining companies developed monitoring concepts to tackle these tasks, and it is a fundamental aim to enhance these concepts continuously (RAG 2014). As a lot of ground water rebound processes are already at a mature stage or can be regarded as completed, a lot of scientific experience have been gathered in deciphering the patterns of these rebound phenomena. Nevertheless, many findings are just of local importance, as both the geological and hydrogeological backgrounds differ from one mining area to another (Baglikow 2010, Rosner 2011, Goerke-Mallet 2000, Goerke-Mallet et al. 2017).

2 Current study

Currently, no systematic collection and interpretation of mine water rebound experiences on a European scale exists. Therefore, the Research Institute of Post-Mining at TH Georg Agricola, Bochum, Germany, initiated a first-time project, systematically investigating mine water rebounds in European hard coal mining districts. Within this study, all European coalfields will be considered and examined in detail regarding the experience made with processes and patterns of mine water rebound. The main coal mining areas to be surveyed are as follows (Figure 1):

- Germany (Ruhr area, Saar area, Ibbenbüren, Aachen-Erkelenz, Saxony),
- United Kingdom (Yorkshire, Durham & Northumberland, East Fife),
- France (Lorraine),
- Netherlands (South Limburg),
- Poland (Upper Silesia),
- Czech Republic (Upper Silesia)
- Spain (Asturias).

