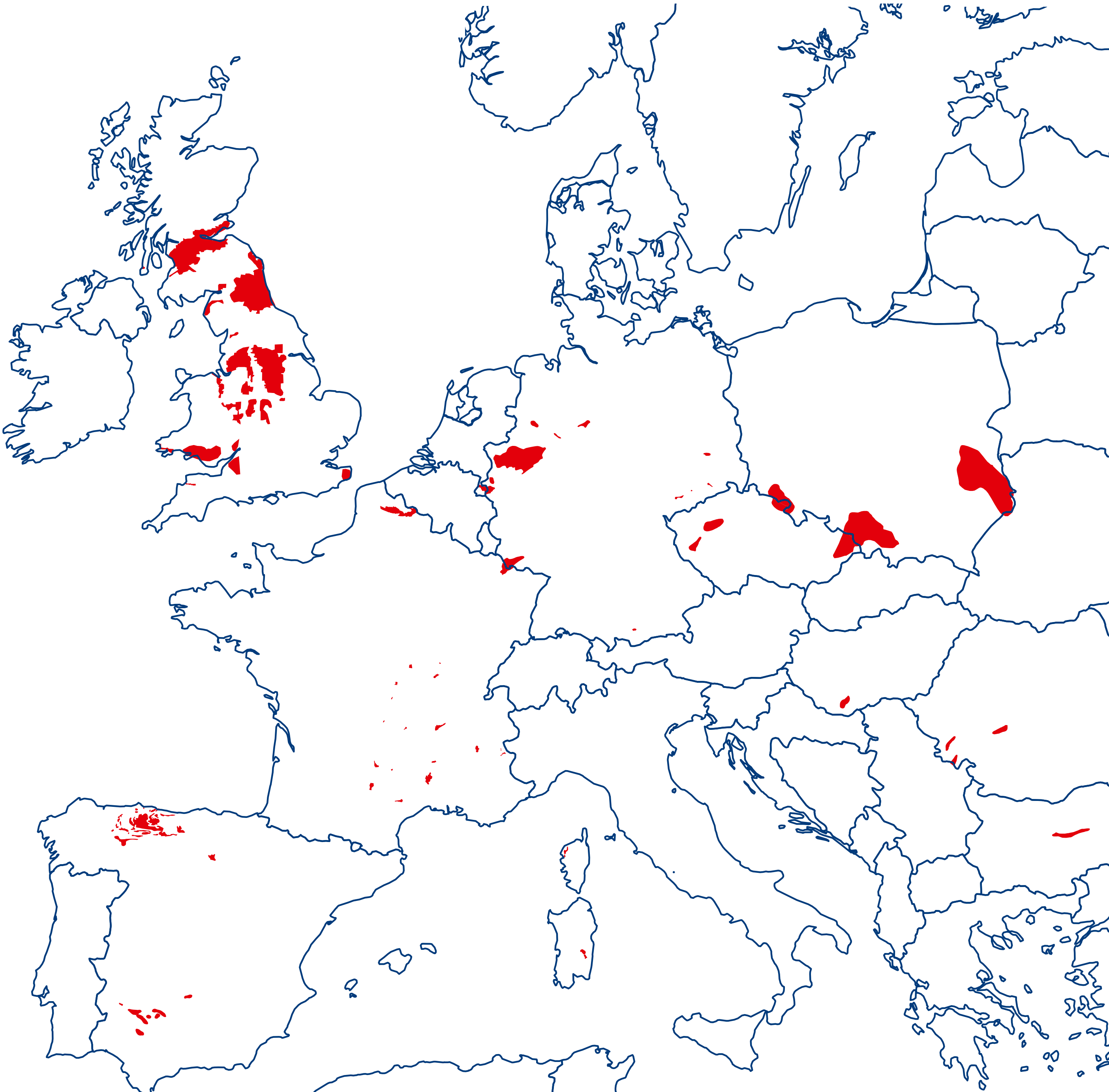
Technische Hochschule Georg Agricola University

Project report

Evaluation of Mine Water Rebound Processes

Christian Melchers, Sebastian Westermann, Bastian Reker



Technische Hochschule Georg Agricola University

Project report

Evaluation of Mine Water Rebound Processes

in the German Coalfields of Ruhr, Saar, Ibbenbüren, and the adjacent European Countries

Prof. Dr. rer. nat. Christian Melchers
Dr.-Ing. Sebastian Westermann
Dr. rer. nat. Bastian Reker

Technische Hochschule Georg Agricola - University (THGA)
Research Centre of Post-Mining
Herner Str. 45, 44787 Bochum, Germany

with the collaboration of
Prof. Dr. rer. nat. Wilhelm Georg Coldewey,
Prof. Dr. Coldewey GmbH, Sperberweg 1, 48249 Dülmen (Germany)
Dr.-Ing. Michael Eckart (†),
DMT GmbH & Co. KG, Am TÜV 1, 45307 Essen (Germany)
Dipl.-Math. Holger Kories,
DMT GmbH & Co. KG, Am TÜV 1, 45307 Essen (Germany)
Prof. Dr.-Ing. Dmitry V. Rudakov,
Dnipro University of Technology,
D. Yavornytskyi Avenue 19, 49005, Dnipro (Ukraine)
Dipl.-Geol. Peter Rüterkamp,
DMT GmbH & Co. KG, Am TÜV 1, 45307 Essen (Germany)
Prof. Dr. rer. nat. Christian Wolkersdorfer,
Tshwane University of Technology,
SARChI Chair for Acid Mine Drainage Treatment,
Staatsartillerie Road, 0001 Pretoria (South Africa)

Selbstverlag des Deutschen Bergbau-Museums Bochum 2020

Imprint

Address
Technische Hochschule Georg Agricola –
University (THGA)
Herner Str. 45
44787 Bochum, Germany

Translated from German by
M.A. Kirsten Wächter,
Dipl.-Geol. Henning Jasnowski-Peters

Original title
Evaluierung von Grubenwasserasntiegsprozessen
im Ruhrgebiet, Saarland, in Ibbenbüren sowie
weiteren deutschen Steinkohlenrevieren und dem
angrenzenden europäischen Ausland

Concept and design
wedeldesign, Bochum, Germany

Print
Buch- and Offsetdruckerei Häuser KG, Cologne,
Germany

ISBN **978-3-937203-89-8**

Technische Hochschule Georg Agricola –
University (THGA) is a state-acknowledged
private university of the DMT-Gesellschaft
für Lehre und Bildung mbH, Bochum, and
represented by its president.

Contents

Terms which are defined in the Glossary (chapter 6) are written in *italics* the first time they are mentioned in the text.

Additional related information is provided in the respective info boxes which are marked with this icon:

Acknowledgments

Funded by RAGSTIFTUNG

The authors are grateful for the support of the people mentioned below regarding their constructive contributions to the discussion and leveraging their scientific expertise:

Dr. Marwan Al Heib, INERIS Ecole des Mines de Nancy, Nancy (France)
A. d. M. Dr.-Ing. Volker Baglikow, VBHG, Herten (Germany)
Isabelle Balzer, RAG AG, Essen (Germany)
David Banks, Holymoor Consultancy Ltd., Chesterfield (United Kingdom)
Dr. Sean Burke, British Geological Survey, Keyworth (United Kingdom)
Prof. Dr. Francisco Javier de Cos Juez, Universität Oviedo, Oviedo (Spain)
Antek Czapnik, Centralny Zaklad Odwadniania Kopaln, Cźeladź (Poland)
A. d. M. Dr.-Ing. Michael Drobniewski, RAG AG, Essen (Germany)
Pedro Riesgo Fernández, Universität Oviedo, Oviedo (Spain)
Dr.-Ing. Lukasz Gawor, Silesian University of Technology Gliwice, Gliwice (Poland)
Erwin Goczoll (†)
Dr. Luis Manuel Lara Gómez, Universität Oviedo, Oviedo (Spain)
A. d. M. Dipl.-Ing. Stefan Hager, RAG AG, Essen (Germany)
Dr.-Ing. Michael Heitfeld, Ingenieurbüro Heitfeld-Schetelig, Aachen (Germany)
Nicolas Koeberlé, BRGM, Unité Territoriale Après Mine Est, Freyming-Merlebach (France)
Dipl.-Ing. Joachim Löchte, RAG AG, Essen (Germany)
A. d. M. Dipl.-Ing. Hermann Mühlenbeck
Dr. Barbara Palumbo, British Geological Survey, Keyworth (United Kingdom)
Prof. Dr. Marek Pozzi, Silesian University of Technology Gliwice,Gliwice (Poland)
Prof. Dr. Nada Rapantova, VŠB Technical University of Ostrava, Ostrava (Czech Republic)
Dietmar Renner, Wismut GmbH, Königstein (Germany)
Dr. Peter Rosner, Ingenieurbüro Heitfeld-Schetelig, Aachen (Germany)
Dr. Chris Satterley, Coal Authority, Mansfield (United Kingdom)
A. d. M. Dr. mont. Axel Schäfer, RAG AG, Saarbrücken (Germany)
A. d. M. Dipl.-Ing. Sönke Thomsen, RAG AG, Essen (Germany)
Dr. Ian Watson, Coal Authority, Mansfield (United Kingdom)
A. d. M. Dipl.-Ing. Carsten Wedekind, Wismut GmbH, Königstein (Germany)

The authors would like to express their particular gratitude to the foundation RAG-Stiftung not only for their readiness to tackle and explore this important issue, but also for the funding of this project.

Preface

‘Experience is the teacher of all things.’

Gaius Julius Caesar

From its very beginning, mining has always been based on practical experience: the term ‘mining engineering’ is adequate proof as it indicates that experience has been extensively leveraged; experience is also an important driver for post-mining related tasks, in particular where mine water management in the former mining regions of Ruhr, Saar and Ibbenbüren is concerned.

Thus, the key task of the project presented in this report was to summarise mine water rebound patterns as they occurred in European hard-coal mining regions and evaluate the processes involved. For that purpose, the authors spent three years on compiling, evaluating and assessing the data available. Additionally, they visited selected European coalfields in order to gain a more profound understanding of the local conditions. The exchange with the responsible decision-makers and authorities provided invaluable information on the experience made, and on the interdependencies to be faced in the post-mining era.

The detailed analysis of the mine water rebound process is also an essential part of this project. The process as such will be illustrated, and the intrinsic causal effects will be explained thoroughly. The same holds true for the fundamental hydrochemical processes taken place in the mine water. To allow for a better understanding, key terminology are defined and explained. In particular the differentiation of the terms ‘groundwater’, ‘mine water’ and ‘drinking water’ as well as the process-linked terms of ‘mine water rebound’ and ‘inundation’ are elucidated.

Beyond the era of hard-coal mining at Ruhr, Saar and Ibbenbüren, we now have the historical opportunity to establish a self-sustainable hydrological system in the mining regions. With regards to future generations, the task, or rather the necessity does persist to manage this process in such a way that it considers both ecological and economic aspects in a most sustainable manner.

As the following quote states: ‘people are disturbed not by things, but by the views which they take of things’ (Epictetus); hence, this report will be a contribution adding evidenced facts to the public discourse.

We would like to acknowledge all the people who have contributed to the success of this project in many ways. Foremost, we would like to thank the foundation RAG-Stiftung, which, with its commitment to promoting education, science and culture, has significantly supported this project; therefore, we would like to thank two persons in particular, i. e. Bärbel Bergerhoff-Wodopia and Michael Kalthoff.

For the Research Centre of Post-Mining

Prof. Dr. rer. nat. Christian Melchers

1. Introduction

Post-Mining

Post-mining refers to all processes and challenges that need to be undertaken after the extraction of mineral resources has ceased. These tasks include immediate actions of securing and restoring the heritage of mining but also the long-term and sustainable management of the mineral *deposits* and the mining area which has been excavated.

Classical objectives include risk management of abandoned mines and the renaturation and restoration of mining areas and surfaces. Key subjects related to post-mining are the water management including ground- and mine water for hard-coal and lignite mining; the dismantling and filling of exploration and production wells, and the decommissioning of sites operated by the oil and gas industry. These tasks also comprise geo-monitoring of post-mining processes and interdependencies. For successful handling of these tasks, a comprehensive management of data, information and knowledge needs to be provided.

Main aims of post-mining are to develop and accompany the structural transformation of heavy industrial sites in order to utilise their future potential.

Mining companies already need to consider post-mining activities during the entire mining life cycle, i. e. during the exploration and planning stage, and during the active mining phase in order to optimise the decommissioning process regarding sustainability, hence ecological and economic aspects.

Types of Water

In order to avoid uncertainty and confusion, we would like to differentiate the different types of water that play a role in *mine water rebounds*: *'groundwater', 'mine water',* 'drinking water' and 'wastewater' (Burghardt et al. 2017):

Groundwater
With regard to the conditions of formation, deposits and migration paths, different types of water are distinguished in the Earth's crust. According to DIN 4049-3 (1994), 'groundwater' is defined as underground water that coherently fills voids in the lithosphere and whose percolation is solely controlled by gravity. The term 'deep groundwater' or *'deep water'* is defined as groundwater in *aquifers* at deeper levels which are characterised – due to its long retention time – by a high level of mineralisation and reducing redox properties and only participates in the water cycle to a lesser extent (DIN 4049-3 1994). This report generally uses the term 'deep water' when referring to groundwater in deep aquifers.

Mine Water
The term 'mine water' does not have a common definition in German legal or regulative texts on water or mining. The working group of the hydrogeological section of DGGV e. V. defines 'mine water' as follows: mine water refers to all waters that (have) come in contact with underground or opencast mining works. Those mostly include natural water such as leachate and groundwater. Further on, the definition states that surface water can immediately infiltrate the *mine workings* due to e. g. precipitation and *receiving water courses* if the mine workings are not covered by *overburden strata*; water from the overburden strata may enter the mine workings through pore spaces, joints and karst cavities as well as through anthropogenic surface openings such as *shafts*; deep water of partly high mineralisation (saltwater) may infiltrate the mine from the adjacent host rocks and the underlying rocks. However, this definition does not include the hydrochemical properties of the mine water as these differ strongly in relation to the genesis of the mine water and its host rock.

Drinking Water
DIN 4046 (1983) defines drinking water, also known as potable water, as any water suitable for the consumption and food preparation grade; the quality properties are stipulated in the applicable statutory provisions and in the German standards DIN 2000 (2017), DIN 2001-1 (2019), DIN 2001-2 (2018), and DIN 2001-3 (2015).

Wastewater
According to § 54 (1) of the German Federal Water Act (WHG), wastewater is any water whose properties have been modified by domestic, industrial or agricultural and any other use including the water which is discharged with this aforementioned kind of water (drain water) during dry periods and or is collectively discharged from built-on and sealed areas (precipitation water) during periods of precipitation.

1.1. Motivation and Objective

At the end of the year 2018 the subsidised hard-coal mining in Germany ended. The last two remaining collieries, Ibbenbüren Colliery in Tecklenburger Land and Prosper Haniel Colliery in the Ruhr area, were closed down. Abandoning hard-coal production includes the plan of a controlled rise of the mine water in the *mining regions* of Ruhr, Saar and Ibbenbüren. This plan was the reason why the Research Centre of Post-Mining at Technische Hoschule Georg Agricola – University decided to evaluate and assess experiences already made with mine water rebounds in underground hard-coal collieries. As a number of coalfields have already been decommissioned across Europe, and their mine water rebounds has already been accomplished, the institute extended its view to include those internationally gained experiences. The research conducted was part of the project 'Evaluation of Mine Water Rebound Processes in the German Coalfields of Ruhr, Saar, Ibbenbüren, and the adjacent European Countries'. The foundation RAG-Stiftung funded this research project over a period of three years.

During exploitation it is inevitable in most regions to regulate the water inflows in the mining areas. Without pertinent mine dewatering and drainage efforts, mine water would hinder or even make mining operations impossible; on the other hand, uncontrolled water inflows would pose a threat for the mine operations. Accordingly, the development of mine water discharge is as old as ore mineral extraction itself. In pre-industrial time, *mine water drainage* above the receiving water course level occurred into natural surface waters using drainage *adits* or it was laboriously transported manually simply by muscle power. When the steam engine was invented in the 18th century – and its first models were indeed developed for mine drainage – machines were available for the first time which no longer needed muscle power to drive them. That meant that significantly deeper mine working levels could be explored. The further development of more powerful machines over time increased the demand for hard coal as a cost-efficient form of energy, and thus the production was moved to deeper mining *levels*.

After cessation of mining, there was no operational need to continue pumping the mine water (see info box on 'Types of Water'). That marked the beginning of post-mining (see info box on 'Post-Mining'); one key query of this stage is how to manage mine water in the long run. Principally, it makes sense to ensure a controlled rise of the mine water-bearing in mind that the process of a mine water rebounds provides both advantages and risks. Currently, there is a controversial discussion of those advantages and risks among the different stakeholders. The advantages of an immediate and so called 'uncontrolled' mine water rebound up to its initial pre-industrial level (or a higher mine water level) are both ecological and economic; one important aspect is the lower contamination of the receiving water courses by mine water compared to its production level as both the inflow volume would be lower (quantitative improvement) and the hydrochemical composition of the mine water would improve (qualitative improvement). Fundamentals on hydraulic and chemical processes is subject of chapters 2.1. and 2.5. Accordingly, cost reduction of the discharge or treatment of the mine water would be beneficial.

Besides the advantages there are risks which can usually be countered by adjusting the mine water management process. Among others, the flooding-induced *ground movement* (basic principles are provided in Ch. 2.2.), water saturated areas at the ground surface, the release of mine gas (basic principles are provided in Ch. 2.3.) and the contamination of aquifers caused by mine water are currently discussed.

1.2.
Mine Water Concepts of RAG AG for Ruhr, Saar and Ibbenbüren

Mine dewatering measures are necessary to protect the workers who work in underground mining operations. As active and abandoned mines are often connected by means of a wide-range *roadway* system, it is necessary to maintain mine drainage even in adjacent abandoned areas to prevent water inflow to the active parts of the mine. When closing down a mine, the continuous mine dewatering needs to be justified by a new protection aim.

During decommissioning of hard-coal mining in the mining regions of Ruhr, Saar and Ibbenbüren, it will no longer be necessary to maintain the *mine dewatering* (mine water drainage) at that level which was required during the active mining stage. Thus, it is planned to adjust the mine water discharge to the current requirements. In order to optimise the economical aspect of the mine dewatering, the long-term subsidence is meant to be kept as low as possible whilst excluding any negative impact on human beings, nature or infrastructure.

When the Legacy Agreement ('Erblastenvertrag') was agreed on between the 'coal-mining states' of North Rhine-Westphalia and Saarland, and RAG-Stiftung, RAG AG was committed to develop a concept

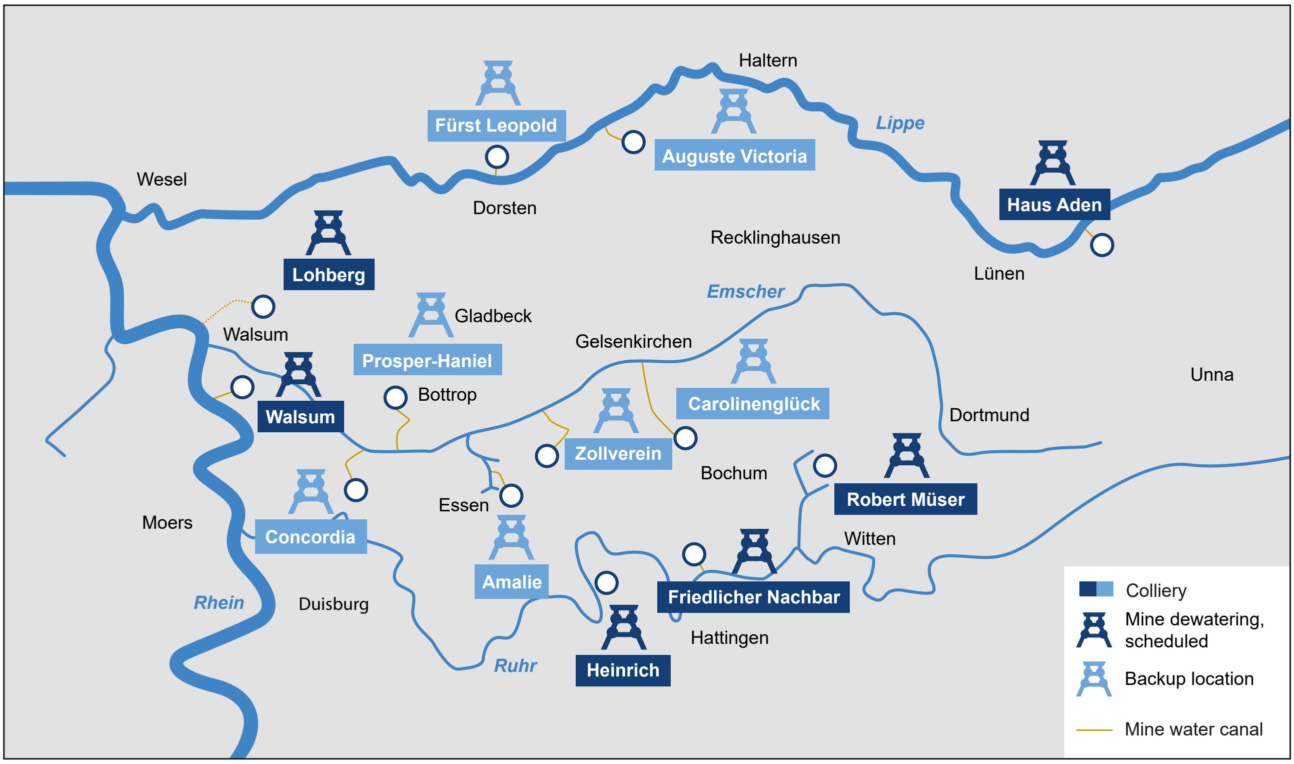


Fig. 1: Overview of the mine water pump locations in the Ruhr mining region, adapted from RAG AG (2016).

of how the mine water discharge could be optimised. This concept is aimed to improve the water quality of surface waterbodies and also to consider the economy, thriftiness and efficiency of the measures to be implemented while maintaining the protection of people and the environment. In 2014, RAG AG presented their individual mine water concepts for the former mining regions of Ruhr, Saar and Ibbenbüren (RAG AG 2014a; 2014b). The planned measures are always to be based on current knowledge of science and technology. Considering the insights gained, the measures to be implemented need to be constantly optimised. The mine water concepts pursue the following objectives of protection:

- Preventing any damage to the public, e. g. contamination of drinking water.
- Avoiding hazards caused by additional methane releases at the largest possible extent.
- Avoiding dramatic damages caused by uplift.
- Avoiding hazards caused by sinkholes where possible.

Concerning the **Ruhr mining region**, the proposed mine water concept of RAG AG intends a stepwise partial rise of the mine water level until 2035 – until a level is reached which can ensure prolonged protection of crucial drinking water reserves (see info box on 'Types of Water'). For example, to protect the drinking water reserves of the Haltern Sands, RAG AG estimates that the mine water rebound has to be limited to approx. 500 m below the ground surface (RAG AG 2014a).

Fig. 2: Submersible motor pump at the mine pumping location in Walsum (photo: RAG AG, Volker Wiciok).

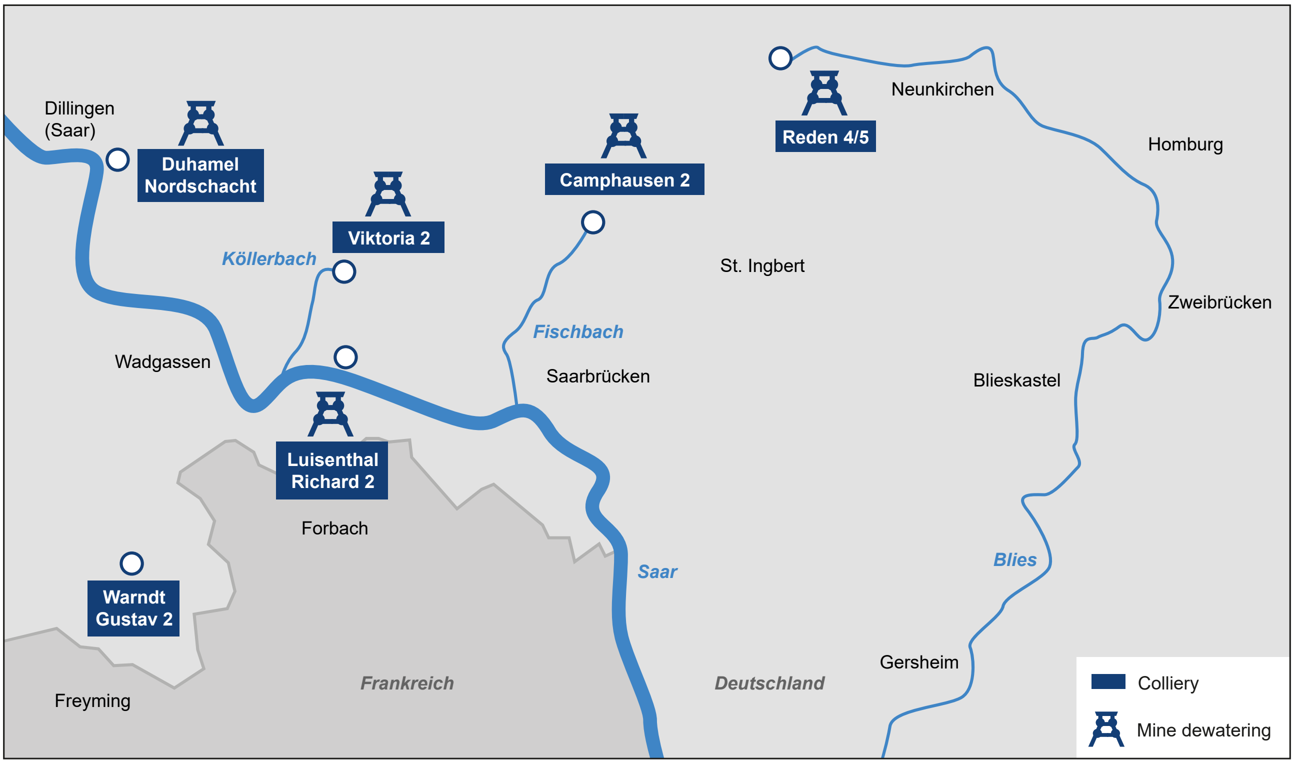


Fig. 3: Overview of current mine water pumping locations in the Saarland (as of 2019), adapted from RAG AG (2016).

The number of *mine dewatering locations* ('pumping locations') at which pumps need to be permanently operated is going to be reduced from 13 to 6 locations; however, this process of centralisation requires that the mine water can continuously flow underground into the mine dewatering system (dark blue locations shown in Fig. 1). This centralisation is only enabled by the partial rise of the mine water. A reduction of mine water discharge locations results in relief of the receiving water courses: in the future, no mine water will be discharged into the river Emscher, and at the river Lippe only one discharge point will be operated.

The future planning forces the replacement of the underground installed centrifugal pumps by submersible pumps which will be installed inside the shafts (Fig. 2). At each of the six mine pumping locations, auxiliary pumps will be installed to ensure a continuous pumping in case of a pump failure. When implementing this modification of the pumping stations, no immediate access to the mine workings will be necessary or possible: in the future, the installation, maintenance and control of the submersible motor pumps will only be managed from surface.

In order to ensure that the protection objectives are achieved, further locations (backup locations) will be transformed in such a way that the controlling access to the mine water either continues or can be re-established very quickly during abandonment of the underground mine workings (light blue locations in Fig. 1). These locations can support the mine dewatering in case major underground roadways will lose their function as a flow path for transporting mine water at the volume required.

In the **Saar mining region** (Fig. 3), the mine water concept subdivides the mine water rebound in two stages (RAG AG 2014b). In stage 1, the mine water level is supposed to rise only in the water provinces

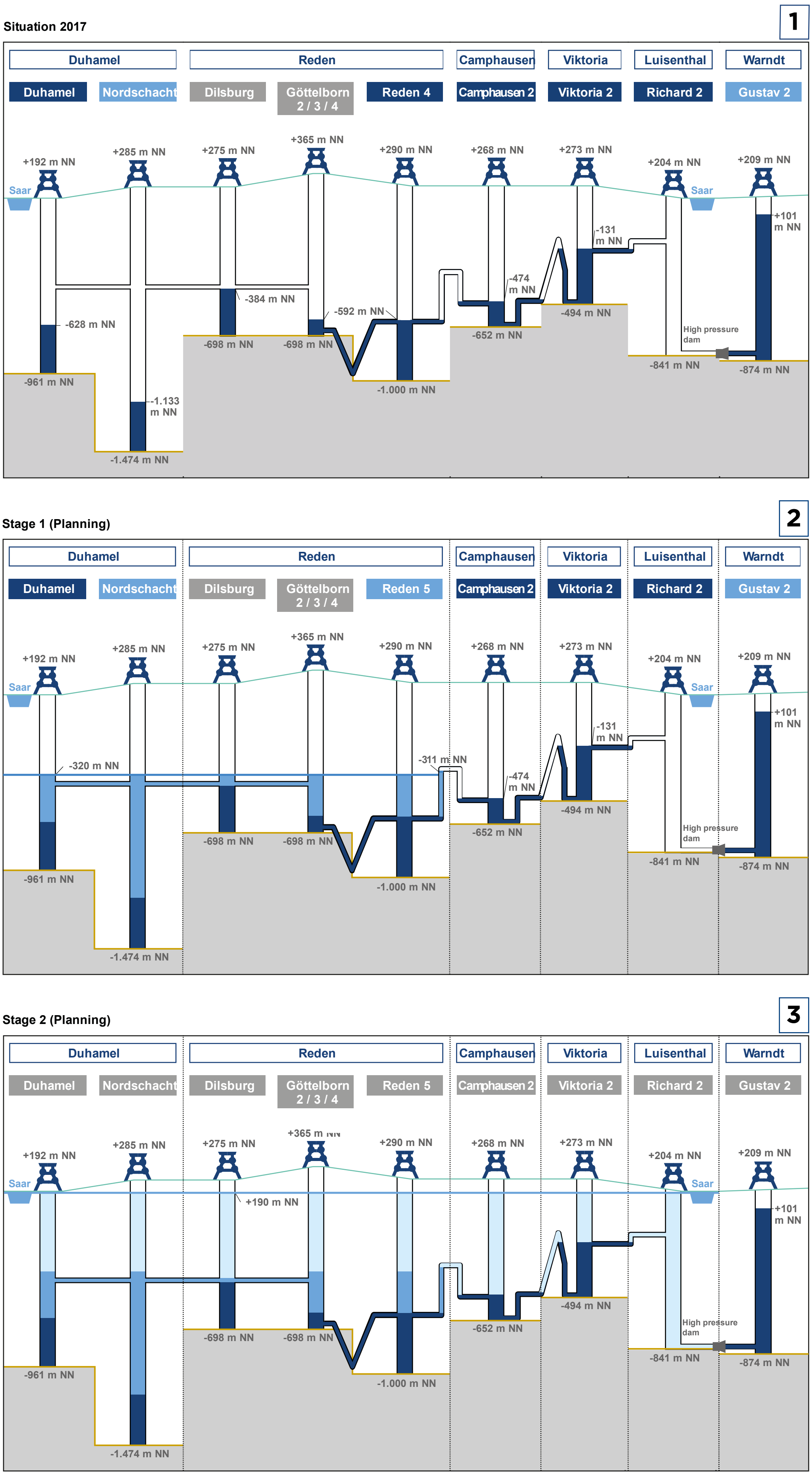


Fig. 4: Planned stages of the mine water rebound in the Saar mining region, adapted from RAG AG (2017). (1) Situation as of 2017. (2) Planning of stage 1. (3) Planning of stage 2 (discharge into the river Saar without use of pumps).

Pumping location

Sounding location

Location

Duhamel and Reden up to a level of 320 m below sea level and subsequently, it will be raised jointly at the Duhamel location (Fig. 4). As a consequence, transfer of mine water into the water province Camphausen is avoided as mine gas is still extracted and used for energy-generating purposes at Camphausen. During the second step, the water level is supposed to continuously rise and infiltrate the other water provinces, too. The long-term goal is an unpressurised discharge of the mine water into the river Saar using a drainage adit at the location of the decommissioned Duhamel Colliery. As in the Ruhr area, the number of mine dewatering locations in the former Saar mining region is to be reduced, and back-up locations must be provided.

Likewise, the mine water concept devised by RAG Anthrazit Ibbenbüren GmbH envisages a long-term condition for **Ibbenbüren Colliery** that will not require any pumping measures. Since the early 1980s, the former mine workings of the coalfield called Westfeld have been drained into the local river using the Dickenberger Stollen (Dickenberg adit). In the future, the mine water from the coalfield called Ostfeld is supposed to rise until it reaches the level of a drainage adit that still needs to be constructed ('mine water canal'); then, together with the Westfeld mine water, it will be discharged by gravity.

All long-term mine water discharges mentioned above are part of the long-term liabilities (see info box on 'Long-Term Liabilities'); their funding is stipulated in the Agreement on Long-Term Liabilities ('Ewigkeitslastenvertrag'), i. e. an agreement on how to cover the cost of the long-term liabilities of RAG AG (internal relationship between RAG AG and RAG-Stiftung), and the abovementioned Legacy Agreement ('Erblastenvertrag'; North Rhine-Westphalia and Saarland and RAG-Stiftung). Honouring these agreements, RAG-Stiftung is committed to covering the funding of the long-term liabilities commencing in 2019. If the funds of the foundation turn out to be insufficient for this purpose, the coal states of North Rhine-Westphalia and Saarland shall share part of the funding. If that case applies, the federal German government will have to cover part of the cost; to which extent is stipulated in the Hard-coal Funding Act.

Long-Term Liabilities

From January 2019 onwards, RAG-Stiftung takes over the funding of the long-term liabilities which mainly concern the mine water discharge, the *polder* measures and the groundwater purification. In 2006, the auditing company KPMG provided a report estimating and assessing the financial costs necessary to manage the long-term impact resulting from mining activities; this 2006 estimate calculated costs of € 220 million per year.

The long-term and environmentally sustainable **mine water discharge** will make up the biggest amount of all inquiries, approximately about 60 % of the total cost (Fig. 5; RAG-Stiftung 2018). After the end of coal production, the mine water will rise to a level that still ensures sufficient distance to the drinking water reserves (RAG AG 2016), thus safeguarding any contact between mine water and groundwater.

The **polder measures** taken in the Ruhr area regulate the groundwater and surface water in areas whose topography has subsided due to the past 150 years of mining (RAG AG 2016). To avoid water logging in *mining subsidence* areas at the Ruhr where no effluents or outflows are in place, the water boards (Emschergenossenschaft [EG], Lippeverband [LV] and Linksrheinische Entwässerungsgenossenschaft [LINEG]) as well as RAG AG operate pumping stations which raise the water and discharge it into the receiving water courses.

On former mining ground often associated with coking plants, soil contaminations which are transported into the groundwater will be eliminated (**groundwater purification**; RAG AG 2016), thus limiting the spread of hazardous substances. This part, however, causes the smallest share of the long-term liabilities.

The damages to infrastructure (*mining damages*) caused by mining activities include the restoration and securing of shafts, the dismantling of mine operation facilities and pension provisions to former mine workers; all of these, however, are not part of the long-term liabilities (RAG AG 2016). Their regulation (mining damages) and funding will still be covered by RAG AG.

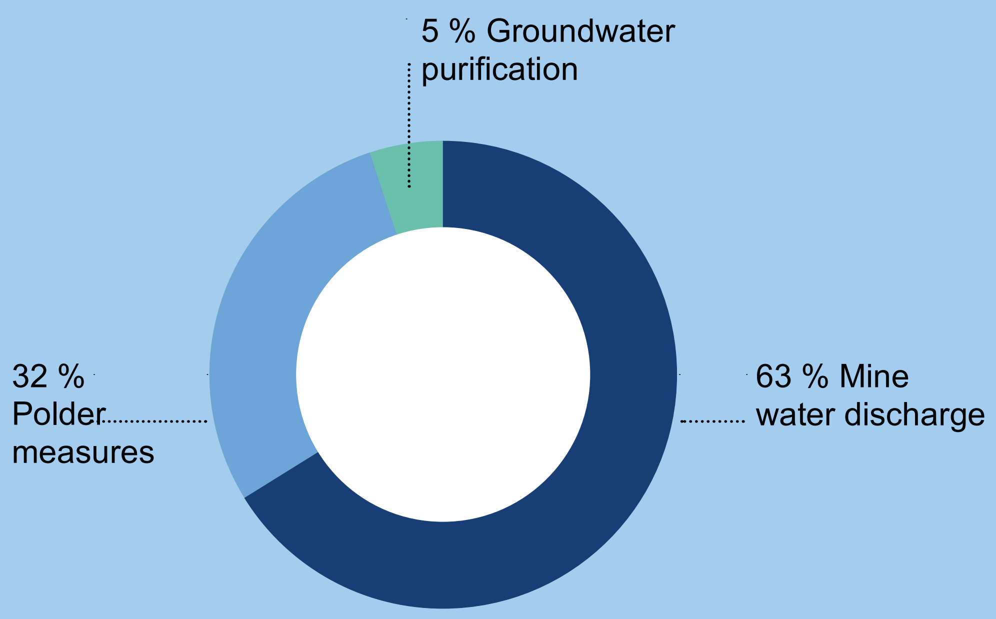
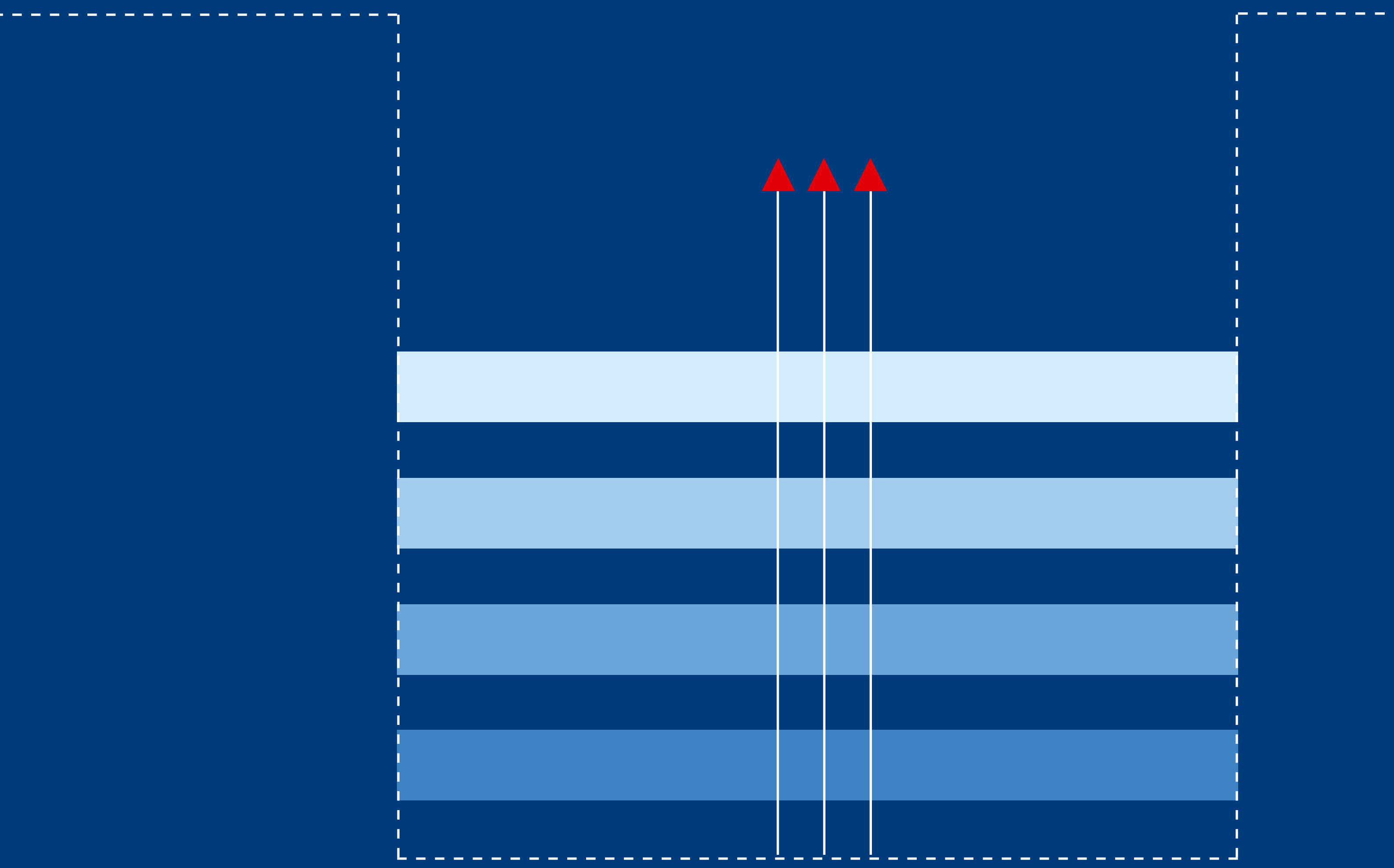


Fig. 5: Cost allocation of long-term liabilities, adapted from RAG-Stiftung (2018).

2. Process Description of the Mine Water Rebound



2.1. Hydraulic Aspects

Mine Water Rebound

As the two terms 'mine water rebound' and 'flooding' tend to be confused quite frequently, let us have a closer look at their definitions following the glossary of mine water management (Burghardt et al. 2017).

Mine Water Rebound
The term 'mine water rebound' describes the rise of the water level in the mine workings as a result from the mitigation or termination of mine dewatering (passive flooding, own flooding, *in situ* flooding) or by actively adding water (active flooding, ex situ flooding).

Flooding
Generally, the term 'flooding' describes the process of the mine water rebound in open-cast and underground mines which is initiated to e. g. increase the geotechnical safety. This process comprises passive flooding, i. e. the natural mine water rebound after the mine dewatering has been mitigated or terminated, as well as active flooding in which the mine water rebound is accelerated by the active inflow of waters or the water quality is improved.

Until now, no active flooding has been carried out in German hard-coal mining; this process is usually applied in open-cast lignite mines for safety reasons. Principally, this report uses the term 'mine water rebound' as this is the most accurate description of the process in underground collieries.

In the process of a mine water rebound (see info box on 'Mine Water Rebound') the mine water level rises in underground mine workings. If a mine is closed down according to plan, the termination or mitigation of the mine dewatering is followed by a controlled mine water rebound. This rebound can be accelerated by forcing water flow into the mine. In addition to planned mine water rebounds, there are also other events that may cause a mine water rebound, for example, water inrushes from adjacent mine workings which might be caused by insufficient *safety distance* (as occurred in the United Kingdom; Job 1987a; 1987b; Vutukuri & Singh 1995), infiltration by surface water from receiving water courses due to mining close to the surface (as occurred in Spain; Ordóñez et al. 2012; Ch. 3.4.), or a failure of the mine dewatering due to e. g. force majeure: all of these factors can lead to a rise of mine water. If any of those situations cause a mine water rebound, then there might be an uncontrolled mine water rebound (Wolkersdorfer 1996).

The following paragraphs will take a closer look at the processes which occur during a mine water rebound and the factors which can influence such a rebound.

2.1.1. Describing the Course of a Mine Water Rebound

The review of finished mine water rebounds in European hard-coal mining regions recognises various patterns (Fig. 7). The reason for that is the geometrical complexity of the mine workings and the specific hydrogeological properties of the host

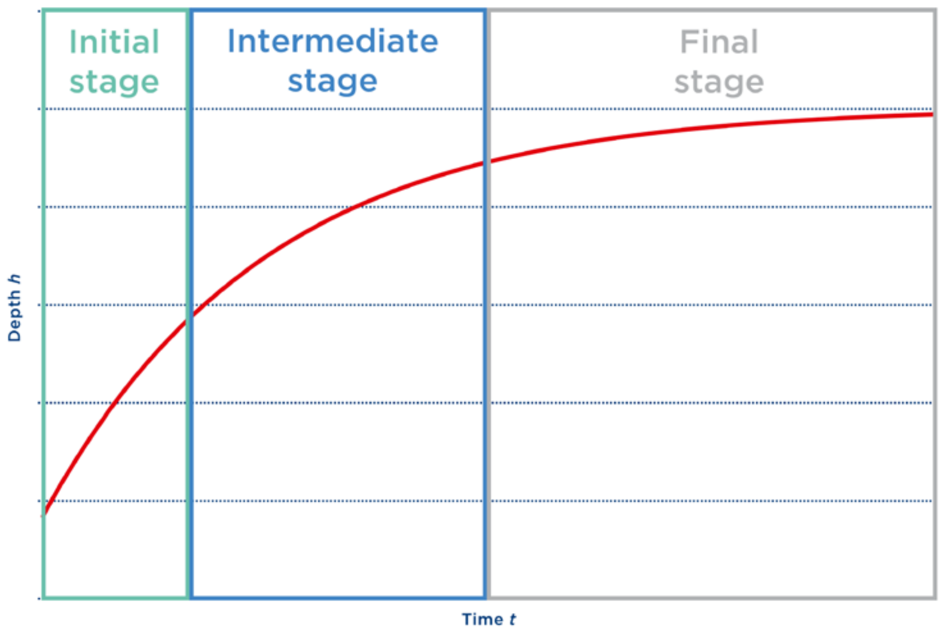


Fig. 6: Idealised curve of a mine water rebound divided into the different stages.

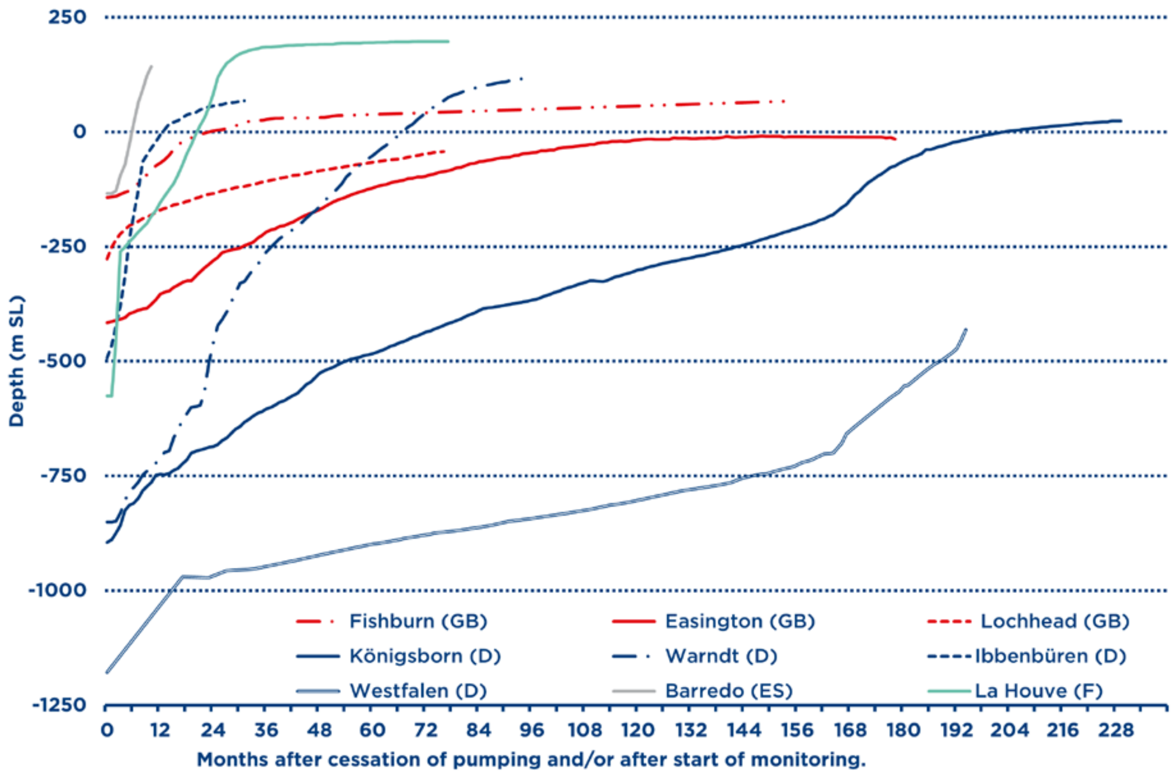


Fig. 7: Initial period of mine water rebounds in European hard-coal mining regions.

rock at each location. During the mine water rebound in an underground mine, a large number of hydrodynamic processes play a role. They are in turn influenced by natural (mainly hydrogeological) and anthropogenic (mainly mining) factors (Fernandez-Rubio 1979; Westermann et al. 2018). However, the analysis of numerous mine water rebounds exhibit a subdivision into three stages: the initial, the intermediate and the final stage (Fig. 6).

Initial Stage (turquoise part of Fig. 6)

During the operating phase of a mine, the areas underneath the lowest mine workings level (*dook workings*) are kept dry by a large number of temporary and local mine dewatering activities (where applicable, only single pumps). As the dook workings, due to regulatory restrictions, are often limited in space, only a small void volume which can be inundated is provided; and it is this void space which is usually filled up first once the mine dewatering is discontinued or its flow rate is reduced (Wolkersdorfer 2008; Rosner 2011). This stage of rising cannot be controlled due to the dismantling of local mine dewatering facilities. At the beginning of the mine water rebound the low water column only results in a low hydrostatic backpressure at the inflow points. Hence, the inflow rates of deep water are increased during the initial stage of the mine water rebound. Due to the combination of little floodable void volume and increased flow rate, the mine water rebounds exhibits the highest rates of water inflow in this stage; rebound velocity of several 100 m/a depending on the local geometry of the mine workings were recorded (Fig. 7). This fast initial inflow of mine water lasts until the lowest transfer point is reached.

Intermediate Stage (blue part of Fig. 6)

Once the lowest transfer point is reached, there is a lateral outflow along the roadways towards the central mine dewatering station. During the progressive mine water rebound the *main working levels* are *hydraulically inundated*. The void volume created by the exploitation is often larger in this area; with a rising mine water column within the mine workings, depending on the hydraulic head difference between deep groundwater and mine water column, the groundwater inflows are successively reduced. As a consequence, the total inflow into the mine workings is reduced and the rebound velocity is continuously lowered.

During the mine water rebound the shafts and roadways dominate as mine water pathways compared to the infiltration into the porous host rock (saturation) which are secondary and delayed (Rosner 2011; Denneborg et al. 2017). Usually, the rebound velocity are less than 100 m/a (Fig. 7). If the *hydraulic head* of the mine water reaches the unworked host rock or the basis of an overburden of low permeability (surrounding rock mass), the rebound velocity in the mine workings increase significantly due to the low floodable void volume. Such an increase of mine water rebound velocity caused by the flooding of an overburden of low permeability is documented, for example, in the mine water rebound at Königsborn Colliery (Ruhr area [Germany]; Fig. 30). On the other hand, if an overburden of high permeability is infiltrated (e.g. Bunter *sandstone* in the Lorraine region [France]; Fig. 7; Fig. 54), the rate of the mine water rise is reduced which is illustrated by a flattening out of the slope within the time-depth graph.

Final Stage
(grey part in Fig. 6)

The mine water rebound is finished once the level of the lowest drainage drift is reached or once the inflow and outflow of water reach a hydraulic balance. Then, almost steady-state flow conditions prevail.

If the level of the hydraulic balance is situated close to the ground surface (or even above, in which case there are confined aquifer conditions), then water logging conditions on the surface cannot be excluded. Examples of such conditions appeared in the mine water rebounds of the Döhlen basin collieries near Dresden-Gittersee (Germany; Ch. 3.1.4.; Mann & Wedekind 2010) and in the western part of the Lorraine mining region (France; Ch. 3.3.).

Mathematically, the idealised curve of a mine water rebound can be described using the saturation function and applied to mines which are hydraulically isolated from adjacent mines (Fig. 6). The equation reads as follows:

$$h_{mw,t} = \Delta h_{mw} \cdot (1 - e^{-\beta \cdot t})$$

in which

$h_{mw,t}$ mine water level at point of time t (m NN),

Δh_{mw} difference between the mine water levels at the end and the beginning of the mine water rebound (m NN),

β kinetic parameter (1/d),

t time (d).

This is a function with an exponent that describes limited growth processes. The curve of the function increases strictly monotonously. In the form used, the growth, i. e. the rise of the mine water level, is bounded from above and declining, in other words: the growth rate – corresponding to the water rebound rate – will decrease continually over time.

2.1.2. Water Flow in the Mine Workings

In the course of a mine water rebound in an underground mine, the major part of the water flow occurs in the open mine workings and in the altered and fissured areas of the *roof* and floor of the roadways (Wolkersdorfer 1996). The geometrical layout of the mine workings, i. e. the spatial layout of the vertical (shafts, drill holes), horizontal (roadways, adits) and inclined elements (rise drifts) as well as the mining levels define the major flow directions for the rise of the mine water level inside the mine.

Individual coalfields or even adjacent mines can be connected via roadways. Two parts of the mine may also be connected by drill holes, geological or tectonic elements (such as *faults*, joints) and altered rock parts close to active excavations and coal mining operations (*seepage waters* from the roof). Therefore, in the entire mine workings, there is an overall hydraulic connection and thus an almost uniform mine water level following the principle of communicating vessels. Prerequisite is, however, that the free water flow is not hindered in any way (e. g. by water dams or fully collapsed roadways). Nevertheless, if failure safety margins related to excavations is reached, because the free water flow is hindered or the hydrostatic pressure increases unilaterally close to the mining level, this may cause uncontrolled *mine water inrushes* into adjacent areas (Job 1987a; 1987b; Vutukuri & Singh 1995).