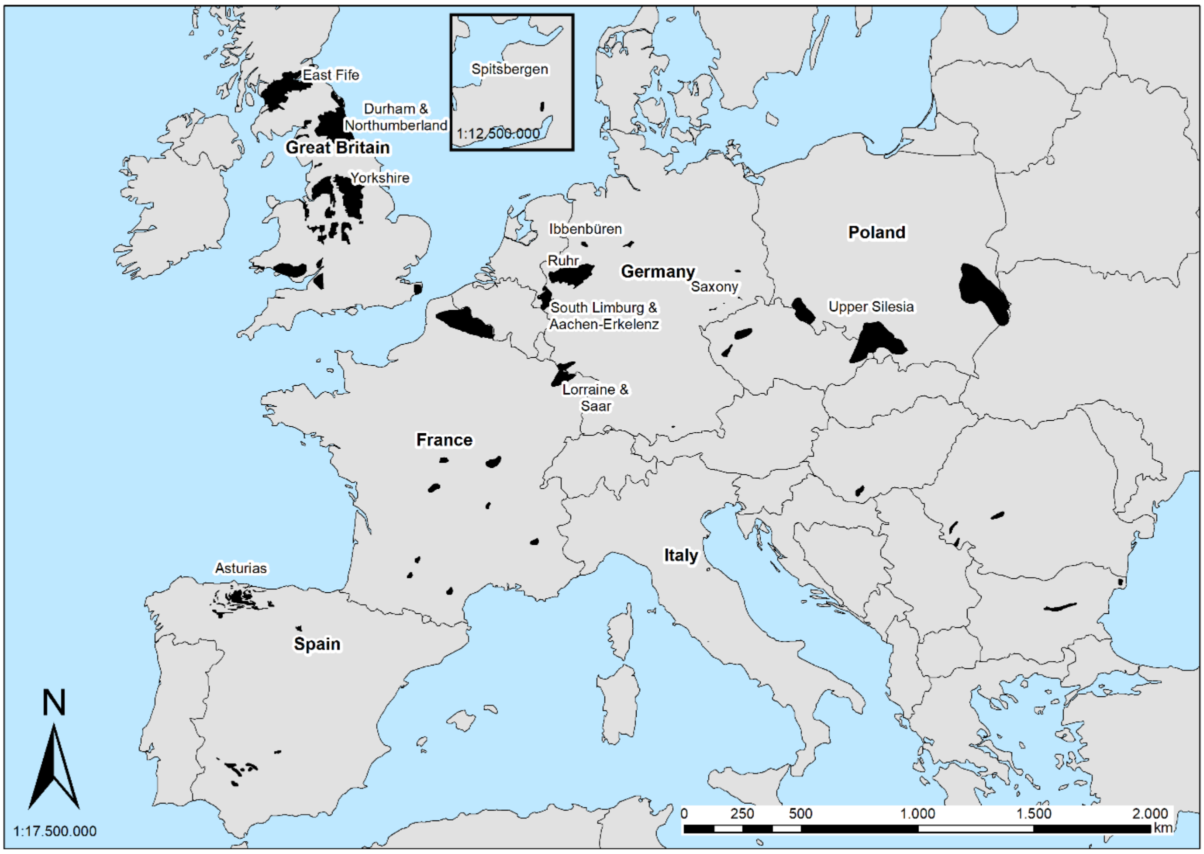

Figure 1: *European Coal mining areas.*

The evaluation focuses on the analysis of the spatial and temporal development of the mine water rebound, the related influences and interdependencies which comprise both the quantitative and qualitative changes of the mine water to be drained; the ground movements caused by the processes and mine gas migrations close to the ground surface. This overall evaluation intends to identify generally applicable causal relations of mine water rebound, to separate the locally specific conditions and to transfer the insights to other hard coal mining areas where mine water table rises are imminent. This objective applies to the Ruhr area, the Saar hard coal mining and the Ibbenbüren colliery.

3 Life Cycle of a mine

The influence of mining activity to the environment does not end with the closure of the mine. As the original pre-mining hydrogeological conditions are often irreversibly altered, the potential environmental impacts should last for a very long time (Wolkersdorfer 2008).

The life cycle of a mine splits into three main phases (Figure 2). The first phase is usually the shortest one and deals with the exploration of a deposit to estimate the profitability and the extent of investment needed to exploit the resources. The second phase corresponds to the actual mining activity and lasts until all resources are being extracted or the profitability of the mine is no longer granted. The third and last phase of the life cycle, the post-mining phase, is usually the longest one. It deals with the consequences of the mining activity and can last up to eternal scales (RAG 2014).

One of the most important parts of the post-mining phase is handling the mine water rebound, which usually starts immediately after mine decommissioning. In an ideal case, the first considerations regarding the rebound process and the appropriate management should be already made in the first phase of the life cycle.