The hydraulic conductivity of the flow paths in the mine workings can change in the course of time as the geotechnical processes can lead to *convergence* and thus to a reduction of the roadway cross section. The roadway can lose its load bearing capacity. Nevertheless, even where roadways fully collapse, experience indicates that the hydraulic conductivity is not entirely lost (Wolkersdorfer 2008).

In order to improve the protection of permanent water pathways underground, RAG AG is installing pipes into the roadways (RAG AG 2017; Ch. 1.2.). At regular intervals these pipes are interrupted by cages which are filled with gravel packs (Fig. 9). These highly permeable gravel packs allow the entry of mine water to the pipeline installed and also serve as a filter.

Melchers et al. (2017) developed a measuring method that allows to monitor the water flow in abandoned mine workings. For that purpose, a multi-parameter probe, normally used in deep sea technology, is used to continuously record in situ different parameters, such as hydraulic ones (e. g. water and air pressures, mine water flow velocity) and physical-chemical ones (e. g. electric conductivity, temperature, methane concentration) and transfers these data in real time to a central data hub (Fig. 10). These probes were initially used at four locations in the mine workings of the abandoned Auguste Victoria Colliery in Marl (Ruhr area; Germany) and are intended for use at other collieries, too.

2.1.3. Factors Influencing the Hydrodynamics of a Mine Water Rebound

The lithology in which the mine water rebound takes place is characterised by a substantial spatial heterogeneity. As a result, the hydrogeological properties are only known to a limited extent or are only valid for this particular location. The factors that influence the spatio-temporal development of a mine water rebound are typically of high variability and differ from mine to mine (i. e. mine water province). Therefore, any descriptions of the hydrodynamic conditions in the underground mine and forecasts of the spatial and temporal course of future mine water rebounds can only be approximations of the actual local conditions

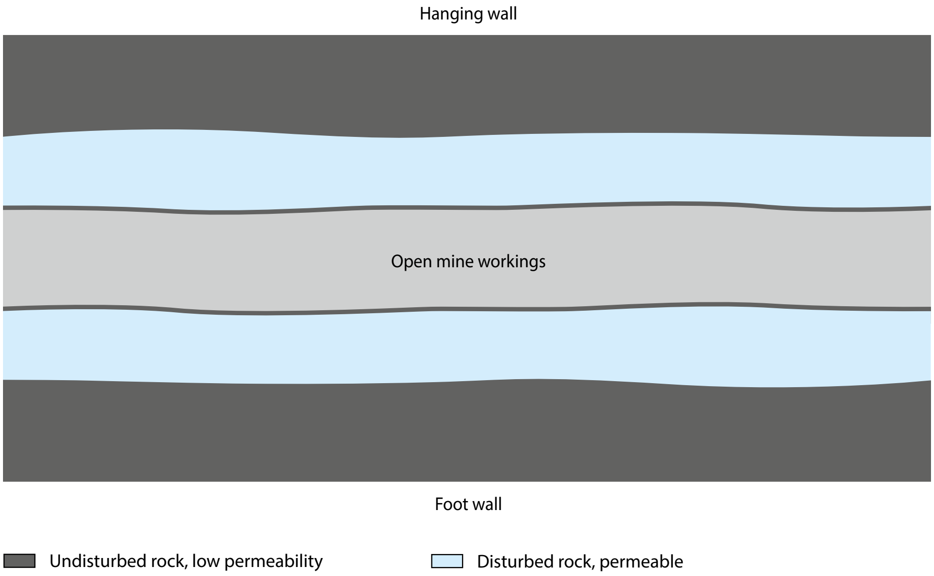


Fig. 8: Water paths inside a mine.

(Sammarco 1995). Among the natural influences there are the following:

- hydraulic conductivity of rock types and strata,
- volumes of pores and joints,
- water inflow rates,
- rate of groundwater recharge,
- thickness and lithology of the overburden,
- water level during post-mining period (anthropogenic influence possible),
- groundwater levels in the catchment area of the mine water rebound.

In addition to the natural factors, i. e. the geological, hydrogeological and hydrological factors, anthropogenically caused changes also influence the mine water rebound. These anthropogenic factors include:

- void volumes initiated by mining,
- hydraulic conductivity of the mine workings,
- targeted control measures,
- *cone of depression* caused by mine drainage.

Fig. 9: Installation of pipelines with inserted gravel fillings to lead the mine water through (photo: RAG Aktiengesellschaft).

All these factors of influence are described in detail in the following paragraphs.

Hydraulic Conductivity of Rock and Rock Mass

The important parameters when describing and quantifying the hydraulic conductivity of any rock type, i.e. how fluid is transmitted through the rock, are the conductivity coefficient k_f and the transmissivity coefficient T_{gw}. The hydraulic conductivity coefficient describes the capacity of rock to transmit fluids (Hölting & Coldewey 2013). Whereas the intrinsic permeability is given for a rock (and thus also referred to as 'rock permeability'), and therefore only applies to a small-space consideration of permeability ('rock-specific'), the transmissivity coefficient is an integral measure that refers to the different permeability coefficients of several levels (thus also referred to as 'rock mass permeability'). The transmissivity coefficient considers any inhomogeneous aspects of the rock mass (e.g. depth-specific permeability, system of divisional surfaces). The permeability coefficient categorises rocks from very low permeability (almost impervious) to very high permeability according to DIN 18130-1 (1998). The classification ranges from > 10^{-2} m/s (very high permeability) to < 10^{-8} m/s (very low permeability; Tab. 1).

The rock fabric can be altered by both anthropogenic activities (such as mining or tunnel drilling) and *tectonic processes*; usually, the hydraulic conductivity is not affected (Fig. 8). Thus, a distinction needs to be made between the permeability of mining induced alteration (*got*) and unaltered (*ungot*) rocks. Mining activities can lead to an increase of the hydraulic conductivity by one order of magnitude due to mining activities (Baltes 1998). Because of the higher plasticity, fine-grained rocks (e.g. clay *marl*) may return to their original condition as a result of the rock pressure; therefore, fine-grained rocks (e.g. clay) exhibit a smaller difference in the permeabilities of disturbed and undisturbed rocks of identical lithology than coarse-grained ones (e.g. sandstones; Baltes 1998).

Often, the hydraulic conductivity coefficients are based on the results of lab tests carried out at drill cores. Thus, these results represent the macroscopic rock mass permeability measured in situ only up to a certain extent. Geohydraulically relevant heterogeneity of the rock mass (e.g. joint system, faults) cannot be considered when analysing rock samples (Hölting & Coldewey 2013). Therefore, these values can only be regarded as approximations of the actual hydraulic conductivity. For example, Paas (1997) states that the hydraulic conductivity of silty rocks from the Upper Carboniferous is about four to five times to the power ten (6×10^{-13} m/s to 4.6×10^{-15} m/s) lower than the rock mass hydraulic conductivity (3×10^{-9} m/s to 3×10^{-10} m/s).

Pore Volumes and Voids Created by Joint Planes

During mine water rebound, mine water can flow to the pores and joint planes (joints, faults, bedding planes and cleavage) where it can be stagnant and/or flow through those (Hölting & Coldewey 2013). Porosity

Fig. 10: Modified deep sea probe used to record the mine water rebound (photo: Markus Schneider, Martin Justa).

Tab. 1: Categorisation of hydraulic conductivity coefficient k_f according to DIN 18130-1 (1998).

Categories	Hydraulic Conductivity Coefficient k_f m/s
very high hydraulic conductivity	$> 10^{-2}$
high hydraulic conductivity	$10^{-2} - 10^{-4}$
conductive	$10^{-4} - 10^{-6}$
low hydraulic conductivity	$10^{-6} - 10^{-8}$
very low hydraulic conductivity	$< 10^{-8}$

is defined as the proportion of all voids present in a rock to the overall rock volume thus determining the hydraulic conductivity of a rock. Fine-grained sediments (such as clays and silts) are of a higher porosity than coarse-grained sediments (such as sands or gravels). The porosity may change due to precipitation (e. g. calcite) or the recrystallisation or newly formed minerals.

However, only a part of the total porosity is available for uptake and storage of water due to the *adhesive, seepage*, *capillary* and adsorptive *waters* ('immobile' fluid volume) already present in the voids (Blume et al. 2010; Fig. 11). This proportion is called a portion of void space that is capable of transmitting a fluid vs. 'immobile' fluid volume or effective porosity (specific yield of pore space; Tab. 2); this is the key factor when estimating the water storage capacity of a rock mass during mine water rebound. Such voids accessible for water storage can mainly be found in the fractured or loosened zone of the mine workings. Rock mass areas situated further away from the mine workings are not disturbed by mining activity, i.e. mine water cannot infiltrate that part of the rock mass, neither when draining these parts of the rock mass towards the roadways nor as part of the mine water rebound from the roadways towards these parts of the rock mass.

In hard rocks, it is mostly the open void space between the joints (depending on the lithology), the width of the joint displacement and the joint frequency (density, degree of cross-linking) called 'joint number' which determines the hydraulic conductivity of the rock (Karrenberg 1981). Finer-grained sediments (e.g. *claystone*) are usually of a denser joint system with smaller widths and thus exhibit a higher flow resistance. On the other hand, the joint system of coarser grained sediments (e.g. sandstones) is less narrow and is indicated by larger widths of joint openings; as a result, the flow resistance is lower. It is not possible to generalise the values of rock-specific void volumes of joints in solid rock because the rock could have experienced different tectonic stresses. Estimated values range from the low per mil level up to ten percent (Baltes 1998).

Water Inflow Rates

During operation phase or after abandonment of the mine, mine water flows into the mine workings. When the mine dewatering is discontinued, this water inflow causes a rise of the mine water level in the mine workings. The mine water

Tab. 2: Sizes of total porosity n_p and effective porosity n_{peff} for sediments and soils according to Garling & Dittrich (1979).

Type of Loose Rock	Total Porosity n_p %	Effective Porosity n_{peff} %
sandy gravel	25 – 35	20 – 25
gravelly sand	28 – 35	15 – 20
medium sand	30 – 38	10 – 15
silty sand	33 – 40	8 – 12
sandy silt	35 – 45	5 – 10
clayey silt	40 – 55	3 – 8
silty clay	45 – 65	2 – 5

inflows of the mine workings can be subdivided as follows: mostly vertical infiltration of groundwater and surface water (hereinafter referred to as 'infiltration water'), the inflow of deep (ground) water, and the lateral inflow of mine waters from adjacent mine workings (Fig. 12).

Mine water only rarely enters the mine workings at distinct points such as boreholes or locally via faults; rather an extensive inflow from the top is a more frequent scenario. During the exploitation phase, volumetrics of the water inflows can be determined either directly e. g. at dams, or indirectly via produced mine water volume excluding both the *process waters* led in from the ground surface and the volumes processed by the *ventilation system* and underground dust prevention. During the rebound process, water inflows which occur below the mine water level can no longer be measured individually. Alternatively, the water inflows can be derived using the pattern of the rebound rise and the accessible void volume as values for approximation.

A major part of the water inflow results from the infiltration of groundwater and surface water (infiltration water) which seeps into the mine workings from the overburden. The infiltration water can immediately, i. e. without notable delay, enter into the mine workings if no overburden is in place (Fig. 13-1). In such cases, the amount of the vertical inflow rate corresponds approximately with the rate of groundwater recharge within the catchment area of the mine workings. Likewise, the seepage from receiving water courses (*leaky aquifers*) can increase the water inflow into mine workings, something that has been observed, for example, in the collieries Barredo and Figaredo in Spain (Ordóñez et al. 2012). Actually, one of the first tracer tests worldwide was carried out in a mine to locate water inflows from surface waters (Semmler 1937).

If coal-bearing strata are covered by overburden rocks, the water inflow into the mine workings (if at all) only occurs delayed and at a reduced level (Fig. 13-2 and Fig. 13-3). Then, the flow rate mostly depends on the thickness and the hydrogeological properties of the overburden as well as on the pressure level of the groundwater level in the roof aquifer. The extensive inflow of infiltration water can be approximately calculated applying the modified equation according to Darcy (1856; Fig. 13):

$$\dot{V}_{\mathrm{Inf}} = k_{\mathrm{f,LS}} \cdot A \cdot \frac{\Delta h}{\Delta l_{\mathrm{LS}}}$$

in which

$\dot{V}_{\mathrm{Inf}}$ infiltration rate (m^3/s),

$k_{\mathrm{f,LS}}$ hydraulic conductivity coefficient of the transmitted layer (low leakage; m/s),

A cross sectional area (perpendicular to flow; m^2),

Δh pressure differential (m) (with $\Delta h = h_{gw} - h_{mw}$

- h_{gw} hydraulic head in the roof aquifer [m NN]
- h_{mw} hydraulic head of the mine water [m NN]),

Δl_{LS} thickness of the transmitted layer (leaky aquifer of low permeability; m).

As long as the piezometric surface of the mine water is situated below beds of low permeability (leaky aquifer stratum), there will be free seepage from the groundwater body of the overlying beds into the groundwater body of the underlying strata (or into the mine workings; Fig. 13 and Fig. 45). As soon as the pressure level of the mine water reaches the base of a leaky aquifer stratum, the groundwater bodies of the overlying and the underlying beds are hydraulically interconnected. In this case the flow rate also depends on the potentiometric difference Δh between the hydraulic head of the mine water h_{mw} and the groundwater level h_{gw} of the aquifer in the overburden (see equation). Hence, the flow rate decreases linearly with the successive rise of the mine water level. Groundwater from the over burden and surroundings is infiltra-

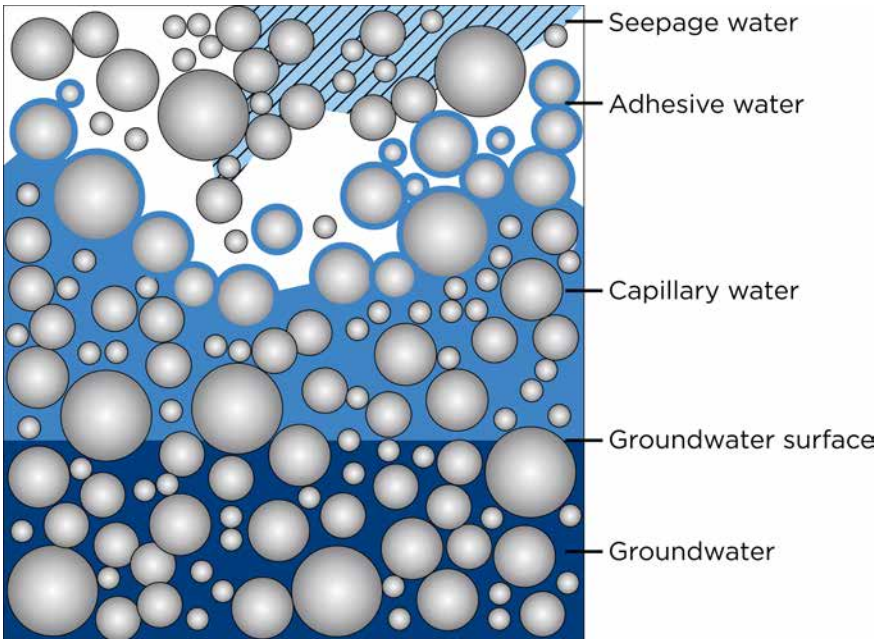


Fig. 11: Appearance of underground water, modified according to Zunker (1930).

ting the mine as long as the hydraulic head between the groundwater and the mine water is equilibrated. Mine water situated in the mine workings starts infiltrating the aquifer in the roof if its hydraulic pressure exceeds the one from the aquifer located in the top section (Denneborg et al. 2017; Ch. 3.2.3.; Fig. 45).

Depending on both the thickness and the lithology of the overburden the influx of deep water can provide a considerable proportion of the overall flow rate. The simplified assumption applies that the thicker the overburden (and/or the lower its hydraulic conductivity), the lower the proportion of infiltration water compared to the overall inflow budget (see equation).

Similarly to the infiltration yield, the deep water flow rates correlate positively with the mine water rebound. The flow rate is determined in comparison of the potentiometric surface of the mine water vs. the water level of the inflow point as well as the level of the feed. The flux of deep water infiltrating the mine can occur from the bottom via laterally extended faults and, during operations at deeper levels, from the top as well. Results of hydrological model calculations demonstrate that the influx of deep water are increasingly reduced if the hydrostatic pressure of the water column successively increases (Banks 2001).

As long as the piezometric surface of the mine water remains below the level of the surrounding inflow, the flow rate is not affected. Only when the potentio-

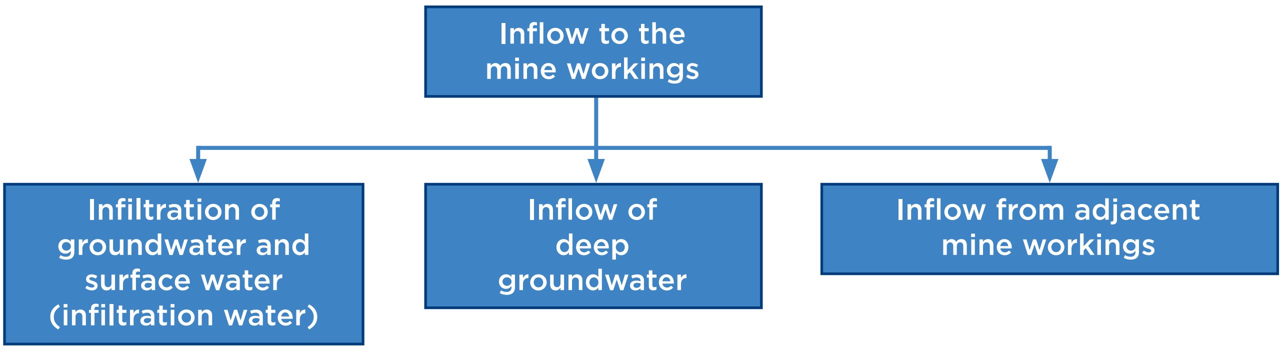


Fig. 12: Distribution of influents into mine workings.

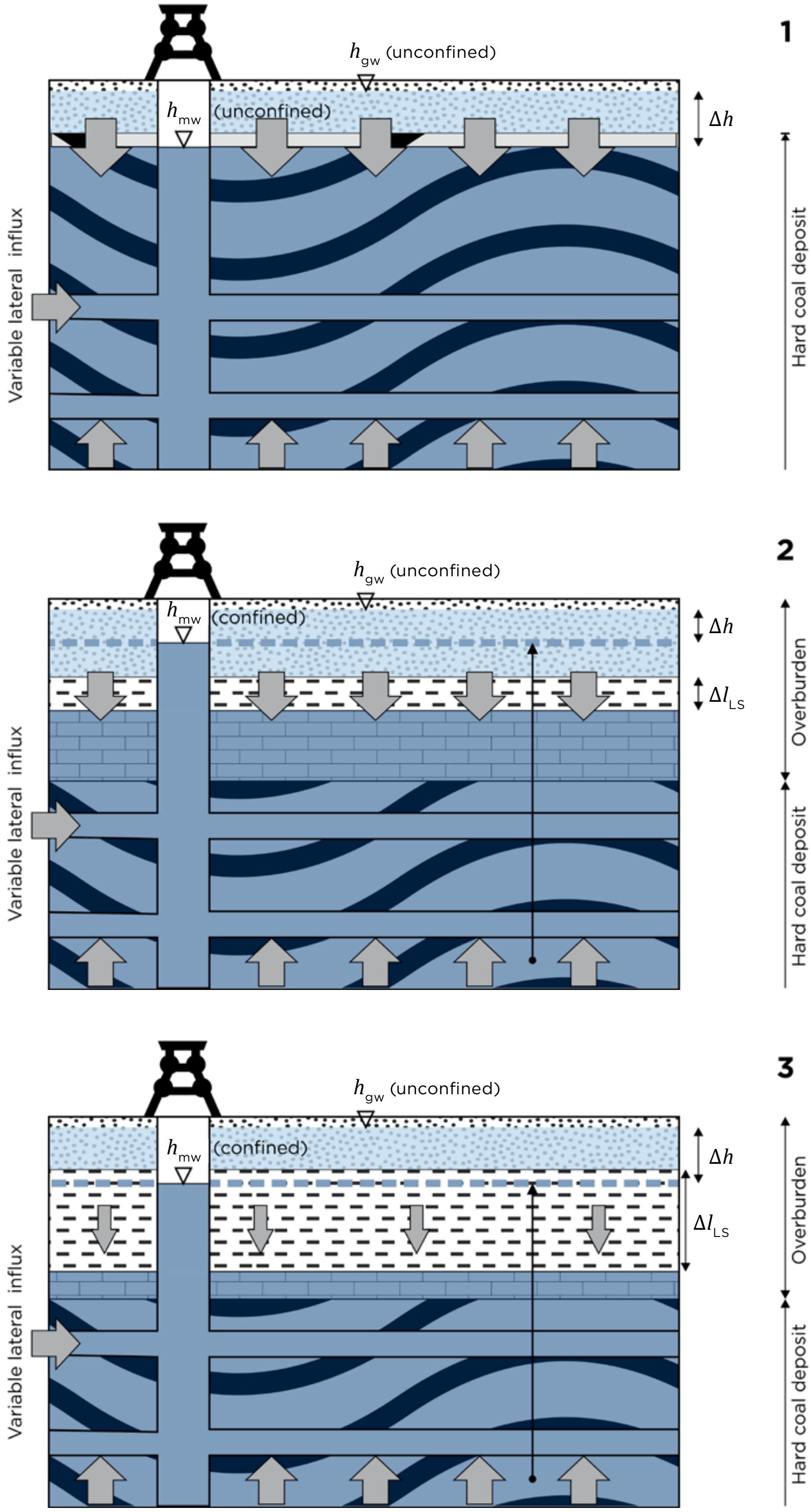


Fig. 13: Flow rates into a mine (1) without overburden, (2) with low to medium overburden thickness and (3) with high overburden thickness; the width of the arrow identifies corresponds to the intensity of flow rate.

metric surface of the mine water is situated above the inflow level of the surrounding infiltrating waters, the rate of the inflow changes and decreases successively the closer the potentiometric surface of the mine water gets to the level of influx. Influx of deep water into the mine fully ceases as soon as the feed of adjacent waters is inundated by the potentiometric surface of the mine water.

Rate of Groundwater Recharge

A major influencing factor in the hydrological cycle is the rate at which groundwater is recharged. According to DIN 4049-3 (1994), the term 'groundwater recharge' describes the access of infiltrated surface water to groundwater. If this term is transferred to mining, it can define the access of precipitation water into the mine workings and thus it is mixing with mine water ('mine water recharge').

Early on it was demonstrated that the inflow rates into mine workings correlate with precipitation rates. Semmler (1955) compared the development of the mean mine water inflow rates with rain gauges. He observed that at numerous mine sites an unequivocal dependency between the two factors existed even at larger thickness of the overburden (with successions up to 450 m; Fig. 14 and Fig. 15). At overburden thicknesses of more than 800 m, a distinct impact of the precipitation rate on mine water fluxes could no longer be clearly recognised. Semmler demonstrated that the proportion of infiltrated precipitation water to the overall quantity of inflow of both infiltration water and deep water supply) was too low to significantly impact the overall inflow level because of the larger overburden thickness.

Thickness and Lithology of Overburden

An important factor which describes the structure of a hard-coal deposit are the thickness and the lithology of the overburden. Depending on the deposition, its thickness and lithology can differ. For example, an overburden can consist of clayey marls of low permeability (Rhenish-Westphalian hard-coal basin [Germany]) or sandstones of good permeability (Lorraine [France]; with a base layer consisting of rocks with low permeability). A hard-coal deposit can also have no sedimentary cover if the coal-bearing strata are outcropping at the surface (e. g. Ibbenbüren, southern Ruhr area, parts of the Saar coal mining region [all in Germany], Asturias [Spain] and the coal-mining area of West Yorkshire [UK]). The geology of the overburden directly impact the flow rate of infiltration water to the mine (see explanations in 'Water Inflow Rates').

Post Mining Related Water Levels

As soon as the mine dewatering of a colliery has ceased, the potentiometric surface of the mine water recovers to reach its initial pre-mining (natural) hydraulic head. The water level that will remain in the long run after the mine water rebound has finished is usually referred to as the 'post-mining water level'. However, due to the mining induced changes to the hydrological system, mine water does not recover up to its initial level; instead, in many cases the mine water rebound is limited due to the lowest discharge level. Only in rare cases the initial pre-mining potentiometric surface is clearly documented for the mining affected area. Thus, assumptions, analogies and comparisons need to be made with adjacent water provinces in which the mine water rebound has already been completed. Information on the original hydraulic head level can be found, for example, by studying springs which exhibited a discharge before mining operations started, but which suffer from a decline of water supply until complete dryness during the mine water level decrease caused by 'modern' hard-coal mining (Huyssen 1855).

Principally, the ultimate goal must be to re-establish pre-mining water levels. Besides cost and energy consumption needed for pumping, this also reduces the overall '*salt freight*', hence the quantity of highly mineralised mine waters being discharged, reflected in a lower contamination of the receiving water courses.

Groundwater Levels in the Catchment Area of the Mine Water Rebound

The hydraulic conditions in the aquifer within the catchment area of the mine water rebound are mostly impacted by mine dewatering measures. Their impact range depends on three aspects: duration, areal extent of the mining activities, and (excavation) depth. Knowledge about the current groundwater levels can be acquired by setting up groundwater monitoring wells.

The water inflows into the mine workings are closely related to the groundwater levels in the catchment area of the mine. These levels most significantly influence the flow rate during both the exploitation stage and the mine water rebound. Infiltration water flow rate reduces with increasing hydraulic head of the mine water (decrease of potential difference between groundwater level and mine water level, i. e. the hydraulic gradient) as the water column – with the rise of the mine water rebound – exerts an increasingly higher counter pressure against the water inflow from the overlying section (see explanations in 'Water Inflow Rates'). Likewise, the cone of depression – which actually reflects the inflow of groundwater and mine water – shrinks, too. The decline of the infiltration water flow rate results in a slowdown of the depletion of the overlying reservoir which, in turn, induces a large-scale increase of the groundwater levels in the catchment area of the mine workings (Ch. 3.1.1.; Fig. 30). If the hydraulic head of the mine water exceeds that of the groundwater, the mine water may also infiltrate the overlying aquifer if water conduits exist. It is assumed that the hydraulic change described here can occur during the course of a mine water rebound wherever significant water inflow from the overburden into the mine workings could be observed during the exploitation stage (Rosner 2011).

Void Volumes Created by Mining

Constructing shafts, cutting roadways and adits and extracting raw materials – all of these are mining activities that create a large-scale network of underground void spaces which are usually referred to as mine workings. Hydrogeologically speaking, a 'mine aquifer' (as defined by Wolkersdorfer 2008) is created. The voids created by mining can be divided into temporarily open voids

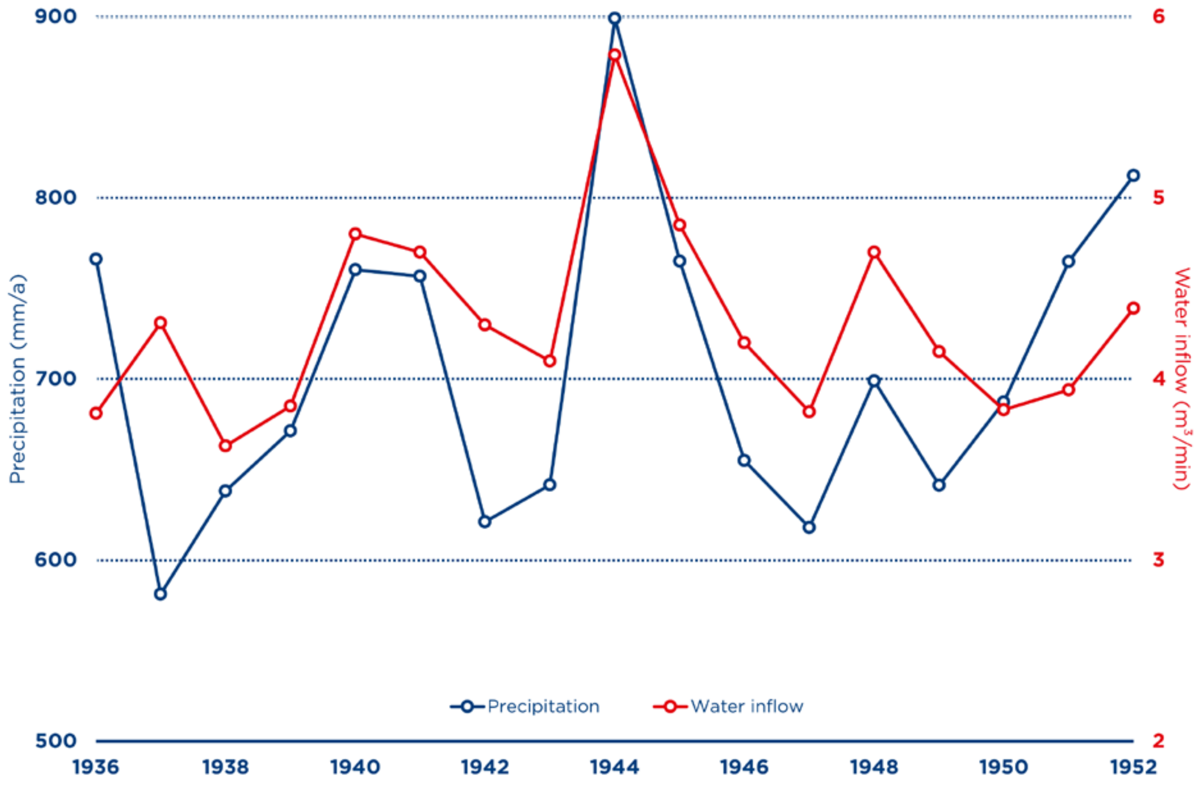


Fig. 14: Dependence of mine water inflows on the precipitation between 1936 and 1952 in a mine with an overburden from 0-100 m; data adapted from Semmler (1955).

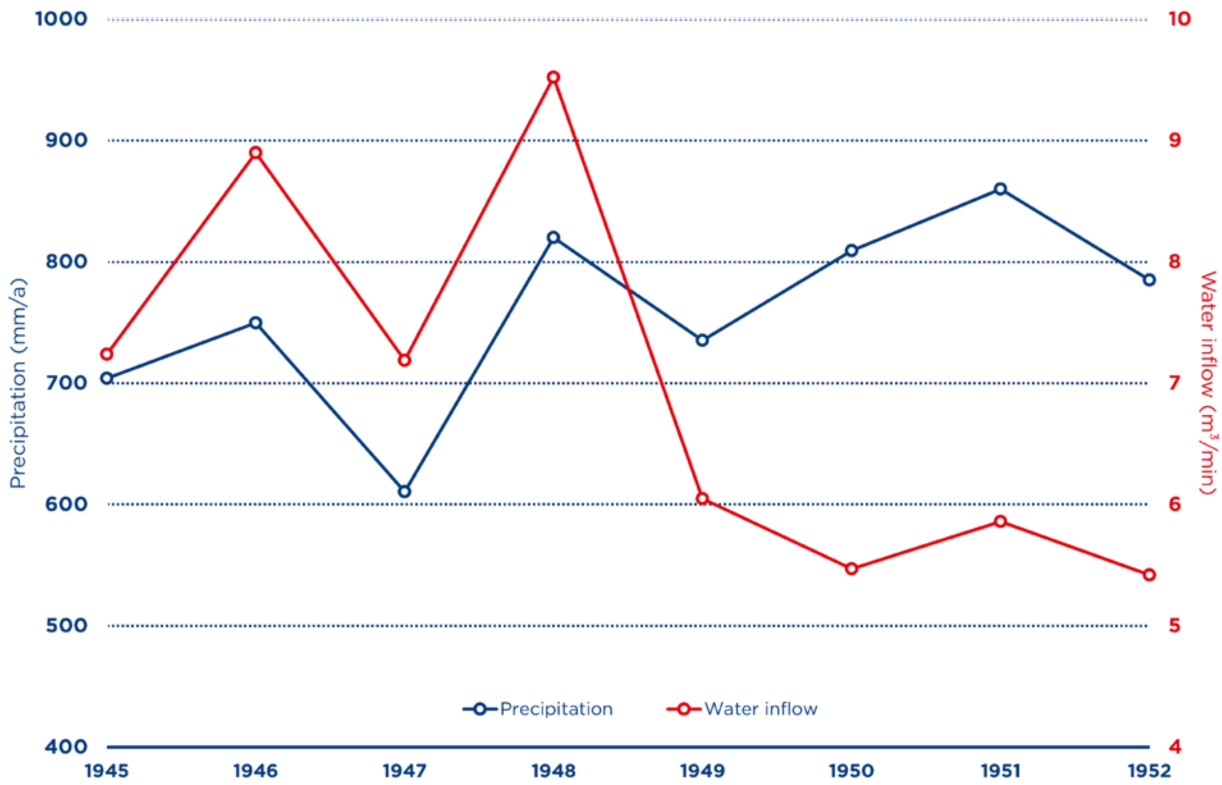


Fig. 15: Dependence of mine water inflows on the precipitation between 1945 and 1952 in a mine with an overburden of 400 m; data adapted from Semmler (1955).

(working area and drifts) and longer-term open voids (e. g. shafts, levels).

To perform the following tasks, it is important to know the areal and depth-related distribution as well as the condition of the underground voids:

- forecasting the process of the mine water rebound regarding its lateral extent and also its velocity,
- evaluating the processes of mine gas release,
- assessing the release and mobilisation of chemical species and thus estimating to which extent groundwater and mine water quality might be impaired (Younger et al. 2002; Wolkersdorfer 2008).

How water flows and circulates or can be stored in geologically termed 'porous media', can be applied to mining-related void spaces. Those voids will be filled at the beginning of a mine water rebound. Only with a delay of one to several decades the pores and joints of the disturbed rock mass between the roadways (loosened rock) and the remaining rock mass (at a lower proportion) will be saturated with water (Denneborg et al. 2017) due to the displacement of air within the pore network. The actual process of rock mass water storage – regarding its duration and depth of infiltration – has not been measured so far in a mine working environment (Denneborg et al. 2017).

In German collieries, the former working levels (*goaf*) provide a significantly higher proportion of the mining-related voids than the shafts and roadways. By experience, the roadway volume in German collieries makes up only 2 – 3 % of initial mine working volume. The volume of mining-related voids is reduced over time due to *settlement* and convergence. The remaining void volume depends on the following factors (Younger et al. 2002; Wolkersdorfer 2008):

- mining depth,
- excavation ratio,
- position and spatial extent of the working level (periphery and centre),
- number of mined and stacked coal seams (related to excavation ratio),
- thickness and *inclination* of coal seams,
- lithostatic pressure of overlying strata,
- rock strength,
- type and amount of backfill,
- extraction methods.

The backfilling process reduces the void volume of the working levels. When accounting for remaining void volumes, so-called 'areas of *stagnant water*', may form in abandoned areas of the mine workings due to infiltration of deep waters. Such volumes needs to be subtracted from the remaining void volume as those areas are no longer available for water storage. As a final statement, to determine available void volume is a very complex task and usually can only be estimated to a certain extent.

Hydraulic Conductivity of Mine Workings

During the mine water rebound, the roadways and shafts mostly serve the purpose of transporting the water and displacing coal mine gases. Depending on the surrounding rock, the quality of the roadway construction, the age of the mine workings and the lithostatic pressure, convergence occurs in the roadways which leads to a reduction of the initial roadway cross section. However, as experienced, convergence does usually not lead to a total closure of the roadway. Even where roadways collapse, there will be a remaining conduit for water transfer (Younger et al. 2002). The free unconfined water motion inside the roadways can only be stopped by constructing water dams. However, those dams are often bypassed by the water through zones of loosened rock (Wolkersdorfer 2001).

Besides the construction of open (long-term stable) mine workings that will over time shrink and collapse again, the hydraulic properties of the rock mass are altered by other mining activities. The mobilisation of the overlying rock mass into the formed void space induces new fractures or existing fracture's aperture widens up. The excavation deformed zone develops mostly around mining induced void space. These areas are defined by an increased permeability in contrast to the strata unaffected by mining activities.

In the concepts developed for the long-term mine water management at Ruhr, Saar and Ibbenbüren the open mine workings often play a key part in the water transfer (Ch. 1.2.; RAG AG 2014a). In major roadways which have been stabilised the mine water will move to the water receiving stations by free drain. In addition, pipes together with gravel filters are installed in the major roadways intended for water conduction (RAG AG 2017); these pipes ensure a steady and sufficient flow of mine water to the water receiving stations.

Targeted Control Measures

Until the late 1970s, mine water rebounds were handled obviously in an uncontrolled manner. The capability and tools for a supervised mine water level control were not in place at that time; thus, a mine water rebound was finished as soon as a hydraulic balance between inflow and outflow was achieved, the level of a drainage adit was reached (Mühlenbeck 2015), or diffuse and uncontrolled water logging occurred at the surface (Mann & Wedekind 2015).

However, both the spatial and the temporal extent of the mine water rebound can be managed in order to avoid uncontrolled water logging at the surface or any contamination of drinking water reserves. For this purpose, pumps are installed or water dams are built. One appropriate method of lowering the mine water level is to construct a drainage adit. During the mine water rebound, mine water is allowed to rise until the floor level of the drainage adit where it will be discharged at atmospheric pressure. Within the current mine water management plans at the Saar mining region (here: phase 2; Ch. 1.2.; RAG AG 2014b) and in Ibbenbüren, discharge of mine water via a 'mine water channel' or a drainage adit will be considered with special attention.

The mine water level is mostly controlled by submersible pumps which are installed in shafts of the mine dewatering stations (Fig. 2). Their use enables for a regulation, stop or to a certain extent *depression* of the mine water as required.

Cone of Depression Caused by Mine Water Management

The removal of water as it is common practice in tunnel construction or during mine life cycles causes the potentiometric surface of the groundwater to be lowered if the water abstraction rate exceeds its infiltration rate. The extent of the cone of depression mostly depends on the hydrogeological properties of the surrounding strata from which the water is removed by pumping. Tectonic structures (e. g. faults of low permeability) can limit the extension of the cone of depression. In an ideal case, a radial cone of depression is formed in homogeneous and isotropic porous aquifers (Hölting & Coldewey 2013). Due to the heterogeneities of rock strata and in mountainous areas the actual shape of a cone of depression usually deviates from this ideal shape.

The spatial extent of the cone of depression influences the rate of drawdown; the rule is that the larger the cone of depression, the more extended the area of abstraction. With the rise of mine water the cone of depression shrinks and, as a consequence, also that of the hydraulically influenced area and the amount of water inflow. Many equations consider the following parameters when determining the extent of the depression (e.g. Sichardt 1928; Kusakin 1935; Rom 1939; Kerkis 1955):

- hydraulic conductivity of the rock mass inside the cone of depression,
- amount of drawdown,
- thickness of the aquifer,
- volumes of infiltration and abstraction.

It needs to be considered that, due to the petrophysical inhomogeneities, the actual range of the cone of depression can only be estimated; the actual range or the shape of the cone of depression can only be determined by means of a sufficiently dimensioned groundwater monitoring (piezometer) network for both, groundwater and mine water, situated in different aquifers (Plotnikov & Roginets 1989).

2.2. Ground Movement

The underground mining of hard coal leads to convergences which are transferred from the rock mass towards the ground surface. This movement process effects a three-dimensional shift of position at the ground surface. The mining-induced ground movements can be divided into vertical components (depression, *shrinkage*, *sagging*) and horizontal components (lateral displacement, change of length). Busch et al. (2012) states the following general factors that cause ground movements:

- large-scale tectonic and seismic events such as subduction, earthquakes or other tremors,
- processes of subrosion and erosion such as karst formation or salt leaching,
- geological and rock-mechanical changes of the Earth's crust, e.g. due to underground raw materials mining,
- hydrogeological and hydrological changes caused by water drainage or flooding.

The latter aspect is the one that concerns the ground movements occurring during a mine water rebound. These rock movements manifest themselves at the ground surface as changes in length of which the vertical component (heaving) is the most crucial one.

Flooding-induced ground upheaval at the ground surface have been the subject of scientific examinations for centuries. In the early 20th century, Hilleegaart (1910) and Buntzel (1911) already began to analyse the upheaval of the ground surface above mining areas. Later, Oberste-Brink (1940) gave the initial report on ground upheaval phenomena in the Ruhr area which had been observed at the outcropping hard-coal deposits of the Witten Syncline (Wittener Mulde) since the 1930s and which were linked to a mine water rebound even then. He correlated the maximum upheaval volumes with the mining areas that were most strongly exploited and interpreted the ground upheaval as a consequence of the swelling capacities of clay-containing rocks. Examinations done by Spickernagel (1975) revealed that ground upheaval caused by a mine water rebound could reach up to the *depression null boundary*. Besides the increase in volume of clay-containing rocks, such ground movements were also traced back to the buoyancy of the rising water. With relation to the mine water rebound in the collieries of the South Limburg mining region, Pöttgens (1985) pointed out that the rebound velocity of the mine water influenced the upheaval motion. Based on this insight, Pöttgens developed a first model to forecast the maximum flooding-induced volumes of ground upheaval that were to be expected. This upheaval mostly results from processes of lateral spreading which are caused by increased buoyancy and changes that this buoyancy induced uplift causes in the stress field of the rock mass. Examinations by Rosner (2011) in the mining regions of Aachen (Germany) and South Limburg (Netherlands) prove that in this area the ground upheaval starts at a delay of approx. five years after the mine dewatering has been discontinued. As soon as the mine water level reaches the base of the overburden, the rate of upheaval increases and extend beyond the boundaries of the mine working area up to a distance of 10 km.

Tab. 3: Overview of ground upheaval caused by mine water rebounds in hard-coal mining regions according to Fenk & Tzscharschuch 2007; extended; DE: Germany; NL: Netherlands; FR: France; BE: Belgium).

Mining Region	Mining Depth in m BGL	Amount of Ground Upheaval at Surface up to cm	Source
Wittener Mulde (DE)	< 440	17	Oberste-Brink 1940
Erkelenz (DE)	150 – 800	28	Baglikow 2019
Aachen (DE)	< 1,200	10	Rosner 2011
Ibbenbüren (Westfeld; DE)	< 625	10	Goerke-Mallet 2000
Zwickau (DE)	< 1,150	17	Fenk 2000
Lugau-Oelsnitz (DE)	< 1,200	9	Löbel & Döhner 2010
Döhlen basin (DE)	390 – 650	6	Gross & Wedekind 2006
Königsborn (DE)	270 – 1,000	24	Heitfeld et al. 2012
Warndt (DE)	< 1,750	20	Melchers & Dogan 2014
Faulquemont (FR)	600 – 925	13	Branchet & Kaiser 2001
South Limburg (NL)	260 – 770	28	Rosner 2011
Campine (BE)	1,090	0.3 – 2.3 (p. a.)	Melchers & Dogan 2014
Liège (BE)	< 1,000	0.25 (p. a.)	Melchers & Dogan 2014

The previous examinations show that the spatial distribution and the timing of the ground movements differ according to the local mine operating conditions. Fenk & Tzscharschuch (2007) carried out literature research to compile the range of flooding induced upheaval volumes in the hard-coal mining regions of central and western Europe; so far, upheaval volumes between 6 cm and 27 cm were verified (Tab. 3).

Mining damages caused by a mine water rebound are only known from a few hard-coal mining regions as the ground surface usually reacts with a lateral and uniform uplift. However, at discontinuities which reach the surface, and in those parts of tectonic faults where different mining levels were worked or the mine water rose at different levels, a mine water rebound can induce different rates of uplift which are relevant to induce damages (Baglikow 2010). Likewise, the mine water rebound can trigger complex interdependencies of the geomechanical properties which, in turn, can cause damage to buildings and infrastructure. Documented evidence and indications of those can be found in the Erkelenz mining region (Baglikow 2003; 2010; Ch. 3.1.3.), in the hard-coal mining areas of Aachen and South Limburg (De Vent & Roest 2012; Baglikow 2019; Ch. 3.1.3.) and in the Döhlen basin (Tunger 2009; Ch. 3.1.4.).

Ground movements, whether induced by mining or flooding, can be observed by means of a monitoring system. In addition to elevation monitoring at *levelling lines* and ‘height’ benchmarks, *Persistent Scatterer Interferometry* [PSI]) has been established as a wide-range and exact monitoring method over the last years (Bamler et al. 2008; Busch 2019). Ground-bound persistent scatterers are needed to support the complex computation and evaluation.

2.3. Mine Gas Release

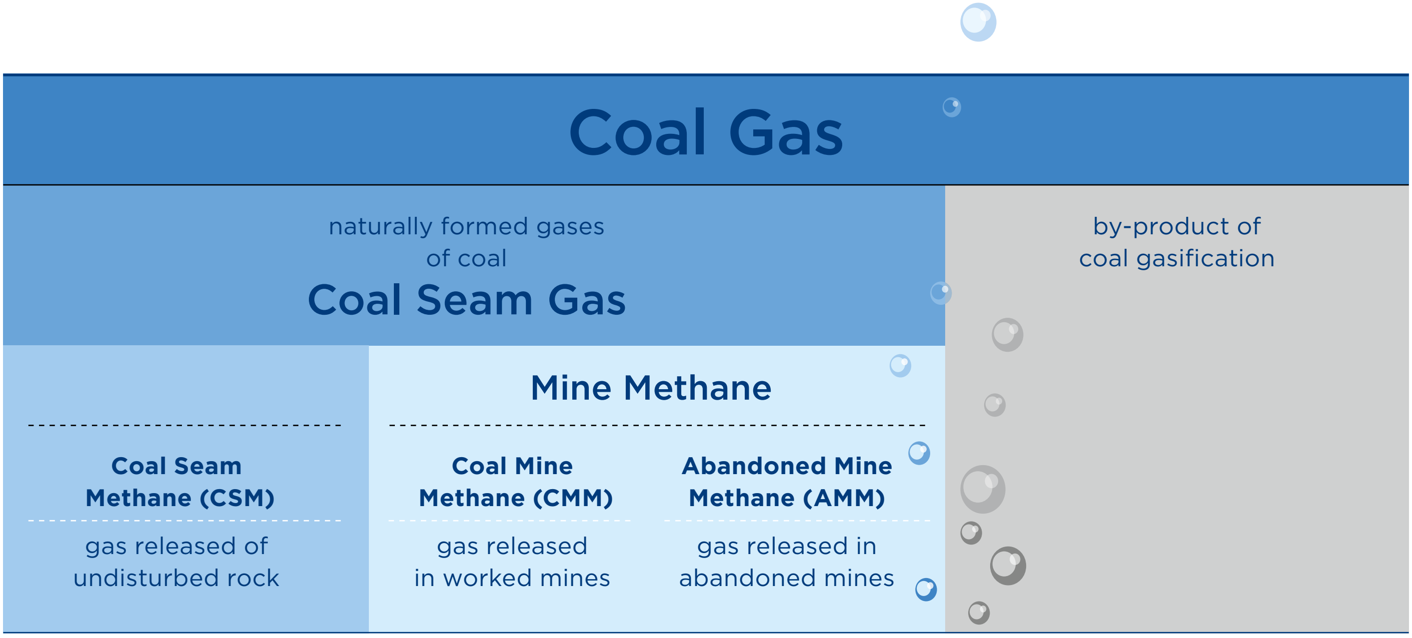


Fig. 16: Classification of coal mine related gases according to Thielemann (2002) and UNECE (2016).

In areas like the Ruhr area which have been shaped by mining, occurrences of mine gas release can be regularly observed at the ground surface (Thielemann et al. 2001; Henscheid 2012). According to Thielemann (2000) and UNECE (2016), a distinction is made between coal gas which is a byproduct of coal gasification, and *coal seam gas*. These gases, which emit during formation of the coal deposit, are gas mixtures consisting of methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO), oxygen (O_2), nitrogen (N_2) and other higher hydrocarbons (Tab. 4). Coal gas is the generic term for naturally formed thermogenic gases from coal and also for gases created by anthropogenic processes such as the technical coal gasification (Fig. 16). Contrary to that, all natural gases that occur in the coal are summarised under the term 'coal seam gas'; these gases include coal seam methane and (underground) *mine methane* (Tab. 4).

Whereas coal seam methane (CSM) can, for example, be released by drilling into coal seams of undisturbed rock and is bound to its natural place of occurrence, (underground) mine methane, because of the mining activities, enters into artificially created voids like the mine workings, either immediately or delayed. Underground mine methane is then categorised as either *coal mine methane* (CMM, released in worked mines by extraction and *ventilation*) or abandoned mine methane (AMM, released in abandoned mines; UNECE 2016). These gases differ in the concentration of the individual gas species of which methane is by far the most abundant (Tab. 4).

Carbon monoxide is a gas which is toxic for people and can cause health issues if inhaled; on the other hand, methane, the hydrocarbon of the simplest structure, is a colourless, odourless and tasteless gas which is neither toxic nor noxious nor hazardous to health.

However, at certain concentration ranges (between 4.4 Vol.-% and 16.5 Vol.-%) an explosive mixture in the presence of atmospheric oxygen (between 12 Vol.-% and 21 Vol.-%) can be formed (Christensen 2007; Fig. 17).

Methane is mostly of organic origin (Schoell 1984); depending on the specific genesis and origin, the distinction is made between 'thermally generated' (or 'thermogenic') and 'bacterially generated' (or 'biogenic') methane. Thermogenic methane refers to gas that has been generated as a product of gradually converting ('cracking') organic material during a process known as *carbonification*. On the other hand, biogenic methane refers to gas that is generated due to the microbial decomposition of organic material. Whereas thermogenic methane is bound to coal seams, biogenic methane can be recently generated by bacterial activity. Due to the chemical composition of the gas release in combination with characteristic stable carbon and hydrogen isotope signatures, it is possible to distinguish thermogenic methane from biogenic methane (Fig. 18), a method which allows to recognise areas in which recent bacterial methanogenesis occurs.

The phenomenon of mine methane entering the mine workings is generally known from hard-coal mining. Mining activities loosen the rock strata above and below the coal seams – something which enables the mine methane to flow from the coal-bearing rock into the mine workings. For safety reasons, the mine methane has to be diluted by technical measures such as the intake of fresh air (ventilation) or, when mining coal seams of high methane content, the gas has to be extracted through drill holes and removed (pre-degassing process).

This natural gas release does not end once the mine has been closed down. A part of the mine methane remains in the underground workings as residual natural gas. This final volume of gas depends, among others, on the excavation ratio of the deposit. The process of releasing mine methane can last for decades after mining has ceased. Particularly in old underground workings which are no longer aerated methane can accumulate; as a result, these old underground workings can still contain a high residual gas level in particular if they are close to coal seams of high methane concentration. The level of the gas release after the mine closure depends on the concentration of the residual gas and on barometric pressure variations.

At low atmospheric pressure, mine methane can escape from the mine workings to the ground surface. At high atmospheric pressure, however, the flow direction may turn around and fresh air will flow into the mine workings. Mining shafts and other surface openings are the preferred flow paths from the surface into mine workings. Even pipelines that were not dismantled (in particular degassing pipelines) are suitable paths along which the mine methane will migrate.

Tab. 4: Category overview for coal seam gases according to Thielemann (2002).

Coal Seam Methane (CSM)		Mine Methane			
		Coal Mine Methane (CMM)		Abandoned Mine Methane (AMM)	
Component	Vol.-%	Component	Vol.-%	Component	Vol.-%
CH_4	90 – 95	CH_4	25 – 60	CH_4	60 – 80
CO_2	2 – 4	CO_2	1 – 6	CO_2	8 – 15
CO	0	CO	0.1 – 0.4	CO	0
O_2	0	O_2	7 – 17	O_2	0
N_2	1 – 8	N_2	4 – 40	N_2	5 – 32
Concentration of higher hydrocarbons in traces					

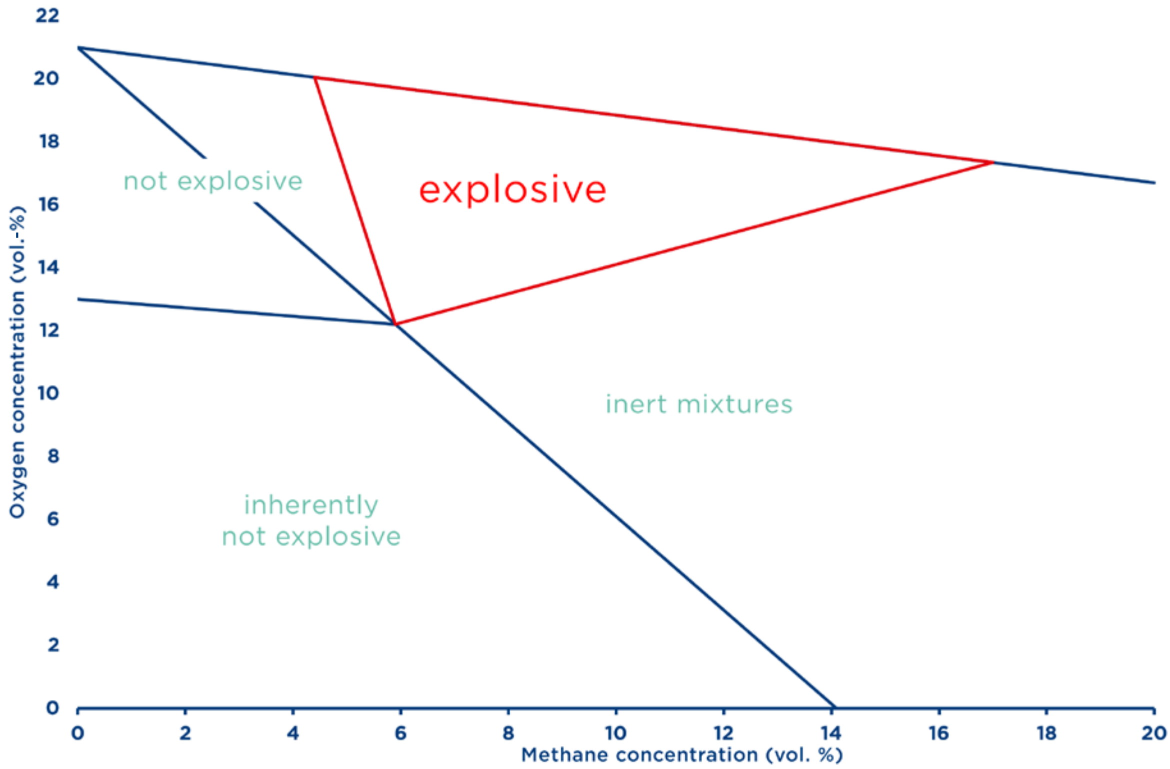


Fig. 17: Explosive areas for air/methane mixtures according to Christensen (2007).