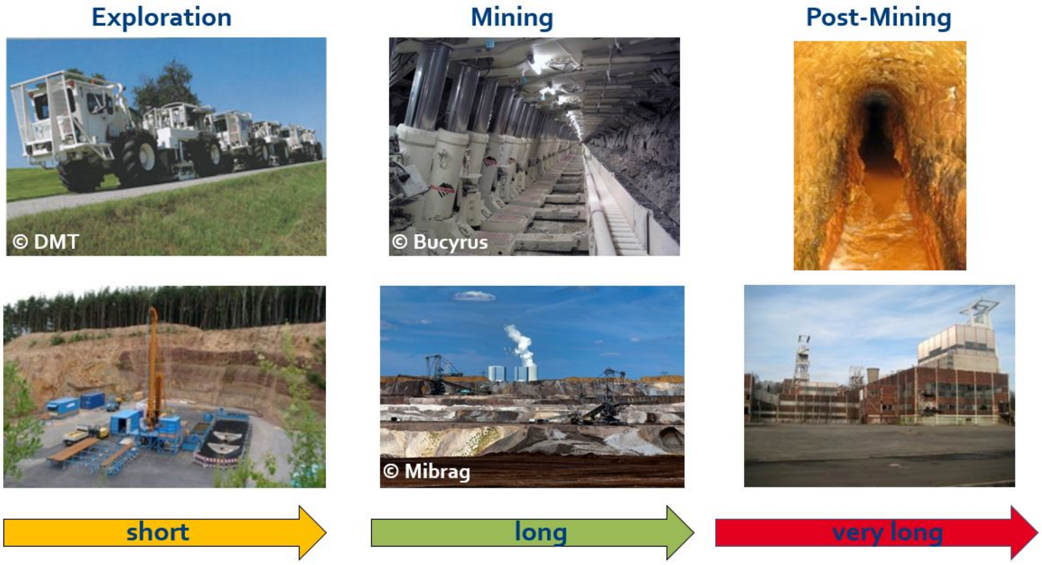

Figure 2: *Life cycle of a mine.*

4 Potential parameters influencing mine water rebound

The mine water table rise is often monitored in old shafts or boreholes and for a graphical visualization, the measured water level data is plotted against time. Usually that is done to estimate the time the entire rebound process lasts. Basically, this time is a result of the two parameters: floodable volume and water influx. The floodable volume of the underground workings as well as the influx of the water into these mine workings is not evenly distributed with depth. The floodable volume is largest in the worked main coal seams and decreases above and under these horizons. If mining plans are available, the floodable volume may be calculated in an accurate way excluding compaction and estimating mean porosities of goaf areas. This is not a trivial exercise. The estimation and/or calculation of the water influx in every depth of the mine is associated with higher uncertainty. Even if reliable data of the water abstraction of a single colliery is available, amongst other things, the source of the water as well as its corresponding decrease of the potential difference, and thus, the decrease of the influx must be regarded. For the latter, a model is presented and discussed in Banks (2001). A lot of effects influencing the spatial-temporal rebound process have been extensively studied and described in Wolkersdorfer (1996, 2006), and many parameters influence the rebound process (Table 1).

Table 1: *Rating matrix of the essential parameters of mine water rebound (Goerke-Mallet et al 2017).*

SECTOR 1	GEOLOGICAL CONDITIONS					
	Cap rock					
Features	Lithology	Tectonics	Aquifer	Floodable Volume	Ground Water recharge	Environment
Boundary conditions	*Variety of layer sequence*	*Hydraulic activity*		*Tectonic elements*	*Precipitation dependency*	*Hydraulic head*
				Ground water horizons		
	Deposit					
Boundary conditions	*Type of resource*	*Tectonic stress*	*Floodable volume*	*Water inflows*		
				Inflow of juvenile water		
				Seepage		
				Hydraulic balance		
SECTOR 2	**Mine**					
Features	Mining depth	Underground workings	Rock mechanics	Hydraulic routeing	Infiltration rate	Mass of water body
Boundary conditions	*Mining method*	*Residual volume mining horizons and workings*	*Rock pressure*	*Hydraulic effectiveness*	*Goaf*	*Deformation of floor / layers*
	Excavation ratio	*Floodable volume*	*Rock strength*		*Rock mass*	
		Damming	*Pressure ratios*			
		Water joinings				
		Water inflows and their locations				
		Hydrochemistry				
SECTOR 3	**Rock and ground movements**					
Features	Stratigraphy	Mining depth	Uplift			
Boundary conditions	*Lithology*					
	Rock strength		*Excavation radio*			
			Aquifer			
			Increase in floodable volume			

A lot of these parameters indicate a strong dependence with depth and have potential interdependencies. It is a goal of the present research to qualify, quantify and finally rank these parameters in terms of their effects on the rebound process. The links and dependencies of each of the parameters, hence their reinforcing or weakening effects needs to be considered as well. The evaluation of many complete or nearly complete rebound processes helps to better understand the governing effects, develop future strategies for sustainable water management approaches and predict the associated environmental impacts.

5 Monitoring

For the scientific analysis of the rebound process and its influencing parameters, as well as an adequate risk evaluation and appropriate management of the post-mining challenges, monitoring of relevant parameters is essential (Goerke-Mallet et al. 2017). The Research Institute of Post-Mining at the THGA in cooperation with RAG AG has developed a novel hydrogeochemical probe head, which allows continuous measurements of relevant in-situ parameters as well as data transmission using General Packet Radio Service (GPRS) (Kruse et al. 2017). These parameters include water pressure, temperature, electrical conductivity, flow rate and flow direction. This equipment allows to obtain insights into the temporal and spatial development of the rebound process.

6 Environmental effects and process understanding

Mine water table rise can cause several risks for people, ecology and infrastructure. These risks are even higher, i.e. unpredictable, if the rebound is not accompanied by a reliable monitoring system as well as potential corrective mechanisms, which can control the mine water rise and mitigate environmental effects. Mining operators, authorities and scientists have to deal with include increased gas emissions, impaired water quality or ground heavings (Westermann et al. 2017, Figure 3).

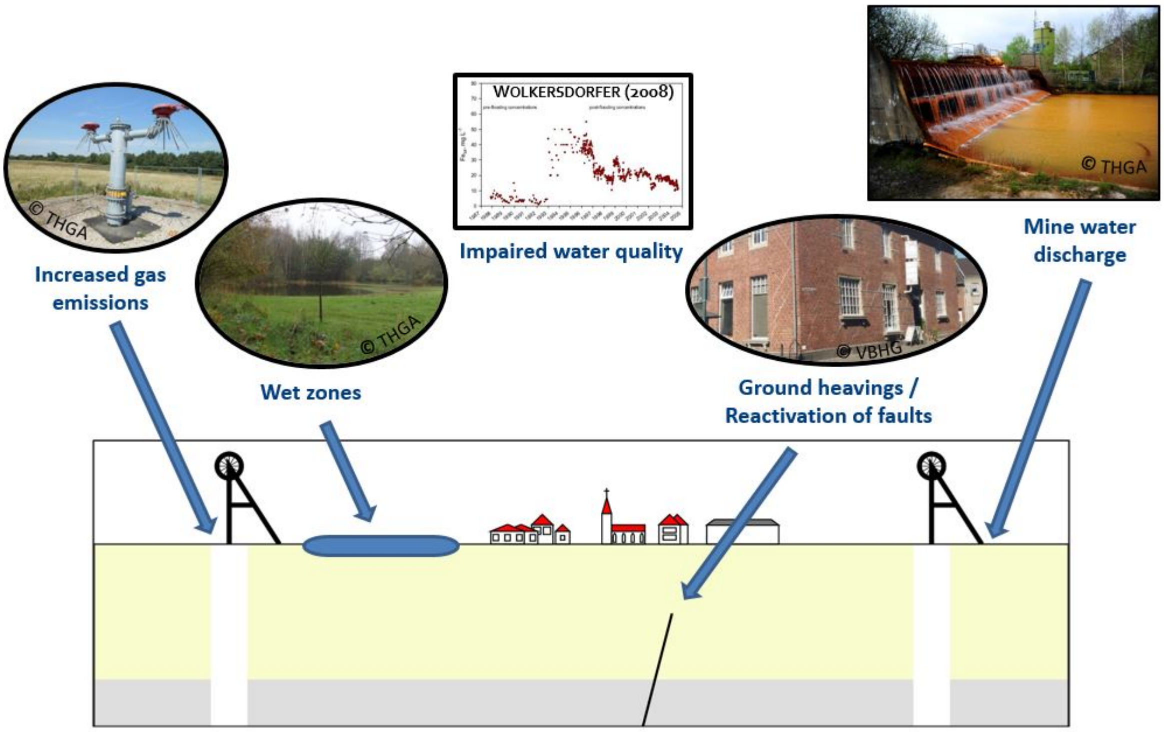

Figure 3: *Possible environmental impacts of mine water rebound.*

Understanding the processes that are associated with these environmental impacts is a key to predict the consequences. This includes a profound process-understanding of three essential parts:

- Hydraulics and hydrodynamics,
- hydrochemistry,
- geomechanics.

6.1 Hydraulics and hydrodynamics

As stated above, the speed of the mine water level rise is a function of the infiltrating water, the floodable volume and the available water conduits (Àlvarez et al 2018). These factors influence the course of the rebound. The origin of the infiltrating water is often a mixture of ground water and infiltrating water. However, these water intrusions are successively decreasing when they get gradually suppressed by the rising mine water table. Furthermore, the infiltration pathways influence the retention time of the infiltrating mine water and thus the hydrochemistry as outlined below. The precise quantification of the floodable volume is usually uncertain as it depends on the extent of the underground workings, the mined volume, the storage volume of the dewatered strata, the mining induced void volume (collapsing rock, goaf and fractures) and tectonic elements (void space of faults), amongst others (Table 1). Besides the absolute values of these volumes which do change with time due to general vertical compaction or collapse of mine workings, the distribution of them with depth further influences the rebound process. A good example for this issue can be seen at the Barredo and Figaredo Mines in Asturias, Spain. Ordonez et al (2012) calculated the void space and its distribution within the reservoir of both connected collieries and their water influx. Plotting the mined horizons against the rebound speed shows that the rebound speed decreases drastically when the rising water table reaches a mined horizon (Figure 4). Between these areas of elevated void volume the rebound speed increases, as the lower availability of void volume in the intact strata also suggests (Younger & Adams 1999).