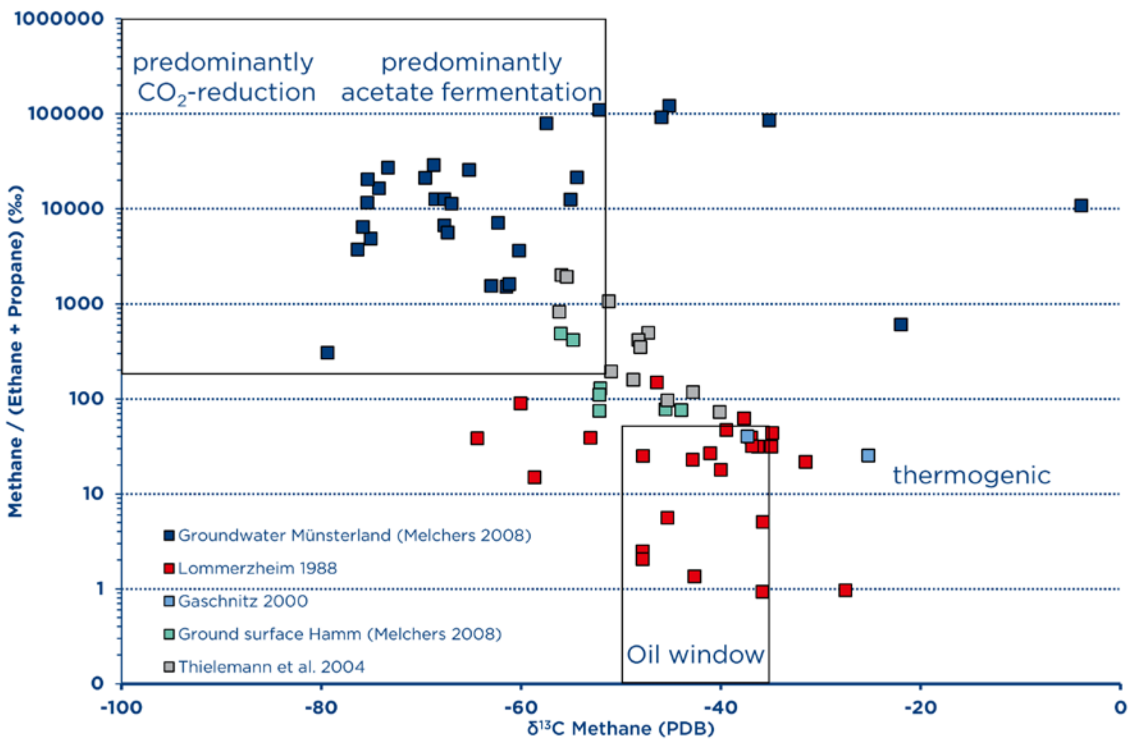


Fig. 18: Extended classification diagram according to Bernard et al. (1977; in Melchers 2008).

2.4. Mine Water Chemistry

In addition, the mine methane can also escape to the ground surface via tectonic faults in combination with a thin overburden. Whereas gas releases at the degassing pipes of the shafts and surface openings can be accurately located, the releases at tectonic faults often are dispersed and diffuse.

Due to the mine water rebound, the void volume which is available for methane storage is reduced as the void volume in place is increasingly saturated by water, and the inflow of mine gas from the *hard-coal bearing* rock decreases. Where isolated parts of the mine exists which are pressurised by the mine water rebound, a displacement of the residual gas content can occur. If that is the case, free gases will be mobilised and can eventually lead to gas releases at the ground surface.

As soon as the hydrostatic pressure of the rising mine water exceeds the remaining desorption pressure of methane, no mine gas will be discharged from the coal seams. After all seams and workings have been inundated (i. e. the mine water level has reached the top boundary of the coal measure), it has to be assumed that the gas release rate has reached its minimum, and thus the gas release process can be regarded as finished. Nevertheless, as tests in Lorraine (France) have indicated, small amounts of methane continue to be dissolved in the mine water and released even after the mine water rebound has been finished (Klinger et al. 2013).

As a discipline of hydrogeology, hydrochemistry deals mainly with chemical species that exist in water. These species can be either dissolved or undissolved. The dissolved species mostly include electrolytes, *anions* and *cations*, gases, organic compounds and hydrated complexes. Undissolved species is usually particulate matter such as solid particles of micrometre size (e.g. colloids, fine-grained clay particles or even microorganisms such as bacteria) or emulsions – finely dispersed droplets of liquids that are immiscible in water such as lipids or petroleum. Usually, dissolved and undissolved species are separated using filters of specific pore sizes (i.e. 0.45 µm; Wisotzky et al. 2018).

Solubility

More than 80 years ago, Noddack (1936) published the hypothesis that each chemical element (which was known at that time) was present in each 'matter' whether it is of natural or artificial origin. This postulate was also known as the 'omnipresence of elements'. Today, *thermodynamics* have changed this term slightly and uses the expression 'omnipresence of chemical species'. This principle means that basically every species is soluble in any other species in a certain concentration depending on pressure and temperature, and thus, the system is in *thermodynamic* equilibrium. Transferred to aqueous solutions and, in particular, mine water, this means that there have been several dissolution processes after migration of mine water through the rock strata. As a consequence, every naturally occurring chemical element can be present in water at large or small concentrations (Wolkersdorfer 2013).

The extent at which groundwater and mine water may be enriched mostly with dissolved species results from the origin of water which again depends on several factors. It is important on the one hand, which types of rock the water has infiltrated on its way and what residence time the water had experienced in order to (partly) dissolve the mineral constituents of these rocks. Here, the types of mineral components are fundamental, i. e. whether they have a high solubility (e. g. rock salt, calcite, gypsum) or a low one (e. g. silicates). On the other hand, physical parameters such as pressure and temperature or the grain size of the mineral phases influence the solubility. Here, the rule applies that most species become more water soluble at higher temperatures and higher pressures. The grain size of the mineral components is another very important factor as it influences the effective surface area for the chemical reactions taking place (Lottermoser 2010; Tremblay & Hogan 2014). The amount of dissolved species also impacts the solubility of other substances (for example, if two mineral phases share ion pairs, such as NaCl and KCl [ion effect – reduces solubility]) and can lead to a change of the pH value (see info box 'Chemical Definitions'), a value which in turn also controls the solubility of many mineral compounds.

Additional factors influencing solubility are the *sorption processes* (adsorption, absorption and desorption) which play a role with organic substances; these organic substances may occur naturally in the mine or they are of anthropogenic origin, for example, hydraulic fluids or lubricants (Denneborg et al. 2017).

Fig. 19: Pyrite aggregate with typical longitudinal striation of the cubic crystals (photo: Bastian Reker).

Apparently, there are many different processes at stake which influence each other and can lead to higher or lower rate of dissolution. A significant role for mine water chemistry play the mineral phases which were formed by sulphide *oxidation* (commonly referred to as pyrite weathering or *pyrite oxidation*) and which are transported as solute species during the mine water rebound.

Sulphide Concentration of Hard Coals

The concentrations of sulphides and disulphides such as pyrite (Fig. 19) or marcasite differ in hard-coal deposits due to their origin (marine or terrestrial). Often, hard coals of marine or so called paralic formation show higher sulphide concentrations compared to terrestrial or *limnic* formation. Under anoxic conditions these sulphide minerals are mostly stable. The oxygen, dissolved in water, is generally not sufficient to oxidise notable amounts of sulphide. During mining and the necessary processes of mine dewatering and ventilation, a significant amount of atmospheric oxygen is transferred into the mine, and as result, sulphide minerals start to oxidise and a significant number of different intermediate hydrated sulphate complexes are formed, such as römerite, jarosite or schwertmannite.

Disulphide Oxidation

The process of disulphide oxidation is initiated when, for example, pyrite reacts with oxygen and water, releasing ferrous (or divalent) iron, sulphate and protons:

$$FeS_2 + \tfrac{7}{2} O_2 + H_2O \overset{Bac.}{\rightarrow} Fe^{2+} + 2SO_4^{2-} + 2H^+$$

In turn, the dissolved divalent iron reacts with the oxygen and protons which forms trivalent (ferric) iron and water:

$$Fe^{2+} + \tfrac{1}{4} O_2 + H^+ \overset{Bac.}{\rightarrow} Fe^{3+} + \tfrac{1}{2} H_2O$$

These two reactions are usually bacterially catalysed by bacterial strains named *Acidithiobacillus ferrooxidans* (oxidising iron and sulphur) and *Acidithiobacillus thiooxidans* (oxidising sulphur; Kelly & Wood 2000; Johnson & Hallberg 2003) and accelerate the oxidation process by a factor of up to 10^6. The second reaction in particular is an important step as trivalent iron acts as an oxidant for the disulphide:

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

Thus, this is a process which is self-reinforcing over time and which is, with the help of the bacterial *catalysis*, responsible for the high concentrations of metal iron and sulphate in the mine water. Moreover, the release of protons significantly increases the *acidity* (see info box on 'Chemical Definitions') of the mine water (Singer & Stumm 1970). The particle size of the disulphide minerals also plays a significant role in the kinetics of the mineral deterioration which is going on (Tremblay & Hogan 2014). Pyrite crystals of framboidal or polyframboidal shapes, whose size often does not exceed the micrometre range and which are of a large surface area, are recognised as particularly reactive (Evangelou 1995).

As a last step, the trivalent iron precipitates as hydroxide, releasing further protons:

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

Fig. 20: Typical impact of uncontrolled mine water logging at the ground surface with characteristic ferric-oxyhydroxide sedimentation in South Africa (photo: Bastian Reker).

In total, these previous redox reactions are summarised in the overall equation (Younger 2000):

$$FeS_2 + \frac{15}{4} O_2 + \frac{7}{2} H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+$$

Basically, this process describes a phenomenon that is also known as juvenile acidity (see info box on 'Chemical Definitions'). Usually, it is not taking place during the entire mine dewatering activities of a colliery. Instead, infiltrating water and the humidity entering the mine workings as part of the ventilation process, form, particularly in the acidic oxidation environment (Cravotta 1993), a number of different iron sulphate hydrates induced by the sulphide oxidation (compared to the hydroxides!). These intermediate mineral precipitates are also referred to as 'acid generating salts' (Randall & Olyphant 1993). They are formed within the mine if their ion products exceed their solubility products from the oxidizing solutions (Alpers et al. 1994). The *sulphates* formed are mostly iron(II)sulphates and iron(III) sulphates and a mixture of both in hydrated forms. These reaction products are what Younger (1997) calls 'vestigial acidity'. As these salts are readily water soluble, they are easily dissolved during a mine water rebound and are thus either available as oxidants for further sulphide oxidation or transported as solutes to the surface. This causes the so called 'first flush effect' (see info box on 'First Flush Effect') and typical yellowish to reddish precipitations of iron(oxy)hydroxides at the surface (Fig. 20). Waters that are enriched in such a way are also referred to as influenced by acid mine drainage (AMD) in international literature.

Chemical Definitions

In chemistry, there are numerous definitions for the terms ‘acid’ and ‘base’. The simplest and oldest concept according to Arrhenius defines an acid as a hydrogen compound which dissociates in an aqueous solution and forms hydrogen ions (H^+) and the corresponding anion.
A compound which dissociates in water completely, and thus forms a high activity or concentration of positively charged hydrogen ions, is called a strong acid. A base, on the other hand, dissociates in an aqueous solution to form hydroxide ions (OH^-). Here, corresponding to the acid, the same rule applies: the more complete the dissociation of the base, and thus the higher the activity or concentration of the hydroxide ions, the stronger the base (Binnewies et al. 2016). Thus, the sum up of the H^+-ions and the OH^--ions determine whether a solution behaves in an acidic or alkaline manner. This condition is given by the pH value which is defined as a negative common logarithm of the numeric value of the activity of hydrogen ions:

$$\mathrm{pH} = -\log a(H^+)$$

A more recent and general definition of acids and bases in chemistry is provided by the Brønstedt-Lowry-concept which defines acids as proton donors and bases as proton acceptors. Further explanations can be found in Binnewies et al. (2016).

The term ‘acidity’ is defined in hydrochemistry as the sum of species in water which react in an acidic manner, i. e. which are able to form hydrogen ions in water. These can include dissociated metals, but also organic or inorganic acids (Hedin et al. 1994; Wolkersdorfer 2013). Correspondingly, the base capacity describes the potential of a solution to neutralise a base by providing acidity. In other words, a liquid of high base capacity is acidic, and, vice versa, a liquid of high acid capacity is alkaline. Whether a water behaves in total as an acid or as an alkaline solution is decided due to the difference between those two parameters (Hedin et al. 1994):

- net alkaline:
  alkalinity > acidity
  (or acid capacity > base capacity)
- net acidic:
  acidity > alkalinity
  (or base capacity > acid capacity)

As the pH value only considers the activity of hydrogen ions in water and does not take into account all components that react in an acidic or alkaline manner, it can only be used as an indicator of net acidic or net alkaline water. Mine water is referred as acidic if a pH value below 5.6 is determined (Wolkersdorfer 2013). Waters of a pH value around 7 are called circumneutral, and those exhibiting a pH value of > 7 are called alkaline.

The terms ‘rudimentary acidity’ (vestigial acidity) and juvenile acidity were introduced by Younger in 1997. ‘Vestigial acidity’ in relation to mine water is defined as the release of secondary mineral components which were formed during the leaching induced by sulphide oxidation (Wolkersdorfer 2013; see above). ‘Juvenile acidity’, on the other hand, defines the acidity which is generated directly from the acidity of protons and metals (mainly dissolved iron, manganese and aluminium; Hedin et al. 1994) of the disulphide oxidation within the water level deviation in the partially inundated mine area (Younger 1997).

Leaching in a Mine – First Flush Effect

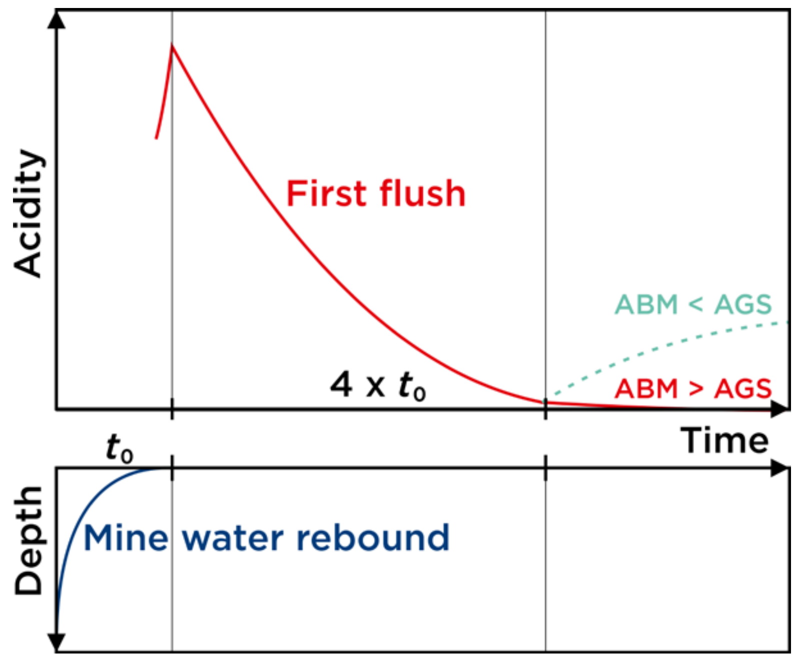


Fig. 21: Comparison of time taken by the mine water rebound with the temporal development of the overall acidity during and after the first flush (axes are non-dimensional). ABM: acid-buffering mineral phases; AGS: acid-generating salts; adjusted and extended according to Wolkersdorfer & Younger (2002).

The term 'first flush' was introduced by Younger (1997). It describes the initial, steep increase of mostly iron and sulphate concentrations followed by their gradual decrease after the mine water rebound in a colliery has ceased. The responsible agent is the vestigial acidity (see info box on 'Chemical Definitions'), i.e. the dissolution or leaching of secondary minerals which were formed during disulphide oxidation. The following empirical formula helps to estimate the duration of this process (Younger 2000; Wolkersdorfer 2013):

$$t_f = f(aci_{rem}, r_{ox}, V, K, \dot{h}_{gw}) \approx (3.95 \pm 1.2) \cdot t_{Wi}$$

with

- t_f duration of first flush,
- t_{Wi} duration of rebound,
- aci_{rem} reduction of acidity,
- r_{ox} oxidation rate of acid-containing minerals,
- V volume of mine voids,
- K hydraulic conductivity of mine voids,
- $\dot{h}_{gw}$ rate of groundwater recharge.

This equation indicates that the duration of the first flush, i.e. the increased concentrations of sulphates and iron, is about four times as high as that of the mine water rebound (Fig. 21).

Here, two fundamental patterns of total acidity trend need to be distinguished (Fig. 21): if the amount of the acid-buffering mineral phases (minerals that consume protons when dissolving and thus reduce acidity, e. g. carbonates) is larger than the amount of acid-generating mineral phases, then the acidity and ion concentration (mostly iron, manganese, aluminium) will reduce to a significantly lower level than at the beginning of the first flush. Acid-generating mineral phases refer mainly to sulphates as secondary minerals formed (see above).

A different curve shape is valid if the opposite case applies, i. e. the amount of the acid-buffering mineral phases is smaller than the amount of the acid-generating mineral phases (green broken line in Fig. 21). After a minimum of total acidity is achieved, the buffering mineral phases are used up, and the acidity increases again. Short-term and long-term concentrations of iron during the first flush (i. e. at the beginning and at the end of this process) can be estimated referring to the overall sulphur concentration of the mined hard coal. If those values have not been measured, such estimates can be done looking at the proximity of the worked coal seams to marine horizons: the smaller the distance between the marine horizons and the worked coal seams, the higher usually the sulphur concentration. This observation corresponds with the experience that marine or paralic hard coal generally shows higher disulphide concentrations than limnic hard coal (see above). Long-term concentration patterns can also be estimated based on the spatial proximity between the distance of the point of mine water logging at the ground surface and the outcrop of the closest associated coal seam, i.e. the zone of potentially ongoing pyrite oxidation (Younger & Adams 1999).

2.5. Stratification

Two or more fluids of different densities can either mix, or they can separate and stratify. Which process occurs depends on the vertical density gradient. The differences in density can result from a number of factors: differences in temperature, the concentrations of dissolved species (i. e termed '*salinity*') or a combination of both. If the density gradient between the layers are sufficiently high, the fluids will form stable vertical stratified fluids with a sharp boundary.

If both water masses remain stable and do not mix along the boundary, then this condition is known as stratification. Generally, the fluid of higher density is situated below the fluid of lower density. In many mines, this refers to the case as the deep waters laterally flowing in an area of a significantly higher salinity compared to groundwater close to the surface (Melchers et al. 2019). However, this trend is diminished by the geothermal gradient which causes a temperature increase in the deeper situated waters, something which reduces their density. Whether a stable stratification can be formed depends on the aforementioned factors – if one dominates or how these two factors interact.

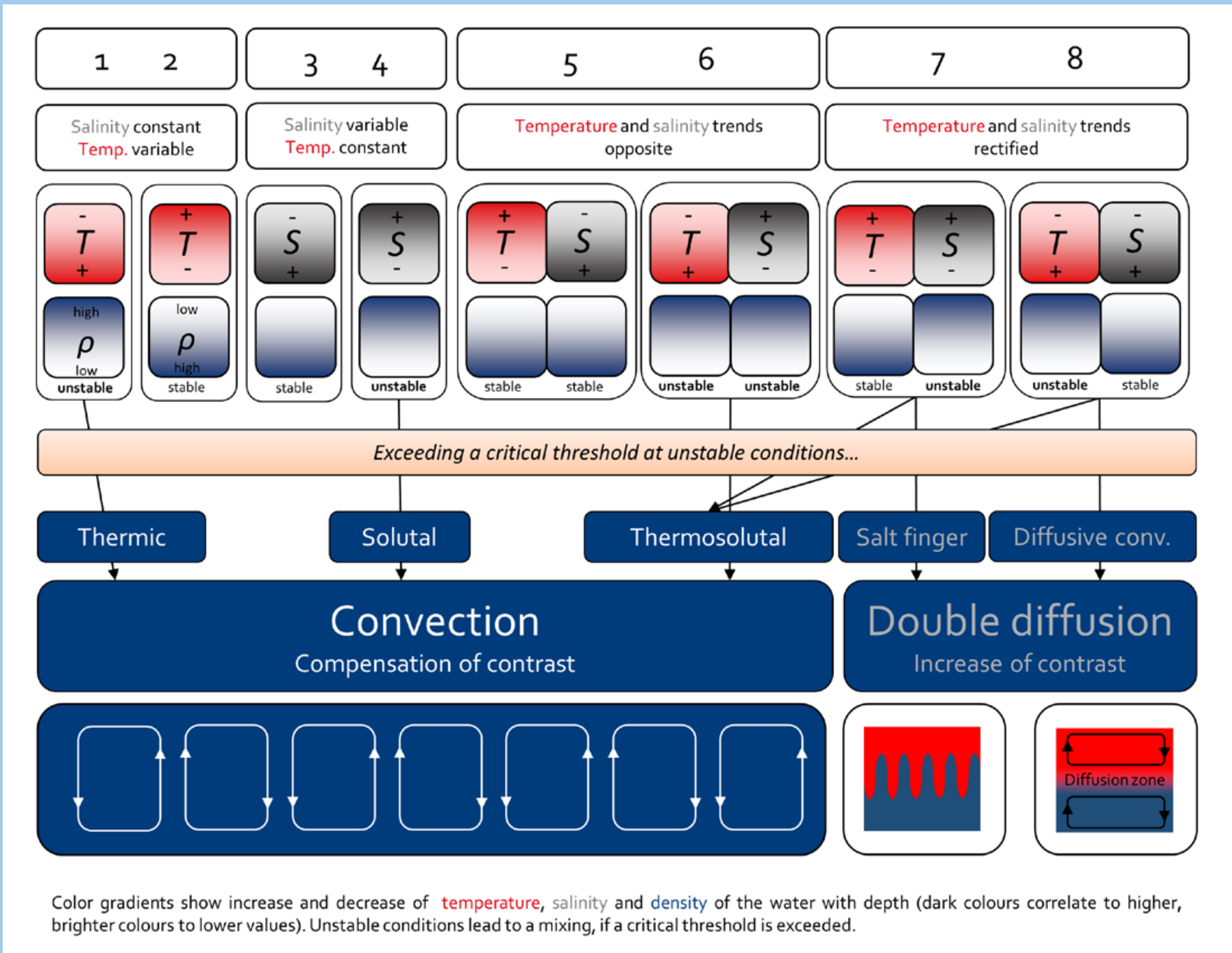
Overall, a stratification causes a very limited transport of mass or heat fluxes between two fluids. Primarily, any mass transfer during the stratification stage is accomplished via a double diffusion process or 'internal waves' induced by gravitation:

- **Double diffusion** causes no mixing of the fluids (Fig. 22). Any transport phenomena (heat or mass flow) takes place at molecular scale where heat is transported much faster (by the factor 100) than solute concentration equilibrates (Berthold 2009). Double diffusion can have two modes: the formation of salt fingers and diffuse convection (see info box 'Driving Forces of Stratification Mechanisms').
- **Internal waves**, contrary to normal surface waves, are formed inside the water column if a continuous or discrete density stratification pattern with depth occurs. They are a type of gravity waves and their existence and propagation are driven by gravitation. They are described as *oscillations* of a stratification which propagate in space and time (Büttner et al. 2012). If they propagate in a continuous fashion, they will not affect any heat or mass flux apart from diffusion processes within the fluid. However, if these waves break, they cause turbulent mixing of the stratified layer (Burchard et al. 2008).

A detailed illustration of the processes which lead to fluid stratification can be found in Berthold (2009).

Driving Forces of Stratification Mechanisms

Salt fingers may form if the temperature and the salinity of the water in a deeper water layer are lower compared to the water layer above (Fig. 22). The temperature factor leads to lower densities in the upper water column whereas the salinity trend leads to lower densities in the deeper water layer. Thus, both factors act in reverse. A water molecule of the upper water layer (i. e. warm and saline), deflected by a small momentum, sinks and spontaneously transfers its heat to surrounding water molecules due to diffusion whereas its inherited solute concentration remains almost constant due to comparable much smaller diffusivity. As the temperature of the water molecules is decreased, its density increases which accelerates its downward movement. During this process, the heat is transferred to cooler water mass of lower salinity, which enables this water to move upward in the water column. As a result, finger-like structures are formed between two water layers of different density. At their transition zone those differences are balanced by means of diffusion, but within the transition zone by means of convection (Berthold 2009). One interesting aspect of these processes is that, when looking at the entire system, the mass flow, i. e. salinity transport, plays a more important role than the heat flow although its diffusion process occurs at a much lower rate. This is due to the fact



that the salt fingers cause a certain perturbation which allows the mass transport to take place.