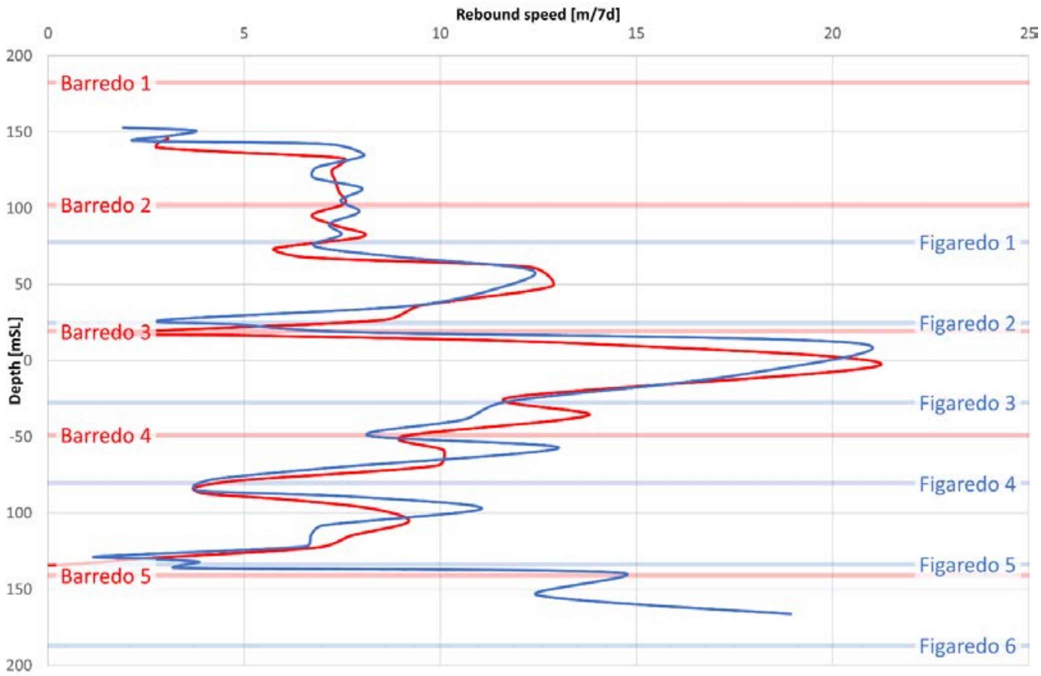

Figure 4: *Plot of the rebound velocity against the depth of the mined horizons (red lines for mined horizons at Barredo mine, blue lines for Figaredo mine (Asturias)). The rebound speeds for Barredo and Figaredo are shown as red and blue lines as well. Calculations based on reproduced rebound data from Ordonez et al (2012).*

Another good example of the influence of available void volume gives the Königsborn colliery in the Ruhr area. This rebound can be subdivided into three main phases (Figure 5) due to the availability of void space: In the first rise stage, in which underground mine workings and deepest horizons are flooded, high rise velocities occur, if converted accordingly, of in parts several hundreds of metres per year. On the one hand, this is due to the excavation ratio which is much lower at the deeper horizons and thus the cavity volumes are much smaller there; on the other hand, there is an increased influx of deep waters at this early stage which are pushed back with the rise of the mine water table. That stage is followed by a phase in which the main working levels are flooded. This stage is often marked by a more or less even rise. Changes of the hydrogeological properties, for example, the mine water table reaching the base of the overburden or of individual levels are reflected by the course. The continuing rise pushes the water influx from both the top and the bottom further down. Therefore, the rise velocity decreases and the curve levels off. The mine water rebound ceases to rise once it has reached an equilibrium between inflow and outflow of water or the level of a dewatering adit.

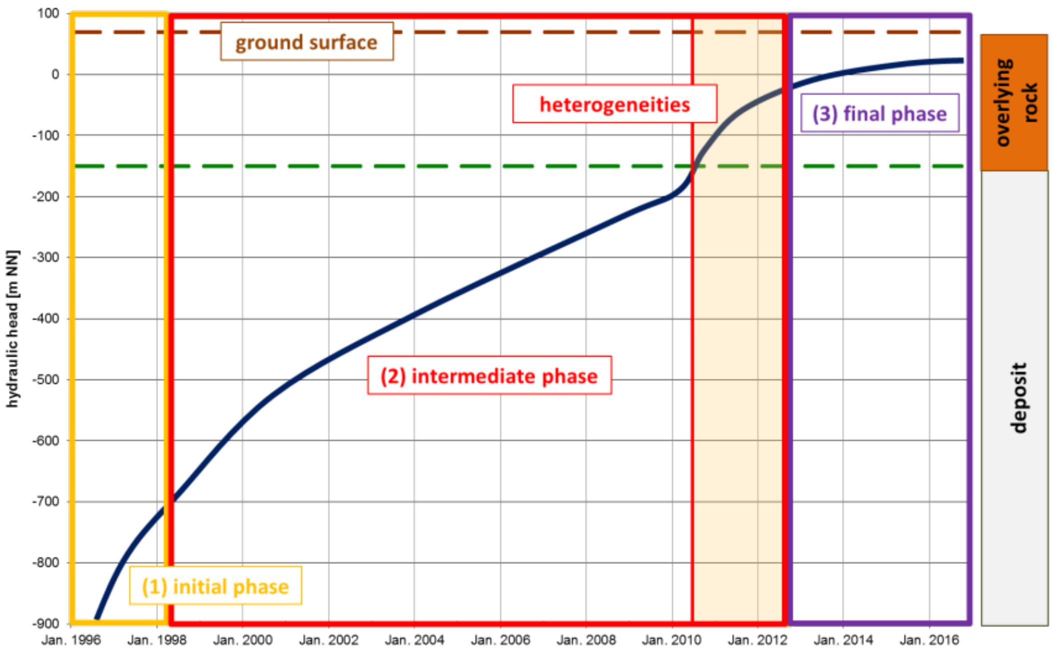

Figure 5: *Graph of the mine water rebound at Königsborn colliery (Ruhr) and its separation into phases (modified after Rosner 2011).*

Underground connections to adjacent collieries, as it is common in many coal mining areas, can lead to a temporal stagnation of the water level due to the increased void space of the connected workings. The difficulties to handle these uncertainties can be seen at the connected mine workings of Thurcroft, Silverwood, Treeton and Maltby in the Yorkshire Coalfield, Great Britain. Burke (2000) modelled the rebound of these collieries confronting the problem, that the capacity of the hydraulic connection between Silverwood and Maltby was uncertain. This was mainly due to the lack of monitoring data of the water table in any of these collieries. He handled this issue by considering three possible scenarios for this connection. In scenario one, the roadway failed so that there was no effective hydraulic connection. In scenario two, there was a connection with a medium capable connection, resulting in a "modest flow to Maltby" (Burke 2000). Scenario three emanates from a highly capable hydraulic connection, resulting in an "unrestricted flow to Maltby" (Burke 2000). The results of this modelling approach are shown in Figure 6. For a better overview, just the results of scenarios two and three are shown, as these were the most probable cases. The graph makes clear, that this single uncertainty leads to a difference of the rebound time of several tens of years for the scenarios two and three. It is obvious that such a difference in time is not an effective basis for a sustainable post-mining water management. Although Burke (2000) concluded, that the most probable case was a scenario between two and three, he could not prove this statement until the first monitoring data was available in 2001, confirming his assumption. All in all it should be noticed that even a single uncertainty may lead to big discrepancy between a prediction based on modelling and the actual water table rise. This underlines the importance of an adequate monitoring system.