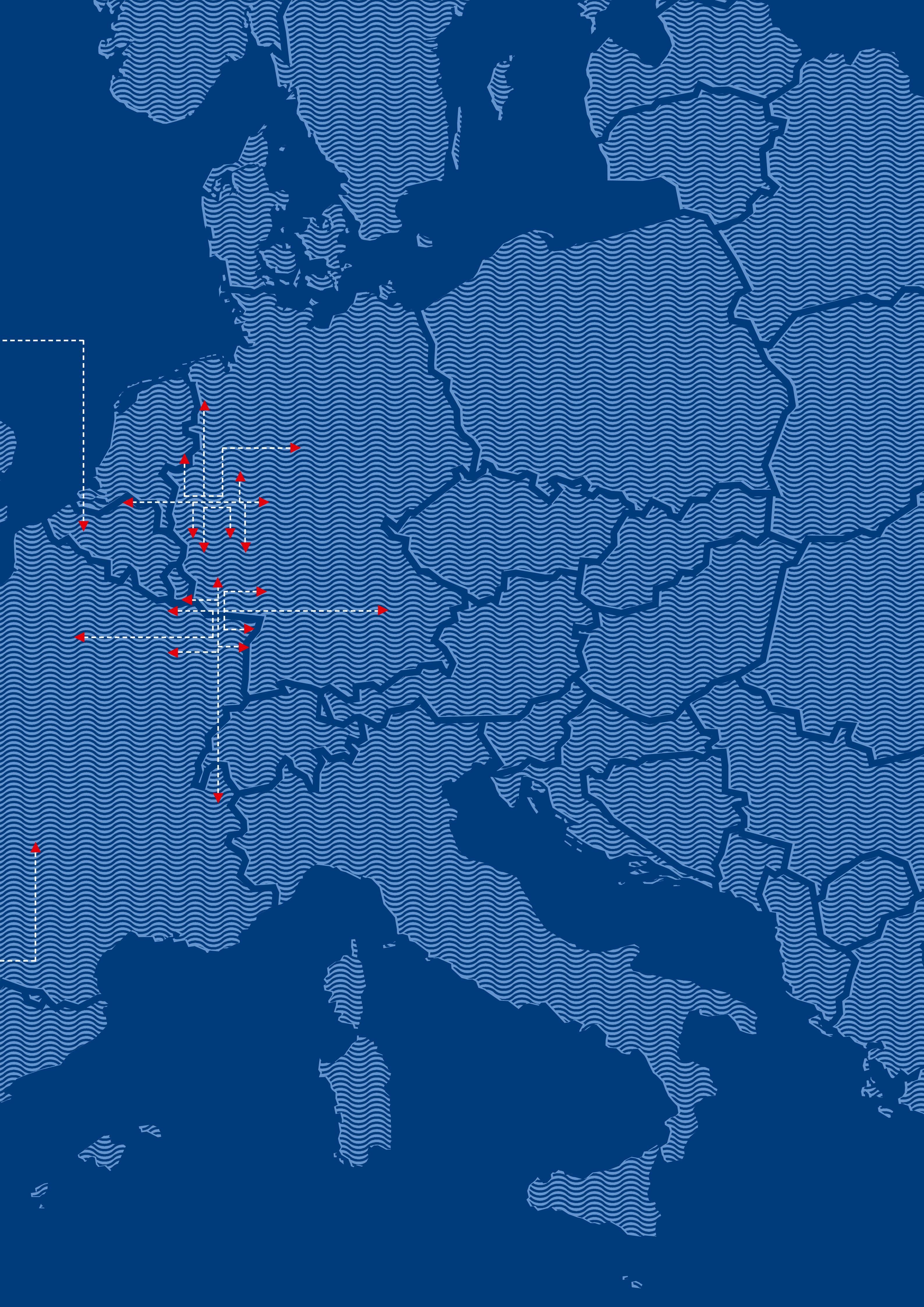
As a result, the top water layer becomes less dense, and the deeper water layer becomes denser. Overall, this process does not lead to a balance of the density gradient but enhances it instead.

Like the salt finger formation, the diffuse convection is also a kind of double diffusion (Fig. 22). It can occur if cooler water of higher density is situated above warm water of lower density and, contemporaneously, the deeper water layer is of higher salinity. Again, both factors cause opposite density gradients, but with opposite signs contrary to the salt finger formation. Via diffusion, the warm deep water passes on its heat to the cooler surface water whilst the salinity remains almost constant. As a consequence, the density of the surface water decreases whereas the density of the deep water increases. This leads to an enhancement of the density gradient between the water layers. Overall, convection cells are generated in both layers which touch each other at the diffusion transition zone. If several of such layers are located on top of each other, the salinity and temperature profiles form their typical staircase-like structures in a plot.

Overall, there are eight possible combinations of temperature and salinity gradients which may lead to either convection processes or double diffusion processes (Fig. 22).

Fig. 22: Eight possible combinations of different salinity and temperature gradients within a vertical water column and the associated transport processes, according to Berthold (2009).

3. Mine Water Management in European Hard-Coal Mining Regions



In a number of European countries hard coal was mined (Fig. 23). Large hard-coal deposits can be found in Germany (i. e. Ruhr and Saar basins), in the United Kingdom (Yorkshire and Durham basins) and in Poland. Table 5 provides an overview of the hard-coal mining regions in Europe. This study examines eleven of those in detail.

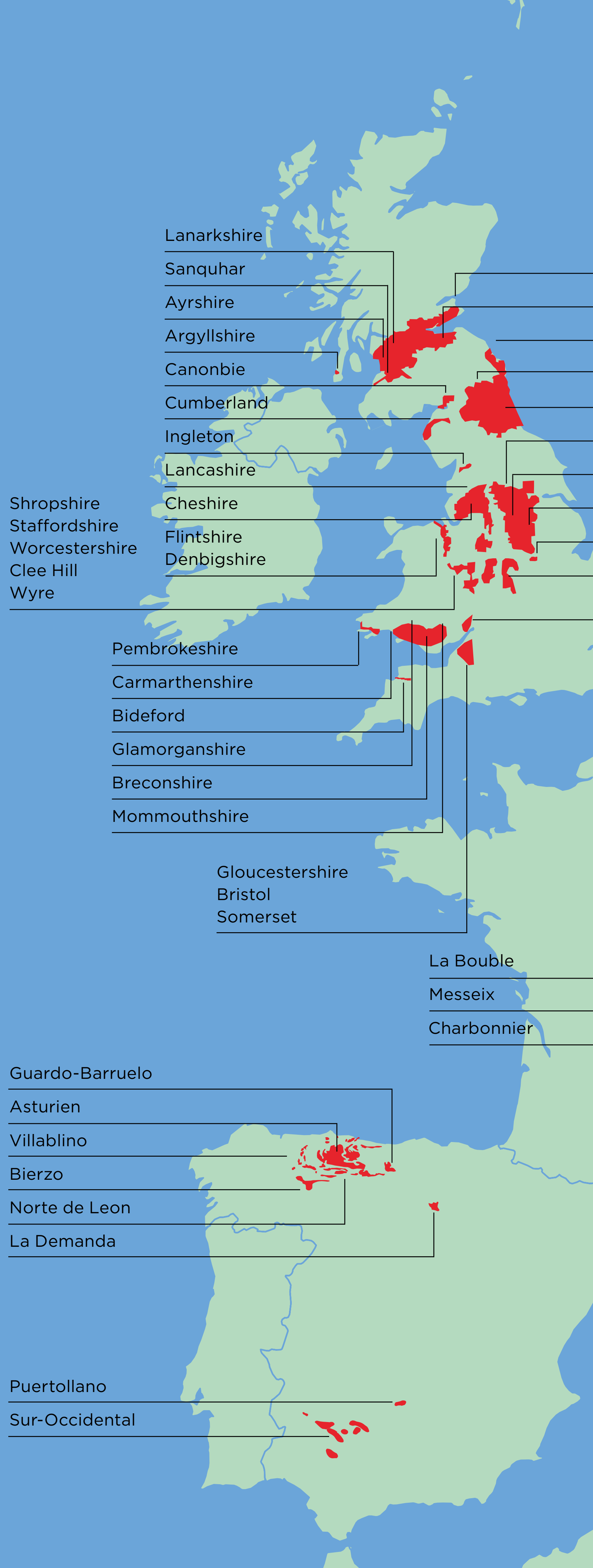


Fig. 23: Hard-coal deposits in Europa


Fifeshire
Lothian & Peeblesshire
Northumberland
Naworth
Durham
Yorkshire
Derbyshire
Nottinghamshire
Leicestershire
Warwickshire
Forest of Dean
Kent
Nord-Pas
de Calais
Lorraine
Ibbenbüren
Deister
Bielefeld
Ruhr area
Aachen
Erkelenz
South-Limburg
Saar
Lugau-Oelsnitz
Zwickau
Doberlug-Kirchhain
Döhlen basin
Lublin
Lower Silesia
Upper Silesia
Žacléř
Kladno
Plzeň
L'Aumence
Decize
Veuvrotte
Blanzy
South bavaria
bituminous coal
Montrambert
Le Freyssinet
St. Jean
St. Jacques
La Mure
Prades
Alès
Graissessac
Cruejouis
Decazeville
Carmaux
Corsica
Sardinia
Mecsek
Banat
Petroşani
Balkan basin

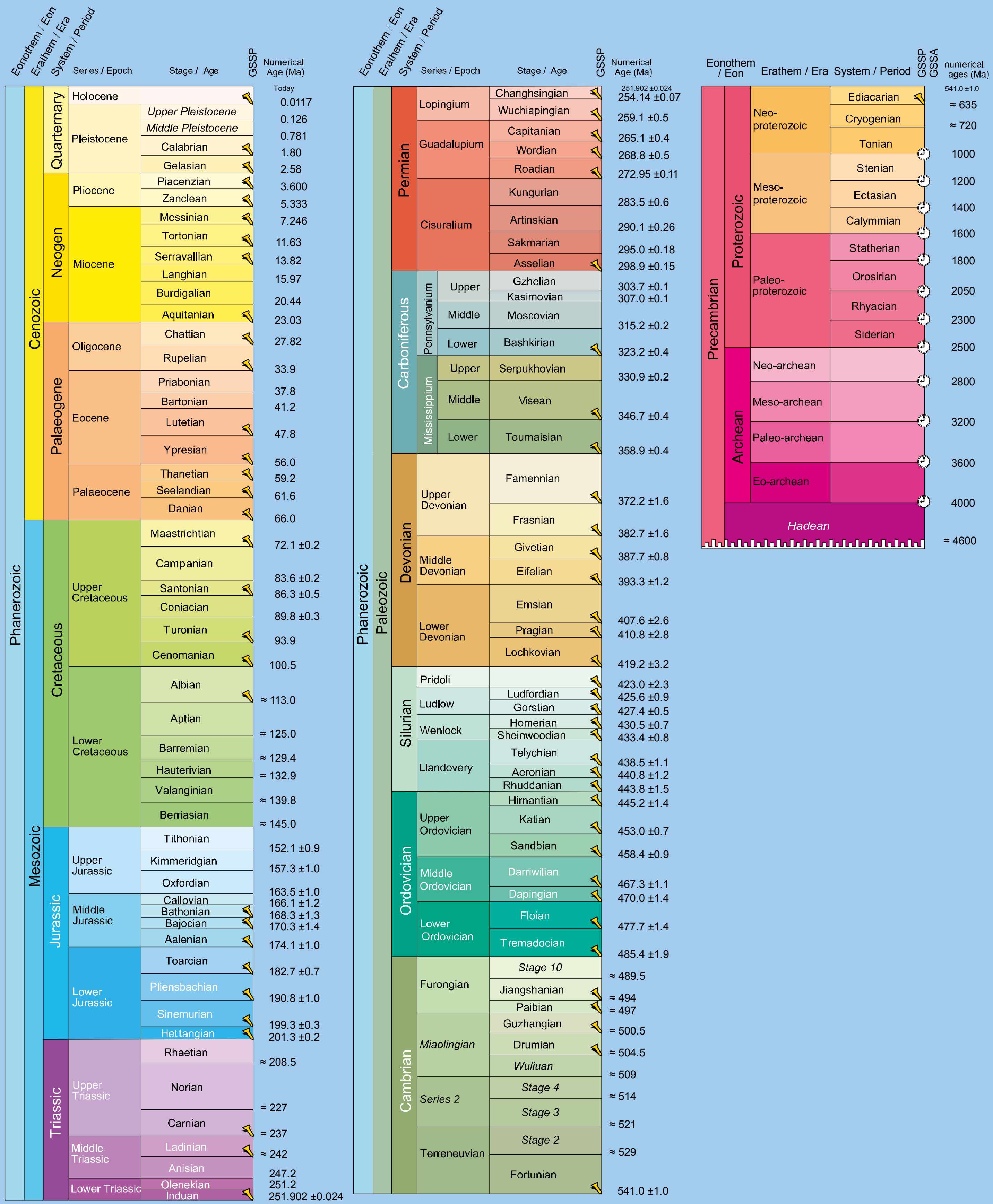


Fig. 24: Stratigraphic table according to Cohen et al. (2013).

Stratigraphy of Hard-Coal Deposits

Stratigraphy (referred to as the science of layered strata) is the branch of the geological sciences concerned with the study of rock successions, taking into account all of their organic and inorganic features and contents in terms of their timing of formation; it also sets up a timescale to help date geological processes and events (Murawski & Meyer 2010). Stratigraphy, as a branch of historical geology, deals with reconstructing the history of Earth.

In its early days, stratigraphy only recognised the qualitative correlation and categorisation of the different rock strata according to the principle that in tectonically undisturbed regions older rocks must be deposited below younger rocks. However, this principle only allowed for establishing local or regional sequences of sediments. This meant that rock successions of same age but different rock type that were deposited in areas that were situated further away could not be correlated. When geologists started considering fossils as so called index fossils, it was possible to establish large-scale correlations between different rock strata. Any absolute dating of rocks referring to ages in total years could be applied after radioactive decay processes were discovered. For that purpose, rock age is defined by radiometric determination using the isotopes of uranium-lead, potassium-argon, rubidium-strontium or ^{14}C called radiocarbon.

The International Commission on Stratigraphy (ICS) defines the history of geology in terms of global units of the international stratigraphic chart or time scale (Fig. 24; Cohen et al. 2013).

Overall, the stratigraphic chart is divided into five units. From the highest to the lowest order, these units are called: eon (eonothem), era (erathem), period (system), epoch (series) and age (stage). Any further distinction below the rank 'age' is mostly adjusted to regional conditions and thus only of regional impact.

To each unit, standardised colours are allocated to be used when creating maps and profile sections; these are also used in this report. Any deviations that might be used for better illustration purposes are explained in the respective segment.

This chart is being continually adjusted to scientific knowledge and is valid across the globe. Therefore, many regional terms, for example, the division of the Upper Carboniferous into Namurium (A to C), Westphalium (A to D) and Stefanium (A to D) which was common in Germany and in parts of Europe, have been replaced by new names of global ICS related time scales. However, as the old terms are still better known at regional level than the international nomenclature, some chapters of this report will refer to the regional terms and time scale for the Carboniferous period.

Most of the hard-coal deposits in the European coalfields were formed more than 300 million years ago in the Upper Carboniferous. The climatic (almost tropical) conditions led to immense growth of plants in the Carboniferous period; when the plants died, the first stage of the carbonification process began, i.e. the conversion of organic material into coal. The terrestrial plants decayed and were buried in the oceans where they did not fully decompose, but the organic matter turned into peat due to the absence of oxygen. Clastic sediments such as clay or sand increasingly buried the organic material, subsequently reducing the water content from it at elevated pressures and temperatures.

Carbon content got enriched compared to the amounts of hydrogen and oxygen (and nitrogen) which were also parts of the initial organic matter. Over the time, peat (carbon ratio: 55 – 64 %, moisture content: 35 – 39 %) was transformed to lignite (carbon ratio: 60 – 75 %, water ratio: 17 – 34 %), and then hard coal (carbon ratio: 78 – 90 %, water ratio: 4 – 19 %) or even anthracite (carbon ratio: 94 – 98 %, water ratio: 1 – 3 %). Important for coal formation was the alternation between sea level rise and fall. Once the sea level fell, plants could grow again and the process repeated itself. In an ideal case, many alternating sequences of sand, clay and conglomerates were deposited in which seams of hard coal were interbedded (cyclothem, rhythmic sedimentation).

However, hard coal was not only formed in the Upper Carboniferous. The Wealden coal deposits, located south-west of Hannover (Barsinghausen, Deister; Fig. 25) and in the Weser-Ems region (Minden), are an example that coal deposits in Germany were also formed during the Lower Cretaceous (Berriasium, 145 – 140 million years ago). As in the Carboniferous period, there was a tropical to subtropical climate prevailing in the Cretaceous period which increased the growth of plants thus favouring the formation of coal.

A stratigraphically younger deposit, but one that has not been as matured as hard coal, is the jet or pitch coal in South Bavaria (South bavarian bituminous coal, found in the region of Peißenberg, Hausham and Miesbach; Fig. 25). This deposit was formed in the Tertiary period around 40 – 35 million years ago. Pitch coal is classified as a meta-lignite to subbituminous coal rank, i.e. a more brittle lignite with a higher maturity.

Globally, there are hard-coal bearing formations vs occurences which were deposited in between the Carboniferous and Cretaceous; most of those are situated in North America, Asia and Australia.

Tab. 5: Hard-coal deposits in Germany and Europe
(Hard-coal mining areas in Germany according to Lahner et al. [2004]; hard-coal mining areas in United Kingdom according to NMRS [2019]; hard-coal mining areas in Spain according to IGME [1985]; hard-coal mining areas in France according to Geinitz et al. [1865]; DM [1963] and Daniel & Jamieson [1992]; hard-coal mining area in Italy according to Geinitz et al. [1865], hard-coal mining areas in the Czech Republic according to Clarke & McConville [1998]; hard-coal mining areas in Bulgaria according to McConville et al. [1999]; hard-coal mining area in Hungary according to Benson [1999]; hard-coal mining areas in Romania according to Couch et al. [1990]; hard-coal mining areas in Poland according to Kotarba et al. [2002]; hard-coal mining area in Norway according to EURACOAL [2010]).

Germany
Ruhr area
Aachen
Saarland
Ibbenbüren
Osnabrück region (Piesberg, Schafberg, Hüggel)
Zwickau
Lugau Oelsnitz
Döhlen basin
Doberlug-Kirchhain
Halle region (Saale) (Wettin, Plötz-Löbejühn)
Ore Mountains (Borna-Ebersdorf, Hainichen, Flöha)
South Bavaria (Peißenberg, Hausham, Miesbach)
Kronach district (Stockheim, Reitsch)
Baden-Württemberg (Baden-Baden, Kinzigtal)
Upper Palatinate (Erbendorf)
Harz
Deister
Schaumburg region
Bielefeld region (Monastery Oesede, Halle [Westf.])

United Kingdom
Bideford
Kent
Somerset
Bristol
Gloucestershire
Forest of Dean
Newent
Warwickshire
Staffordshire
Shropshire
Cheshire
Leicestershire
Nottinghamshire
Derbyshire
Yorkshire
Lancashire
Ingleton
Stainmore
Cumberland
Naworth
Durham
Northumberland
Pembrokeshire
Carmarthenshire
Glamorganshire
Breconshire
Monmouthshire
Denbigshire
Flintshire
Anglesey
Fifeshire
Peeblesshire
East Lothian
West & Mid Lothian
Lanarkshire
Argyllshire
Ayrshire
Sanquhar
Canonbie
North Yorks Moors
Coxwold
North Pennines
Crosby Ravensworth
Yorkshire Dales
Lune Valley
Buxton

Spain
Asturias
North-León
Bierzo
Villablino
Guardo-Barruelo
Sur-Occidental
Puertollano
La Demanda

France
Lorraine
Nord-Pas de Calais
Veuvrotte
Decize
Blanzy
L'Aumance
La Bouble
Messeix
Charbonnier
Montrambert
La Mure

Prades-et-Nieigles
Ales
Decazeville
Carmaux
Cruejouis
Graissessac
Le Freyssinet
Eduits
Gr. Villard
St. Jean
St. Jacques
La Rame
St. Martin-de-Queyrieres
Corsica

Netherlands
South Limburg

Belgium
Campine
Liège
Hainaut

Czech Republic
Žaclér̆
Kladno
Plzeň
Ostrava-Karvina

Bulgaria
Dobrich
Balkan basin

Hungary
Mecsek

Romania
Banat
Petroşani

Poland
Upper Silesia
Lower Silesia
Lublin

Italy
Sardinia

Norway
Svalbard

Elevation Reference Systems

Most European countries have their own geodetic datum which usually refers to the sea level in a coastal town in the same country. Germany uses the vertical datum 'Normalhöhennull (NHN)' as its current reference plane for normal height referring to the height above mean sea level. This new reference system replaces the 'Normalnull (NN)' whose elevation reference did not consider the gravitation field of the Earth. With the change to NHN, Germany joined the United European Levelling Net (UELN). The German references of elevation do no longer deviate from those of other countries which are also part of the UELN. The reference height in Germany is fixed to a level control at the New St. Alexander Church in Wallenhorst (Osnabrück district).

The elevation reference system in Spain is expressed as 'metros sobre el nivel del mar' (abbr. msnm) and refers to the sea level at Alicante. In the United Kingdom, there is either the expression 'ordnance datum' (OD) or 'metres above sea level' (mASL) which both refer to the sea level in Newlyn. In France, the reference is called 'metres au-dessus du niveau de la mer' and refers to the sea level in Marseille.

As the differences between the individual systems are usually only a few centimetres up to 2.5 decimetres maximum and are thus not relevant for the investigations of this report, the abbreviation 'SL' (sea level) will be used throughout this report.

Fig. 25: Hard-coal deposits in Germany; spatial demarcation of the mining regions according to Lahner et al. (2004).

3.1.
Germany

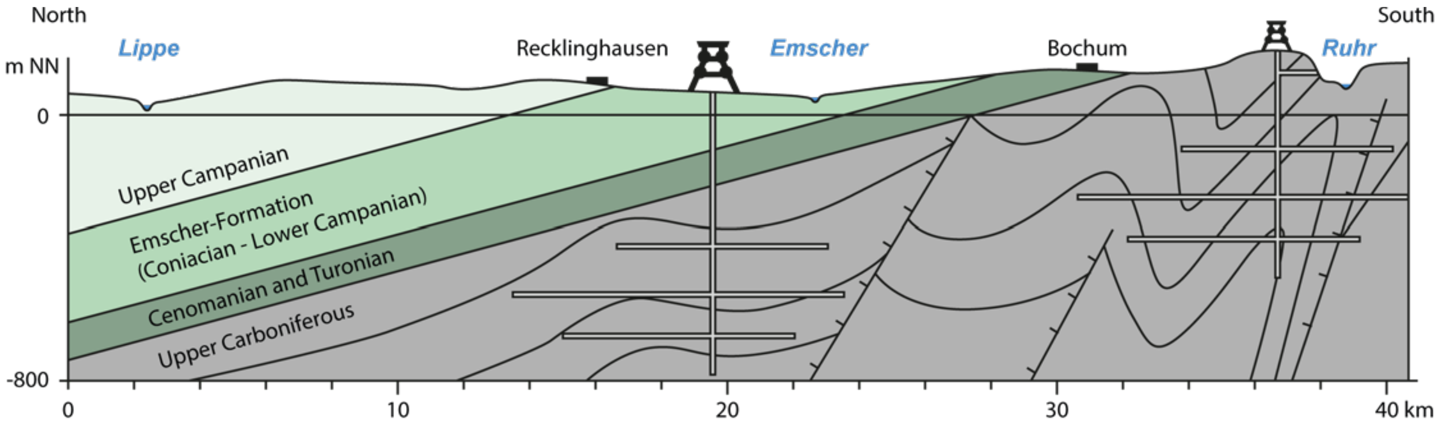


Fig. 26: Hydrogeological section (north-south) of the Ruhr coalfield.

3.1.1.
Ruhr Coalfield

In the Ruhr mining region (Fig. 25) the last colliery, Prosper Haniel, operated by RAG AG, was closed in December 2018. This decommissioning marked the end of a history that has significantly shaped the Ruhr area over centuries. In the 1950s, the peak of German hard-coal mining, more than 600,000 people were employed and worked in 173 collieries in Germany of which most were located in the Ruhr area (GVST 2019). With the completed retreat from the open mine workings, which finalises the closure of hard-coal mining in the Ruhr mining region, the most extensive mine water rebound is planned to be carried out in a European hard-coal mining region.

Geology and Hydrogeology

The succession of the Rhenish-Westphalian hard-coal deposit is divided into the overburden strata of Permian, Triassic, Cretaceous and Tertiary age and into the underlying Palaeozoic hard-coal bearing rock at the base (Fig. 26). The overburden rocks compared to the hard-coal bearing rocks differ regarding their rock composition, tectonics and their hydrogeological properties. Moreover, a distinction needs to be made between the regions of Westphalia (Münsterland Cretaceous basin) and the Lower Rhine Valley (Lower Rhine Depression; Kukuk 1938; Drozdzewski et al. 1995).

In the Westphalian part, the overburden can be subdivided into three depositional successions which are confined lithologically and geohydraulically from each other (from the top to the base):

- upper groundwater storey (e. g. Haltern and Recklinghausen Formation) at the top of the fractured clayey marlstones (thickness up to 200 m; aquifer),
- clayey marlstones as the fundamental geohydraulic barrier (Emscher Formation; thickness up to 600 m; groundwater *aquifuge*),
- lower groundwater storey composed of the marly *limestones* (Cenomanian and Turonian) at the base of the clayey marlstones (thickness up to 300 m; aquifer).

In the Lower Rhine area located to the west, the geology of the overburden changes and the sediments of the Emscher Formation are pinching out. Instead, Permian and Tertiary strata were deposited. Lithologically and geohydraulically, the sedimentary overburden is generally subdivided into four distinct depositional successions (from top to base):

- upper groundwater storey at the top of the clayey *siltstones* (thickness up to 20 m; aquifer),
- clayey horizons (thickness up to 100 m; aquifuge),
- intercalations of aquifer and aquifuge layers from Triassic and Cretaceous strata (thickness up to 300 m; aquifer),
- Permian evaporites (thickness up to 200 m; aquifuge).