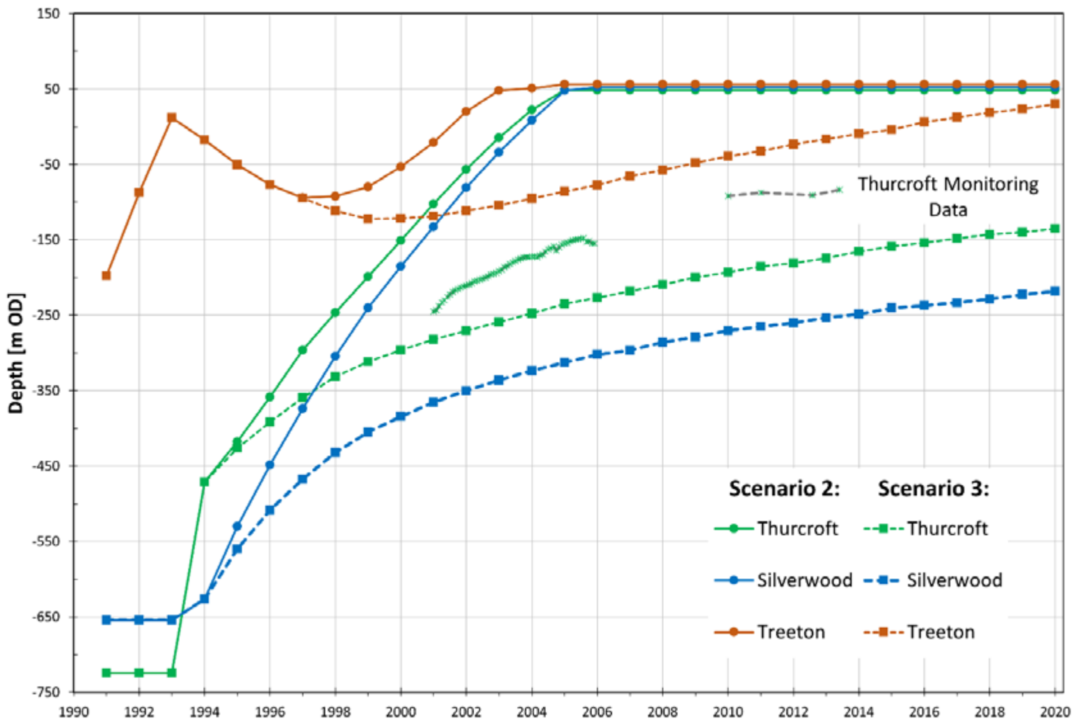

Figure 6: *Modelled mine water rebound at Thurcroft, Silverwood and Treeton and measured mine water rebound at Thurcroft in Yorkshire (UK). Data reproduced from Burke et al (2000, 2004, 2005) and Gandy & Younger (2007).*

In dependence of the spatial distribution and temporal development of the cumulative flows, density layering in the mine workings can result, which is stable over a long time (Wolkersdorfer 2016, Henkel & Melchers 2017). Within this context some interesting observations at collieries that lie close to the sea were made. Whitworth (2002) and Younger (2002) report on a clear tidal effect on the rebound process and the density layering. With respect to the rebound process the water table in the shaft of the colliery fluctuates with a magnitude of some decimetres as a reaction to the tides (Fig 4 right). Younger (2002) explains this observation with the additional load of the high sea level. This additional load of the higher water table results in a compaction of the underlying strata (Figure 7 A). This compaction leads to a lower void volume and thus presses the water out of the rocks (Figure 7 B). This can be recognized by a slight water table rise at the monitoring point. With the lower tide this compaction decreases again and the water table follows this trend (Figure 7 C). The observed time shift between the tides and the maximum effect on the water table is about 2 hours for the collieries in East Fife. A more drastic effect is observed with respect to the density layering in these monitoring points. Wyatt et al (2014) describes a change of the hydrochemistry of the pumped mine water according to the tides and a fluctuation of the density layering by the order of 10 m. The effect that causes this fluctuation is not understood in detail, but Wyatt et al (2014) attribute it to the different densities of the waters, the pumping regime as well as to the tidal forcing.