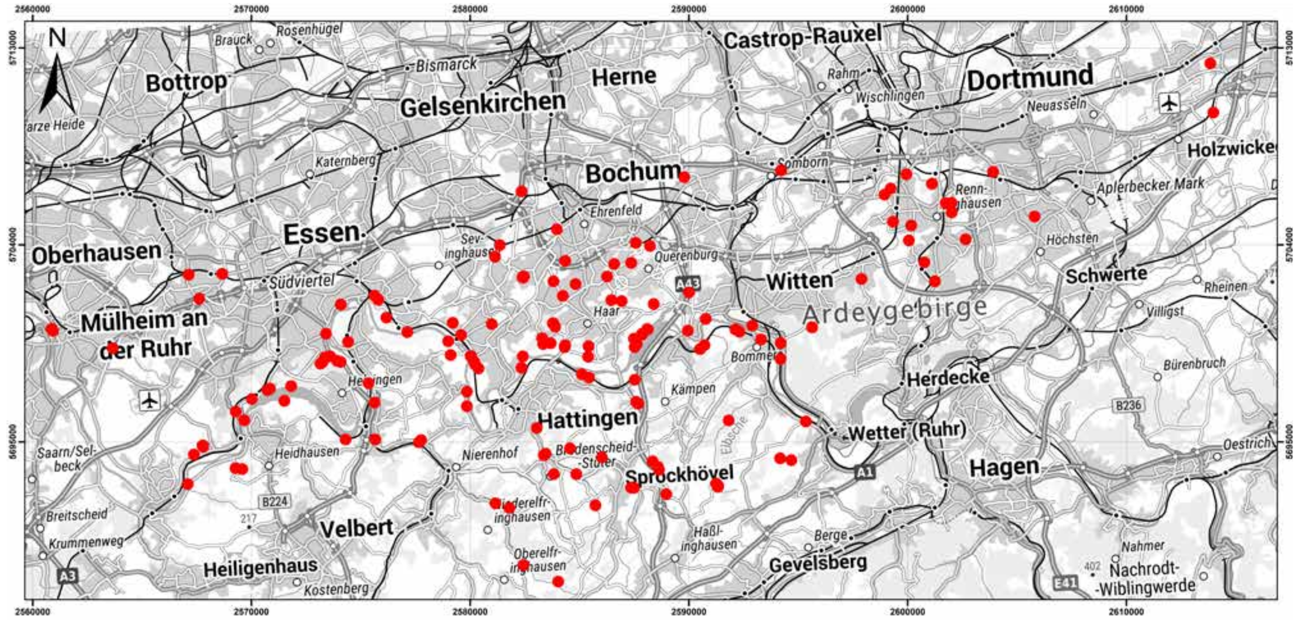


Fig. 27: Position of adit mine portals in the southern Ruhr mining region.

Fig. 28: Adit mine portals in the Ruhr mining region (left: Franziska Erbstollen, drainage adit [Witten]; centre: Vereinigte Pfingstblume [Bochum]; right: St. Johannes drainage adit [Witten]).

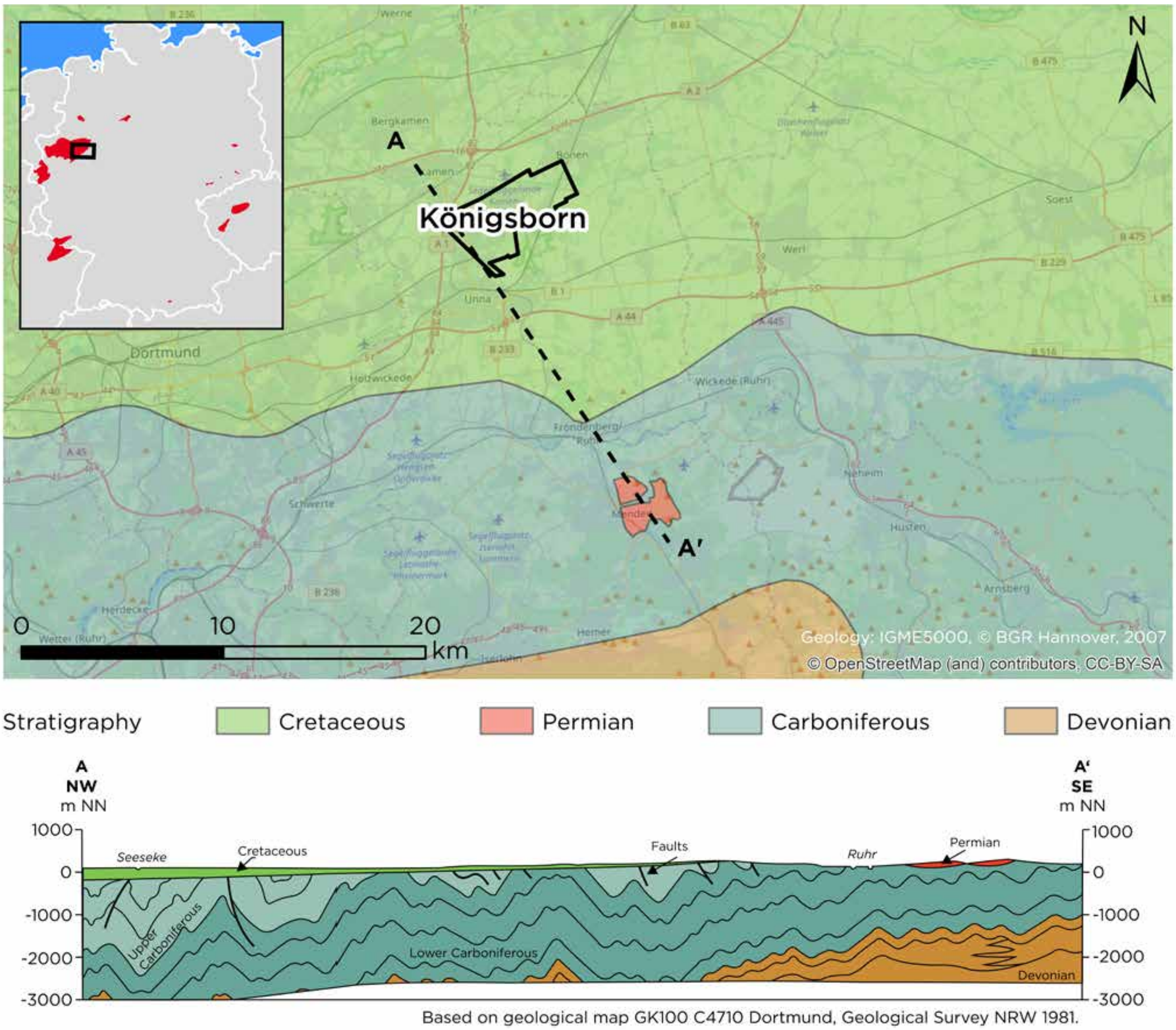


Fig. 29: Geographical and geological overview of Königsborn Colliery; geology according to Geologischer Dienst NRW (1981).

The hard-coal bearing rock was deposited during the Upper Carboniferous (323 – 299 million years ago; Drozdzewski et al. 1995; see info box 'Stratigraphy of Hard-Coal Deposits'). The strata consist of mostly clastic formations (sandstones, claystones and conglomerates) in which more than 200 hard-coal seams are intercalated. The Upper Carboniferous strata are separated at the top from the overburden by an angular unconformity. In the south of the Ruhr area – along a line passing through Mülheim, Essen, Bochum and Dortmund – the strata of the Upper Carboniferous crops out at the surface. The top of the hard-coal bearing Carboniferous beds are dipping with an inclination of 2° to 3° towards a north/northwest direction overlain by overburden strata. At the northern edge of the Ruhr area the Carboniferous strata are buried to a depth of approx. 1,000 m. Towards downdip the thickness of the overburden strata increases (Fig. 26).

Mining and Mine Water Managment

Hard-coal mining in the Ruhr area began as early as the 12th century in the Ruhr valley, i. e. the region where the Upper Carboniferous strata are exposed to the surface (Fig. 26). In this area hard coal was extracted by digging fault pits and cutting adits (Koetter 2001; Bluma et al. 2017). The mine water management was handled using dewatering adits for which drainage rights were often granted. A large number of these adits are still being used today for dewatering (Fig. 27 and Fig. 28; Melchers et al. 2016).

At the end of the 19th century, hard-coal mining moved towards the north, in the direction of the coal deposit, where increasing burial depth of the seams now required a change towards underground mining (Fig. 26). At that time, excavation was mostly done in the low dipping synclines in which the seams were deposited almost flat or slightly tilted. People and materials were now transported via shafts; these shafts nowadays are part of mine dewatering and are used partly for mine water pumping. For that purpose, the Ruhr coalfield was divided into different mine dewatering provinces.

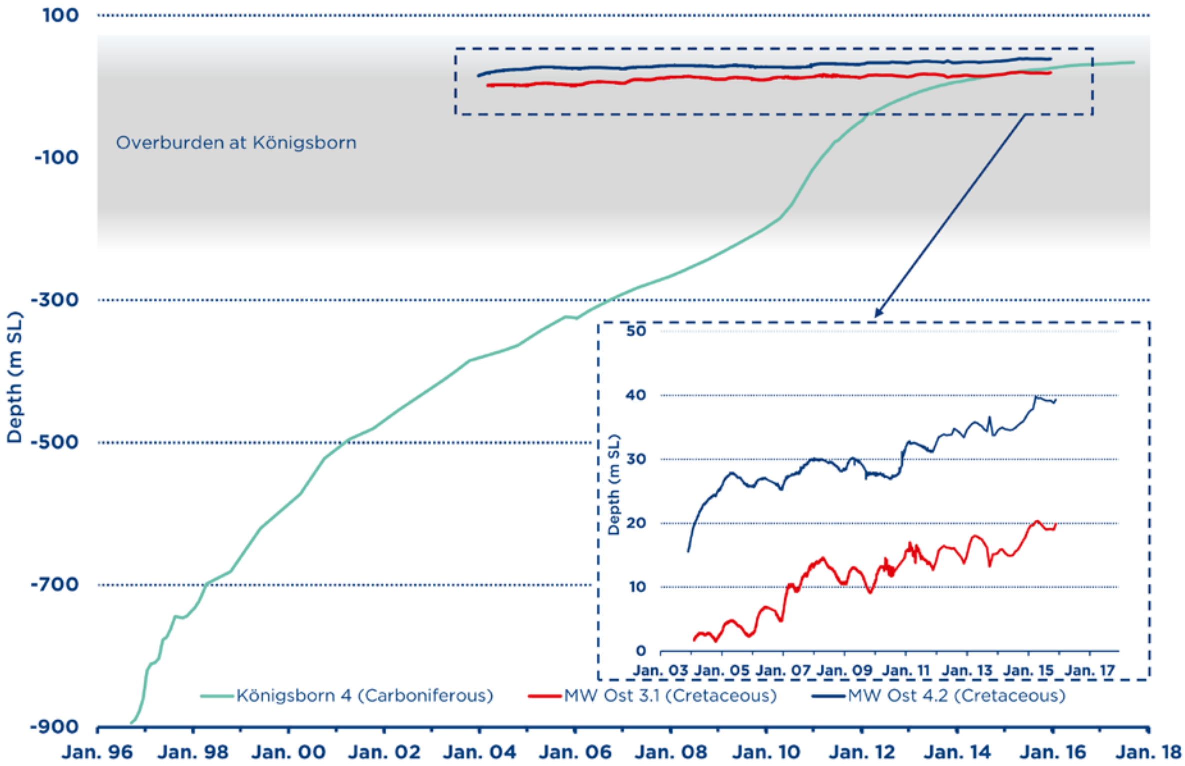


Fig. 30: Mine water rebound at shaft Königsborn 4, and groundwater levels in the Cretaceous carbonate related fractured 'joint type' aquifer; the groundwater monitoring wells (MW) Ost 3.1 and Ost 4.2 are situated north of Königsborn Colliery; data: RAG AG.

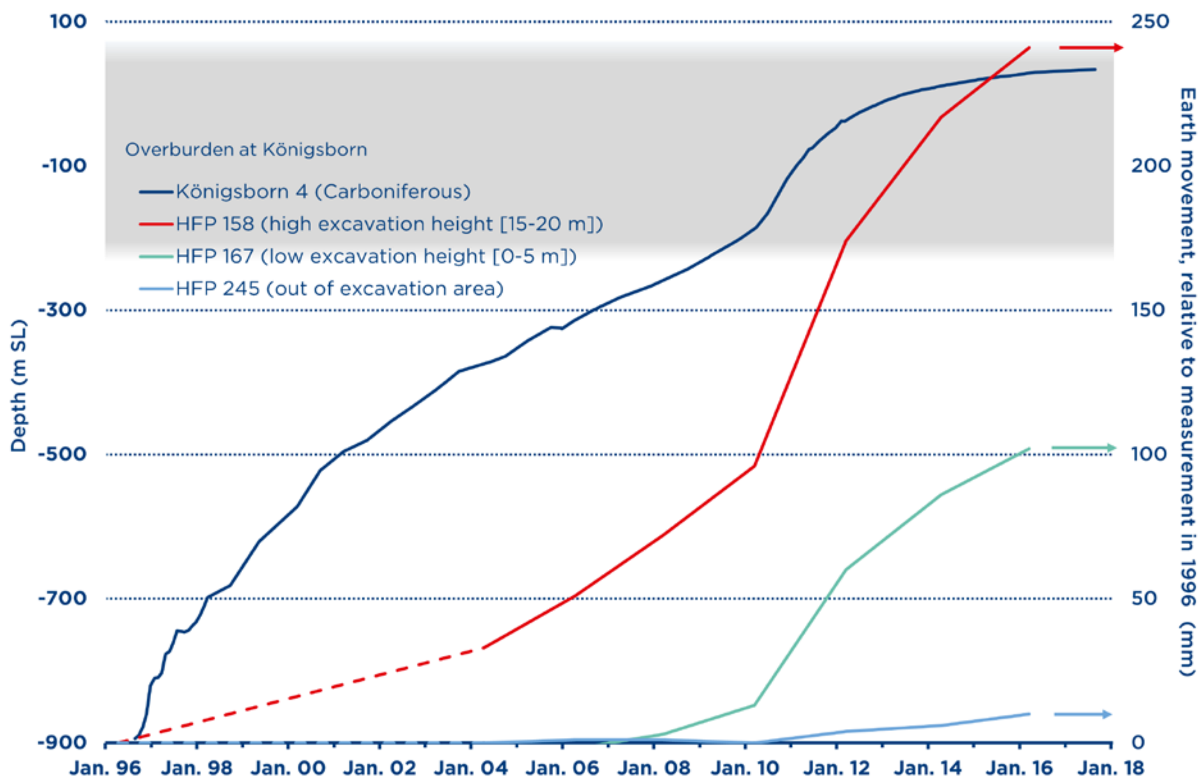


Fig. 31: Mine water rebound at shaft Königsborn 4 and plot of ground upheaval at the level control points HFP 158, HFP 167 and HFP 245, given in relation to the distance to the mine workings of Königsborn Colliery; data: RAG AG.

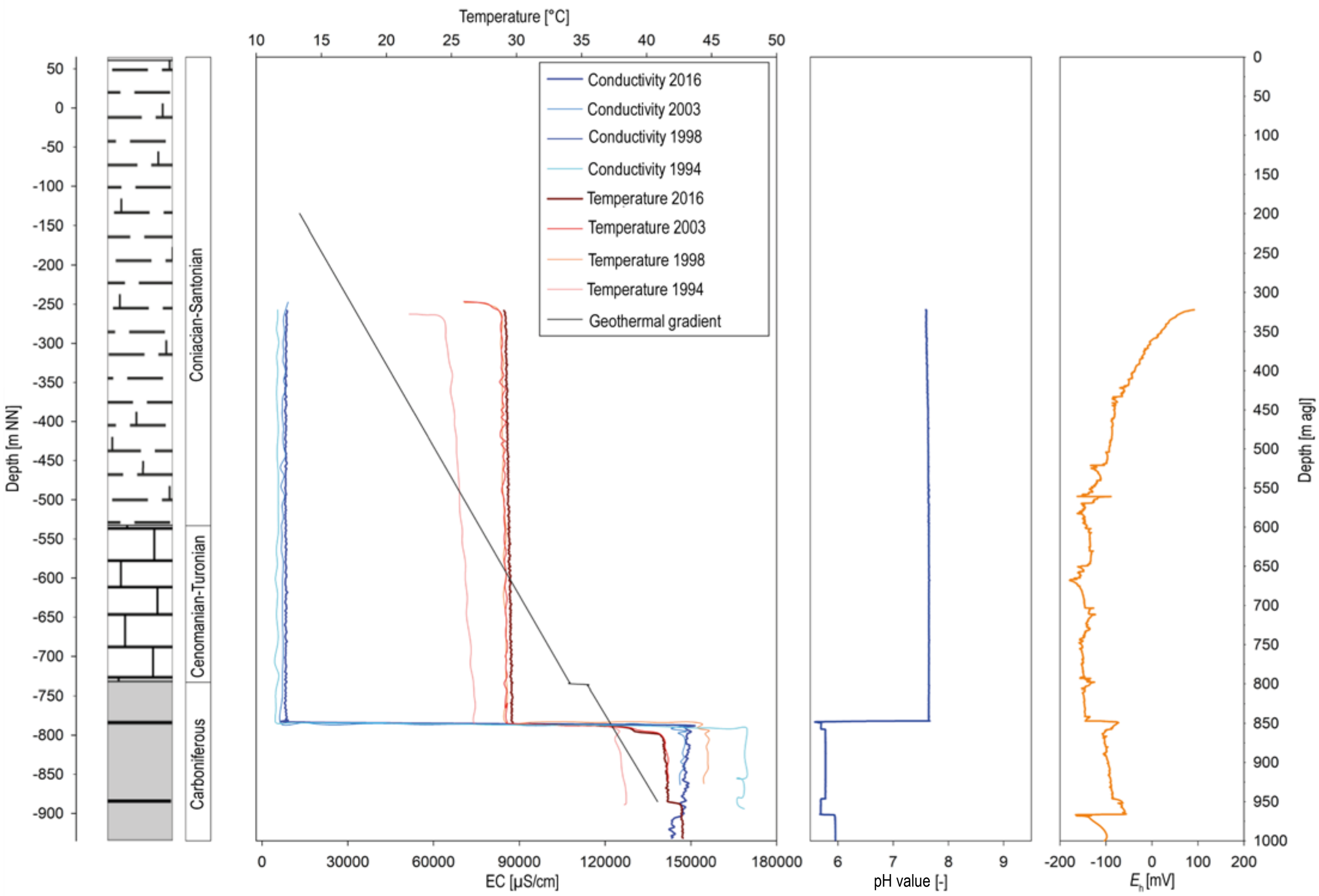


Fig. 32: Depth profile measurement at shaft Hermann 1, Melchers et al. (2019).

Only a few remaining shafts will continue the task of permanently regulating the future mine water level. In particular in the southern and the eastern part of the coal basin, mine water rebound has already taken place in several mines, including the collieries Königsborn (Unna; Fig. 29) and Westfalen (Ahlen; Fig. 35; Westermann et al. 2018). Contrary to the central mine dewatering of the Ruhr mining region, these collieries are hydraulically isolated. In the vicinity of these mines, for example, at Massen underground mining (Unna) or Maximilian Colliery (Hamm), the timing of the mine water rebound has not been documented (DMT GmbH 1994). However, there has been no evidence of ecological impact or damage to the infrastructure so far.

Mine Water Rebound

The following paragraph is looking at Königsborn Colliery as one example of a mine water rebound at a very advanced stage in the eastern Ruhr mining region (Fig. 29 and Fig. 30). Königsborn Colliery was closed down in 1981 while its mine dewatering was maintained until 1996. When discontinuing the mine dewatering at the lowest level, the mine water rebound was initiated. No regulatory alternatives, for example by providing pumps to control the mine water rebound, had and have been intended. Forecasts which were applied based on previous mine water rebounds in collieries nearby assumed that the mine water level would cease just underneath the ground surface (i.e. between +15 m NN and +65 m NN at a terrain elevation of +69 m NN; DMT GmbH 1994).

This mine water rebound is monitored in shaft Königsborn 4 and documented accordingly (Fig. 30). Both shallow and deep groundwater monitoring stations register hydraulic heads of the groundwater in the vicinity of Königsborn Colliery. After a rapid initial rise of the mine water, which inundated the levels of the largest water inflows, the rate of the mine water rise decreased and levelled off at values between 30 m/a and 40 m/a (intermediate stage). Between 2007 and 2009 the mine water reached the overburden aquifers. This inundation process of the overburden was associated with an increase of the mine water rebound velocity, at some points up to 100 m/a. The steep increase of the rebound velocity can be attributed to the decrease of the floodable void volumes. Since 2014, the mine water rebound has reached steady-state conditions (final stage); here, the mine water level was in line with the forecast (+31 m NN; DMT GmbH 1994).

The inundation of the overburden level meant that the hydraulic head of the fractured aquifer at the top increased (increase of the hydraulic potential) as, vice versa, the infiltration into the mine workings decreased (Fig. 30; DMT GmbH 2011). At the top of the Emscher Formation this 'hydraulic' influence was not recognised; only seasonal variations of precipitation were observed.

Flooding-Induced Ground Movements

Since 2004, ground movements in the vicinity of Königsborn Colliery have been measured and documented extensively, i. e. only after the mine water rebound was initiated in 1996 (Fig. 31). The review of the measurements exhibited that ground upheaval started to occur in 2000, i. e. approx. four years after the mine dewatering was discontinued. The reason for this delay of the ground upheaval on the surface is explained with compensation of remaining mining induced subsidence by upheaval related to mine water rebound during its initial stage (Schäfer 2016). The rock mass which is loosened by mining activities is compressed by the hydrostatic pressure generated during the mine water rebound. Only after this compaction has taken place, the extensional strain can be traced at the ground surface (Rosner et al. 2014).

The amount of ground upheaval correlates with the rise pattern of mine water rebound. Experience gained so far shows that once the mine water rebound reaches the base of the overburden, the amount of ground upheaval increases. The extensional processes within the hard-coal bearing rock will be amplified due to similar processes in the overburden. This results in an increase of the total upheaval movements on the surface (Bekendam 2017). The ground upheaval documented so far at the Königsborn site is 0.25 m maximum; no irregular upheaval differences have been revealed so far, and no damage to buildings has been observed, either. Comparable observations of the course and the amount of ground movement have been made in other mining regions, too (e. g. Aachen [Germany] and South Limburg [Netherlands] in Rosner 2011; Saar [Germany] in Schäfer 2016; Belgium in Vervoort & Declercq 2018).

Stratification in Inundated Shafts

In a large number of shafts which belong to abandoned and inundated mines, stratifications are formed between waters of higher and lower salinity (Ch. 2.5.). One site where this stratification exists are the Hermann Shafts in the city of Selm (Ruhr area). The Hermann shafts are located at the north-western border of the Ruhr area and thus are situated outside the catchment area of the active mine dewatering. After a review of available documents it was stated that in these shafts a rebound occurred since 1929 (Melchers et al. 2019). A monitoring campaign undertaken by Coldewey et al. (1999) recorded a stratification in the waterbody of the Hermann shafts for the first time. The current sampling campaigns described in Melchers et al. (2019) confirm the observations made in the first campaign (Fig. 32). Comparable results were also measured at shaft Königsborn 4 situated in the city of Unna and, for the first time, in the Saar area. These investigations provide evidence that the examined stratifications are stable in time and space according to the current state of knowledge.

Conclusion

The mine water rebound has already significantly progressed in some hydraulically isolated mines in the easternmost Ruhr mining region (Königsborn Colliery [Unna], Westfalen Colliery [Ahlen]). The overburden has been inundated.

There is a positive correlation between the pattern of mine water rebound and occurrences of upheaval at the surface; accordingly, there is an interdependency between the rate of mine water rebound and the amount of upheaval at the surface.

The amount of upheaval caused by a mine water rebound can exhibit up to decimetre-scale heights; as long as the ground upheaval takes place in a continuous and conformable area-wide fashion, they will not result in major discontinuities, shear or compressional stresses (Heydenreich 1970).

In water columns of accessible shafts the phenomenon of density stratification occurred. It was proven that this stratification is stable regarding its positioning over a long period of time (Melchers et al. 2019). This stratification physically separates the top water body of lower solute concentration from the bottom water body of higher solute concentration (i. e. salinity).

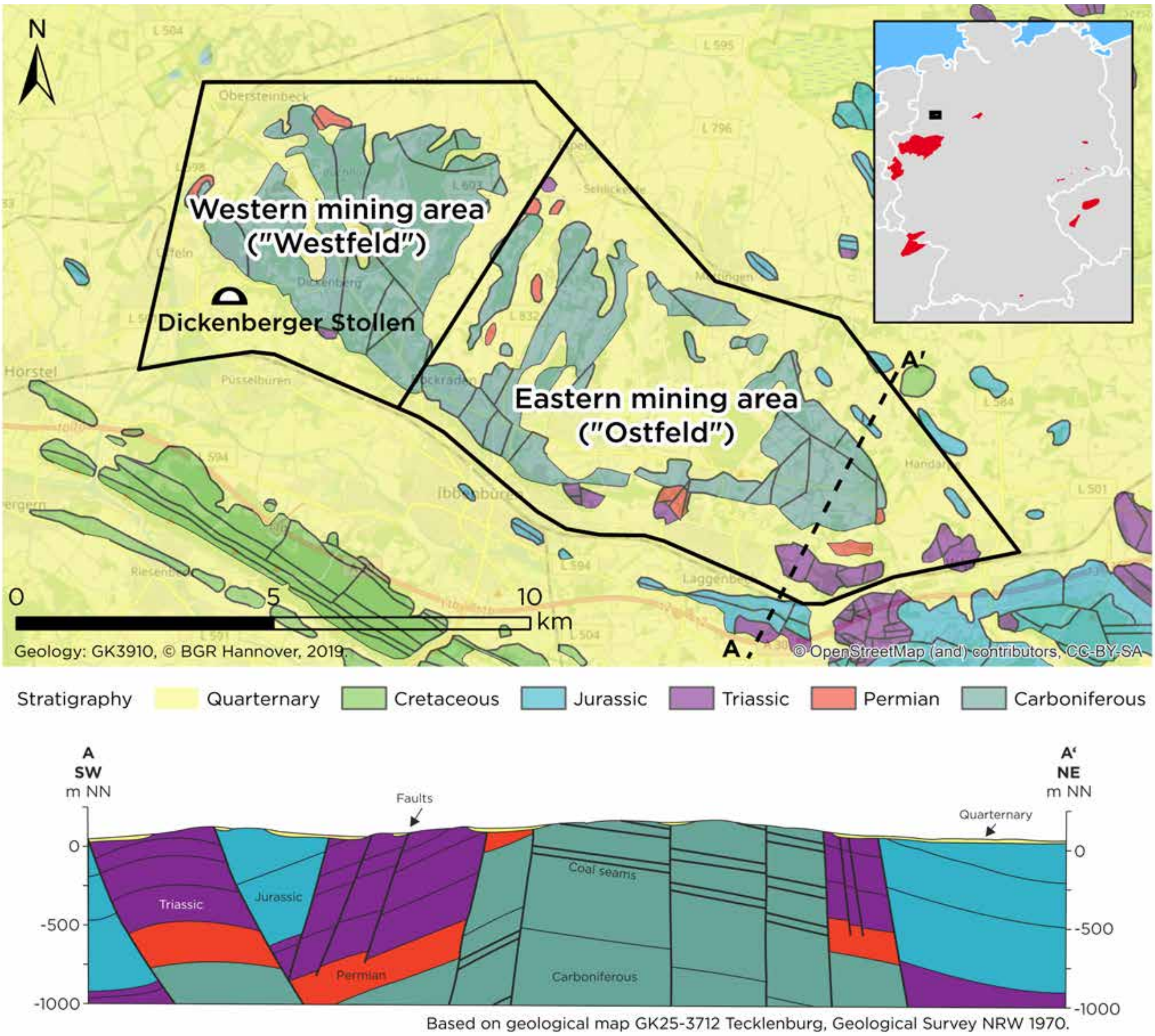


Fig. 33: Geological map and cross section of Ibbenbüren Colliery; geology according to Geological Survey of North Rhine-Westphalia; Geologischer Dienst NRW (1970).