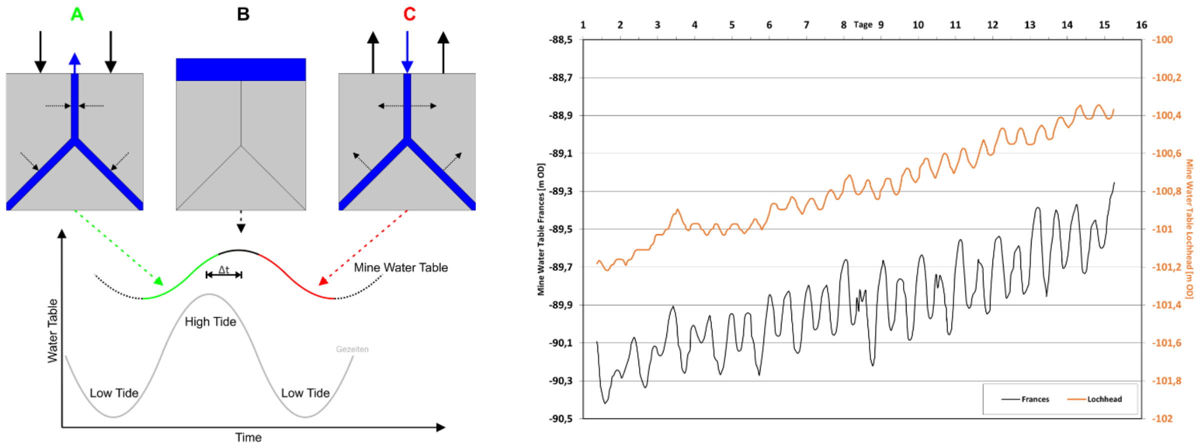

Figure 7: *Tidal effects influencing the rebound process. Left (A-C): Basic mechanism discussed by Younger (2002). Right: Detail of a rebound showing tidal effects at Lochhead and Michael collieries in the East Fife coalfield, Scotland. Data reproduced after Whitworth (2002).*

6.2 Hydrochemistry

The infiltrating water reacts with the rock matrix and with increasing retention times, the water will be continuously mineralised. Due to its genesis, the occurrence of hard coal is mostly associated with disulphide minerals (e.g. pyrite, marcasite or chalcopyrite). The dewatering of the strata when mining activity takes place and the ventilation of the underground workings favours the oxidation of these minerals (Barnes & Clarke 1964; Banks & Younger 1996). The intermediate oxidation products form a wide range of high soluble ferrous and ferric hydroxyl-sulphate phases (Younger 2000). This process is catalysed by acidophilic sulphide-oxidising bacteria, Acidithiobacillus ferrooxidans and Acidithiobacillus thiooxidans (Kelly 2000) (in literature often being referred to with their former names Thiobacillus ferrooxidans and Thiobacillus thiooxidans, Banks & Younger 1997). These evaporite mineral phases are highly soluble in water and are hence getting dissolved when the mine water table rises. If no buffer minerals (e.g. carbonates) are available, this results in Acid Mine Drainage (AMD). Once the mine water rebound has been completed and the water reaches the lowest surface point of discharge, this dissolution leads to a high content of iron and sulphate in the discharging mine water. Exposed to the atmosphere, the dissolved iron precipitates as yellow to red ochre, resulting in an explicit visual effect and a potential threat to the ground water and biosphere. Iron concentrations are usually highest in early phases ("first flush") and decrease exponentially with time (Younger 1997, 2000).

In areas where thick and impermeable rock layers act as a barrier between the rising mine water and the ground water, the risk of a contamination of the aquifer is substantially reduced (Heitfeld & Rosner 2015). Therefore, due to the (hydro-)geological properties of the deposit in the central and northern part of the Ruhr basin, where thick and impermeable claystone of the Upper Cretaceous Emscher Marl formation exists, a rise of the mine water table into the overlying strata of the Emscher Marl formation is unlikely (Hahne & Schmidt 1982, Baltes et al. 1998, Coldewey et al. 2014).

6.3 Geomechanics

The rising mine water table might result in a surface uplift in the centimetre to decimetre range. This can mainly be attributed to two reasons:

1. The rising water causes an increase in the buoyancy forces within the flooded strata.
2. The rising water may lead to a swelling of clayish rocks, resulting in a higher volume.

These ground heavings can be observed in many former mining areas and occur usually at large scale (Fenk & Tzscharschuh 2007). According to observations the heaving movements are less than 10 % of the subsidence volume (Preuße et al. 2017). In most cases, these ground heavings develop evenly and are not necessarily linked to damage-relevant events. Nevertheless, damage on structures caused by mine water rebound were observed in the Aachen-Erkelenz coalfield in Germany. The flooding of the coalfield caused the reactivation of a large fault, which led to heaving differences on both sides of the fault (Baglikow 2010). A second incident was reported by Oberste-Brink (1940) in the Wittener Mulde (Germany). Further reports of fault reactivations and damages to infrastructure because of mine water rebound were reported in the United Kingdom (Donnelly 2003, 2006; Yu et al. 2006). But in contrast to the discussions in Germany uneven uplift of the ground was not described, but a mine water rebound induced uneven subsidence.

7 Outlook

Out of the multiple completed or nearly completed rebound processes in European coal mining areas, many important conclusions regarding the prognosis of future mine water rebounds and their impacts to the environment can be done. The deeper and better understanding of the underlying processes are important steps to improve the long-term strategies and measures regarding the mine water management in accordance with sustainability, environment and profitability.

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