3.1.2. Ibbenbüren

The hard-coal mining in the Osnabrück region has experienced a long history of more than 500 years (Röhrs 1998). Ibbenbüren Colliery was the most northern colliery in Germany and one of the last two mines where hard-coal extraction was ceased in 2018 (Fig. 25). At three spots, the strata of the Upper Carboniferous outcrop at the surface: i. e. the hills of Schafberg, Piesberg and Hüggel, forming a *Carboniferous horst* structure which surmounts the surrounding lowlands by more than 100 m.

Geology and Hydrogeology

The Carboniferous horst structure is bounded to their sites by faults of separating it from the Mesozoic era surrounding strata (Lotze et al. 1962; Keller 1968; Bässler 1970; see info box on 'Stratigraphy of Hard-Coal Deposits'). The uplift of the horst block took place at the end of Cretaceous period. The hard-coal deposit is not overlain by any overburden; Hydrologically, that means that the major amount of precipitation water can seep into the mine workings without significant delay.

A Quarternary (upper) aquifer with a thickness of only a few metres is not present with extensive coverage (Lotze et al. 1962). In Upper Carboniferous coal-bearing strata, it is mostly the mining-impacted sandstone layers which significantly conduct water.

Mining and Mine Water Management

Strike-slip faulting led to a threefold division of the Ibbenbüren coalfield. The three compartments from west to east are: Westfeld (i. e. Western Field and hill of Dickenberg), Bockradener Graben and Ostfeld (i. e. Eastern field and hill of Schafberg; Fig. 33; Lotze et al. 1962). Whereas hard-coal extraction in the Westfeld has ceased as early as the 1970s, the hard coal was mined in the Ostfeld

Fig. 34: Dickenberger Stollen (left: view into the adit; right: sough, photos: Bastian Reker).

until the end of 2018. The Westfeld mine water is discharged via the Dickenberger Stollen (Fig. 34; Goerke-Mallet 2000). Current planning intends to permanently discharge the Ostfeld related mine water in the future via a 'mine water canal' – that still needs to be cut – and via the existing dewatering adit (Ch. 1.2.).

The Westfeld mine dewatering of Ibbenbüren Colliery was discontinued in 1979. Forecasts predicted the duration of the mine water rebound to take approx. 150 days (Goerke-Mallet 2000). However, it took three years until the mine water dewatered at the level of the Dickenberger Stollen. Compared to other mine water rebounds, this rebound of Ibbenbüren Colliery took a rather short period of time (Fig. 35): due to high inflows of water into the mine workings the mine water rose very rapidly in the first year after the mine dewatering had been discontinued (> 400 m/a).

Hydrochemical Development

Initially, the mine water discharge into the Dickenberger Stollen was indicated by high concentrations of iron (up to 1,000 mg/L) and sulphate (up to 4,400 mg/L; Fig. 36; DMT GmbH 2017). Over time, these concentrations of iron and sulphate were reduced due to increased dilution of the products from pyrite oxidation (see info box on 'First Flush Effect'). As the concentrations of iron and sulphate are still at an elevated level and exceed the thresholds for discharging waters, the mine water needs to be treated before it can be discharged into the receiving water courses.

Conclusion

In order to estimate the time when the mine water enters other parts of the mine workings or reaches the ground surface, it is necessary to know the spatio-temporal behaviour of the mine water rebound as exactly as possible. This also helps to determine the deadline for completing the treatment plants or drainage systems required. In many cases, however, forecasts on the probable duration of previous mine water rebounds stated periods that were too short; possible deviations occur due to simplified assumptions or insufficient input data on which the forecasts were based. Moreover, the forecasts often considered a worst-case scenario focusing on the protection of the underground works and the health of people working there: this worst-case scenario helped to early identify and implement controlling and monitoring instalments needed to secure the underground mine workings.

In the case of Ibbenbüren Colliery, several factors were taken into account which might help explain the underestimated forecast for the mine water rebound in the abandoned mining area of the Westfeld. The main reason might have been the parameter of the floodable void volume which was only insufficiently recorded (Goerke-Mallet 2000); for example, the forecast did not

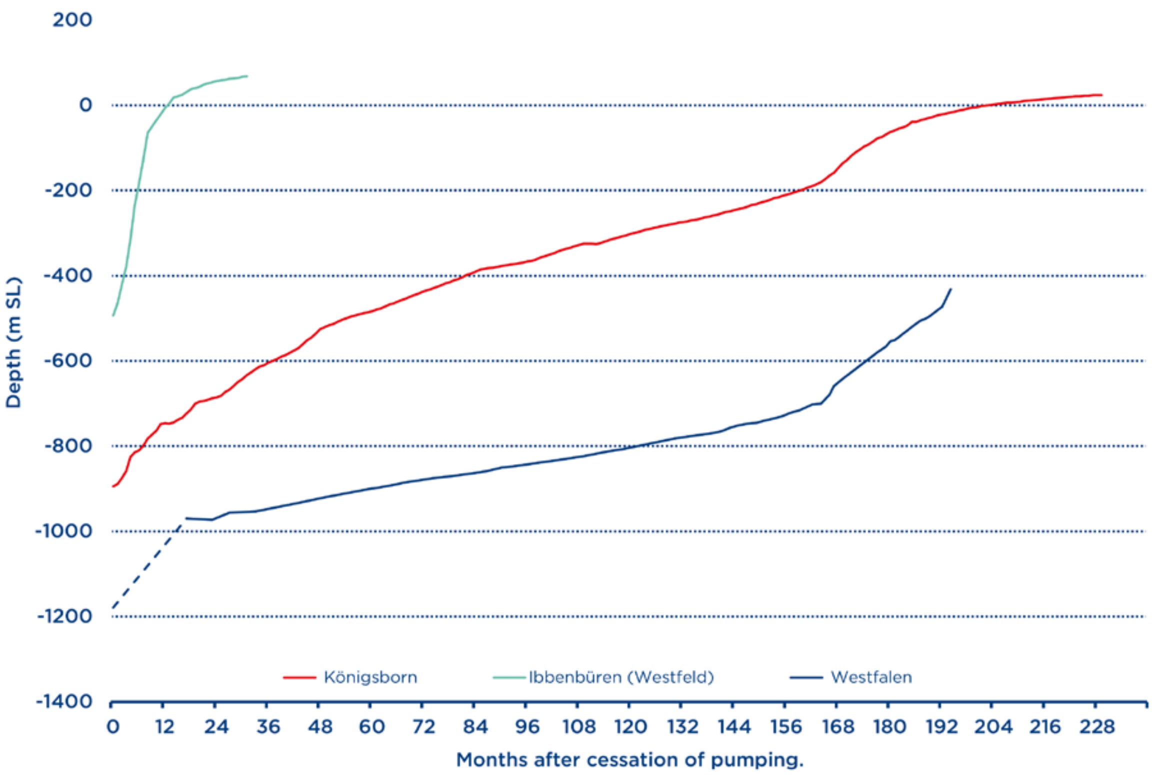


Fig. 35: Mine water rebounds in the collieries Westfalen and Königsborn and in the Westfeld of Ibbenbüren Colliery, Westermann et al. (2018).

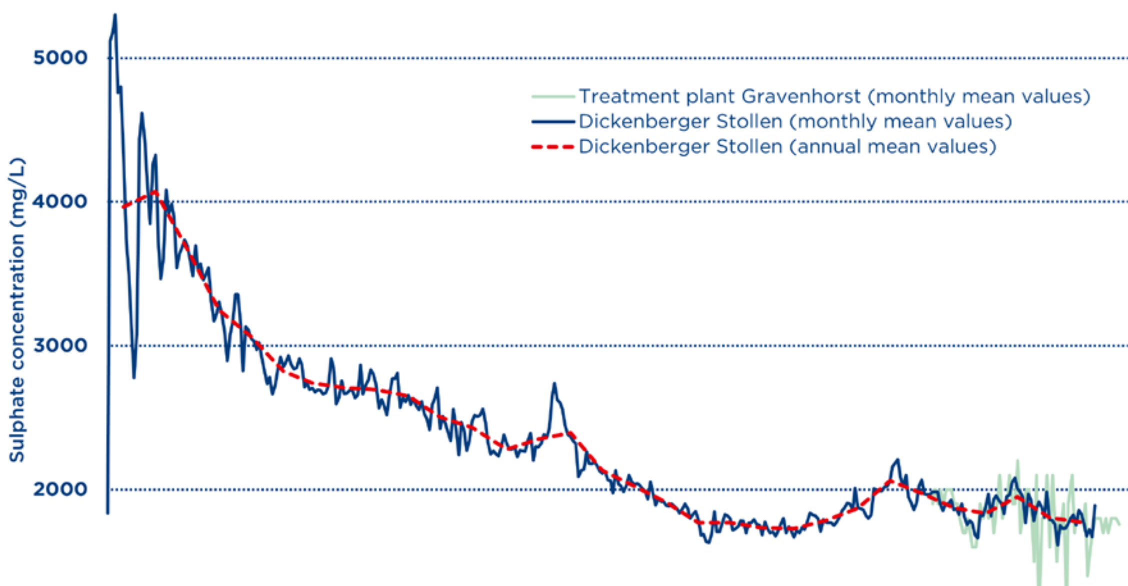


Fig. 36: Sulphate concentrations in the mine water of Ibbenbüren Colliery (Westfeld), data: RAG Anthrazit Ibbenbüren GmbH.

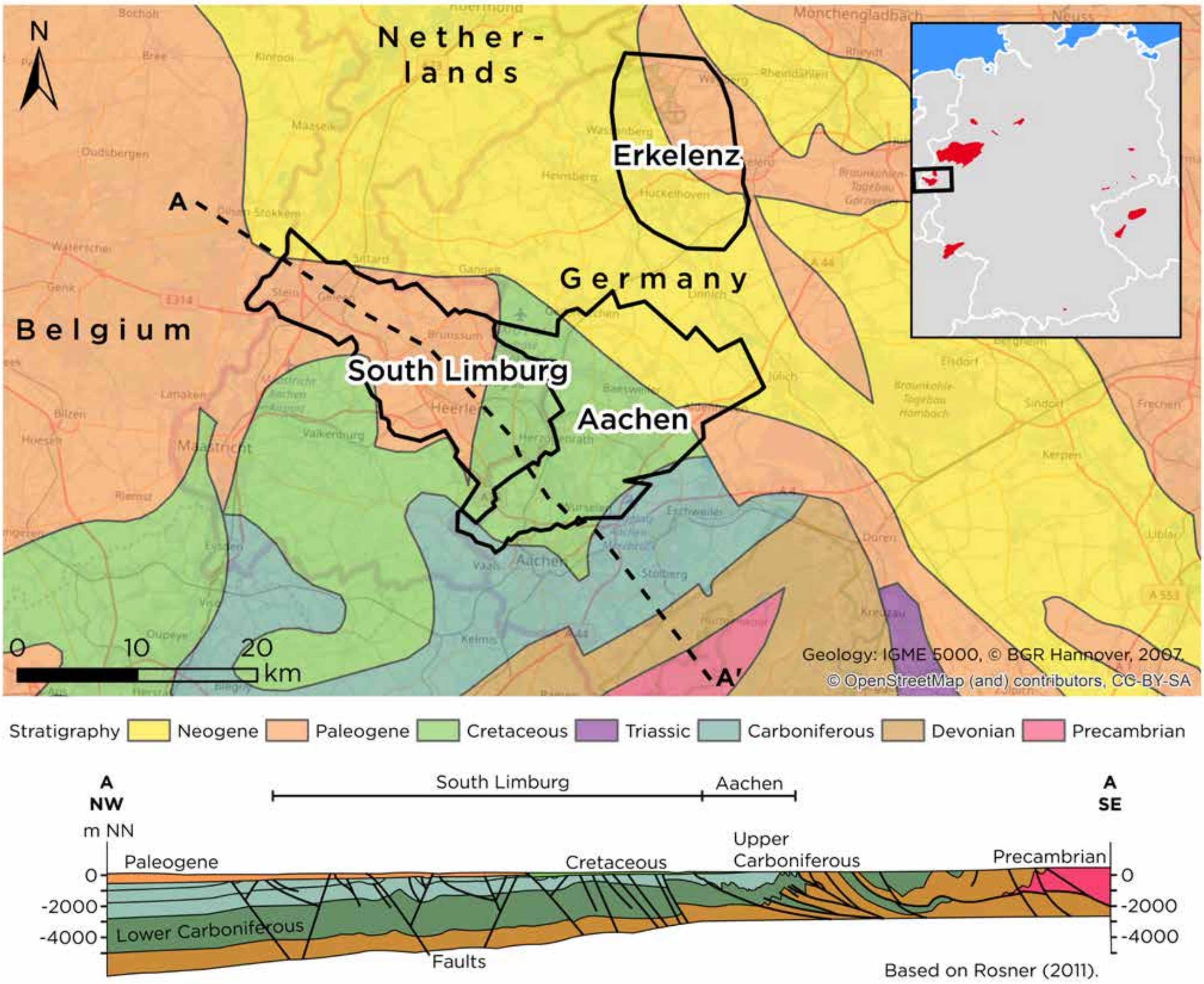


Fig. 37: Geographical and geological overview of the hard-coal coalfields of Aachen, Erkelenz (both in Germany) and South Limburg (Netherlands). Geology according to Asch (2005); geological section and mining fields according to Rosner (2011).

consider the floodable geogenic void volume of the pores and joints. Other factors contributed as well to the fact that forecasts often could only give poor approximation of the actual course of the mine water rebound; these factors included e. g. inadequate balancing of inflow and outflow rates over space and time.

3.1.3. Aachen, Erkelenz and South Limburg

The coalfield of Aachen and South Limburg consists of a cross-border hard-coal deposit between Germany and the Netherlands; this coalfield represents an extensively covered hydraulic system underground (Fig. 25). Only 10 km north-east from the Aachen mining region, the Erkelenz coalfield is situated. The Aachen mining region was closed down in the 1990s after almost 800 years of mining, and thus it is the oldest hard-coal mining region in Germany (Büttgenbach 1898).

Geology and Hydrogeology

The Aachen and South Limburg coalfield is part of the western extension of the European Carboniferous hard-coal belt (Fig. 37). The coal-bearing strata of the Upper Carboniferous outcrop in the Aachen area in the valleys of the rivers Wurm and Inde (Walter 2010; Rosner 2011). The coal-bearing strata dip towards the north-west overlain by an increasing overburden. The overburden consists of a sedimentary succession of Tertiary marine aquifer sediments and aquifuge sediments in which lignite deposits are found at the top (see info box on 'Stratigraphy of Hard-Coal Deposits'). South-west of the Heerlerheider Sprung, i. e. a prominent normal fault, the overburden is composed of Cretaceous sediments (Fig. 37).

The border fault of the Rur (a river near Erkelenz, not to be confused with the river Ruhr) separates the Erkelenz coalfield from the Aachen coalfield to the south. Thus, geologically speaking, the Erkelenz coalfield is defined as an isolated coalfield; the coal-bearing Upper Carboniferous strata are covered by an overburden thickness of 150 – 350 m.

Fig. 38: Damage on buildings caused by mine water rebound in the Erkelenz hard-coal mining region (photos: Volker Baglikow).

Mining and Mine Water Management

Hard-coal extraction in Aachen began around 800 years ago in the valley of the river Wurm in which the coal-bearing strata of the Upper Carboniferous crops out; from there, mining moved towards the northwest (Büttgenbach 1898), and copious underground roadways link the Aachen mining region with that of the collieries across the border.

In South Limburg, hard-coal mining, like in the Aachen area, commenced as early as the 12th century and ceased in the 1970s (Walter 2010; Heitfeld et al. 2017). However, in order to protect the still active collieries on the German side, the mine dewatering in the South Limburg collieries had to be maintained until the early 1990s. In addition, water dams protected against unwanted water transitions. Only after the hard-coal mining was decommissioned in the Aachen mining region by finally closing down Emil Mayrisch Colliery in 1992, the mine dewatering was completely terminated. The mine closures continued in the Erkelenz mining region when Sophia-Jacoba Colliery was discontinued in 1997 together with the mine dewatering process.

A comprehensive description and analysis of the mine water rebound processes in the Aachen and South Limburg mining region can be found in Rosner (2011). According to this, the mine water rebound occurred in two separate water provinces and at discrete time intervals. In the western (Dutch) water province, after the mine closure, the mine water rebound occurred stepwise until it reached certain water overflows into the eastern water province on the German side. The Dutch mine dewatering was continued until 1994 in order to protect the active mines in the east (‘protective mine drainage’). After the last colliery in South Limburg was closed, a controlled mine water rebound took place stepwise (at a mean value of 20 m). Several pumping tests resulted in a profound insight into the hydraulic system. In the eastern water province, no regulation measures (pumping) were intended as part of the mine water rebound – contrary to the Dutch water province. The final operation plan for decommissioning the Aachen mining activities envisages a rise of the mine water until it reaches the level of the natural receiving water course, i. e. the river Wurm (+110 m NN up to +140 m NN; Rosner 2011; Heitfeld et al. 2017). Presumably, this level will ultimately be reached only in the 2030s. There has been no evidence so far of adverse effects on the receiving water courses or the groundwater conditions in the overburden.

Ground Movements Induced by the Mine Water Rebound

In the Erkelenz mining region, mine dewatering was ceased in 1997. During the period from 1997 to 1998 the mine water level was not measured. That was only done from 1998 onwards so that the mine water rebound in the lower mine levels was not documented. Later on, a continuous and steady mine water rebound took place. Most notably Baglikow (2003; 2010) has investigated the mine water rebound in the Erkelenz mining region focussing his observations on the water rebound-induced ground upheaval.

During his investigation he recognised that the ground upheaval occurred along a 9 km long corridor in between the cities of Wassenberg and Hückelhoven, causing a number of damages to buildings (Fig. 38). The reason for those can be linked to differential upheaval at the main Rurrand fault which was partly reactivated during the mine water rebound. Baglikow saw the continual linear development of the infrastructural damage as an indicator of rebound-induced damages. According to the current state of knowledge, these ground movements are still going on (3 mm/a; Baglikow 2019).

Analysing actual claims Baglikow (2003; 2010) observed that the very first building damages occurred already during the mine water rebound 'stage' within the Upper Carboniferous strata and not, as initially assumed, during the water rise in the overburden at a later period of time. Although levelling surveys during that period are missing, temporal assignment of the damages was possible due to discrete monitoring of damage progression. Baglikow (2010) was further able to prove that these damages do not only occur in areas in which mining-induced fault lines exist at the ground surface, but also away from the documented discontinuities and outside the mining-induced catchment area. This insight was new also to the studies of mining damage and led to an extension of the area to be analysed.

For the South Limburg hard-coal area (Netherlands) De Vent and Roest described several mining related cases of damages to residential buildings and a shopping centre in 2012. The types of damages can also be linked to differential ground movements. Moreover, the building damages were situated at documented *terraces* which correspond to previously superimposed boundaries of mined areas. De Vent and Roest assume that these differential ground movements at the terraces were reactivated by the mine water rebound in the region (De Vent & Roest 2012). Contrary to the original assumption that, like in the Erkelenz mining region (see above), substantial mining damage is invariably located at tectonic elements, hydraulic pressure differences related to mining may also effect ground upheaval which cause relevant mining damage. De Vent & Roest (2012) explained that the damage to the shopping centre is caused by mine water rebound which may have mobilised unconsolidated sediments in the rock strata which then entered Karst cavities or mine workings through joints and fractures. Presumably, this displacement of material caused a trough like subsidence structure at the ground surface and, consequently, a *surface collapse*. This assumed causal link demonstrates that, in rare occasions, a mine water rebound might lead to directly associated ground upheaval and subsequently to mining damage, but can also trigger complex interdependencies of hydrogeological and mining site related factors which might induce mining damage.

In the recent past, evidence could be found at one location on the German site of the Aachen mining district that a mining induced terrace was reactivated as part of the regional mine water rebound (Baglikow 2019).

Conclusion

In the cases cited above, the damages were linked to large-scale tectonic structures or to mining-related boundaries where, during the mine water rebound, differential ground upheaval did occur. Generally, however, the probability that discrete ground movements will occur is estimated as rather low. But where those actually occur, an increased risk of damage to buildings has to be assumed.

Monitoring of future mine water rebounds needs to focus on critical areas. These areas need to be defined with regards to the potential use of the ground surface and to the susceptibility to damage of the structures in place (buildings, infrastructure). Such critical areas are characterised by the following properties (Schetelig et al. 2007; Rosner et al. 2014; Heitfeld et al. 2017):

- The mining is limited by a main tectonic fault.
- The tectonic fault zone must be hydraulically sealing.
- The ruptured rock fabric along the tectonic fault stretches into the overburden.
- The excavation is only done at one side of the tectonic fault.
- The mine water rebound leads to a unilateral increase or even a counteracting opposite development of the hydraulic heads in the overlying aquifer within the overburden.
- The overburden needs to exhibit a high strain potential.

Hence, it is possible to assess the risk of damage in the particularly critical areas before a mine water rebound is initiated and to confine the critical area. Baglikow's (2003; 2010)

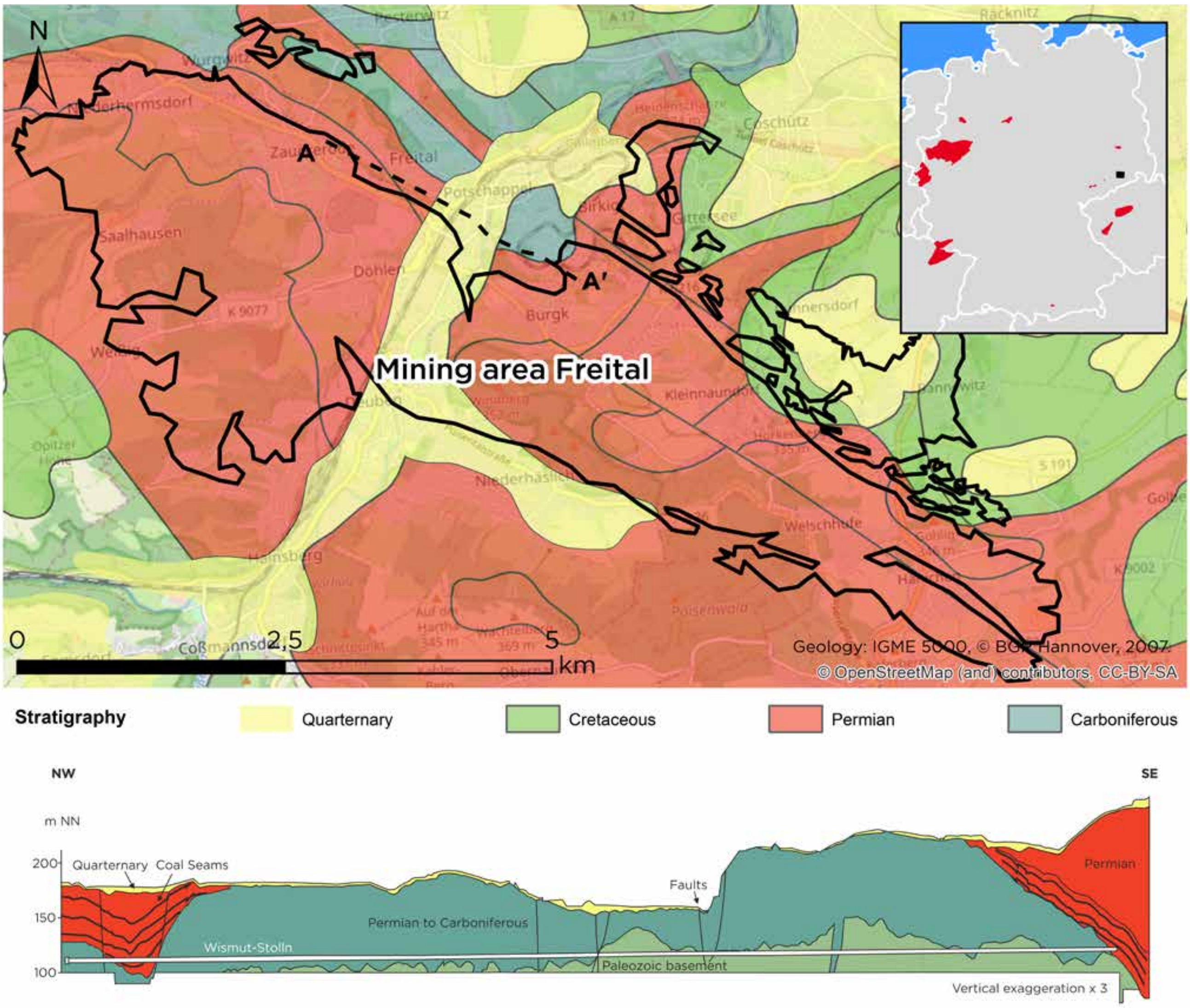


Fig. 39: Geographical and geological overview of the Döhlen basin; geology according to Asch (2005); mining fields according to Wismut GmbH.

investigations show the temporal development and the spatial extension of damages related to mining-induced ground upheaval. Therefore, the ground movements need to be continuously monitored at the beginning of the mine water rebound (i.e. immediately after the mine dewatering has ceased or, even better, before it has ceased), and needs to be extended beyond the mining-induced catchment area. It is recommended that this process is being supported by adding satellite-aided data to the monitoring of ground movements (Busch 2019).

3.1.4. Döhlen basin

Since 1991, the federal Wismut GmbH has been remediating the legacy of uranium mining left by the former Soviet-German stock company (SDAG) Wismut in the federal states of Thuringia and Saxony. In the vicinity of the city of Dresden, hard coal had been excavated in underground mining in the Döhlen basin from the 16th century until 1989 without any interruption (Fig. 25). Between 1949 and 1954 as well as between 1963 and 1989, with interruptions, hard coal containing uranium was mined (Reichel & Schauer 2007).

When these mining activities were discontinued in 1989, concepts were developed for the safekeeping of the mine. One key element of the remediation of the site Dresden-Gittersee was the decommissioning of the mine dewatering and the permanent discharge of the mine water into the river Elbe by means of the adit Tiefer Elbstollen.

This mine water rebound occurred in different stages and was successfully completed with the transition into the newly opened Wismut Stollen in October 2014. During the mine water rebound it was recognised that the actual capacity of the mining voids to receive and conduct water was lower than initially expected.

Geology and Hydrogeology

The Döhlen basin is a Late Palaeozoic sedimentary basin era (Molasse) in

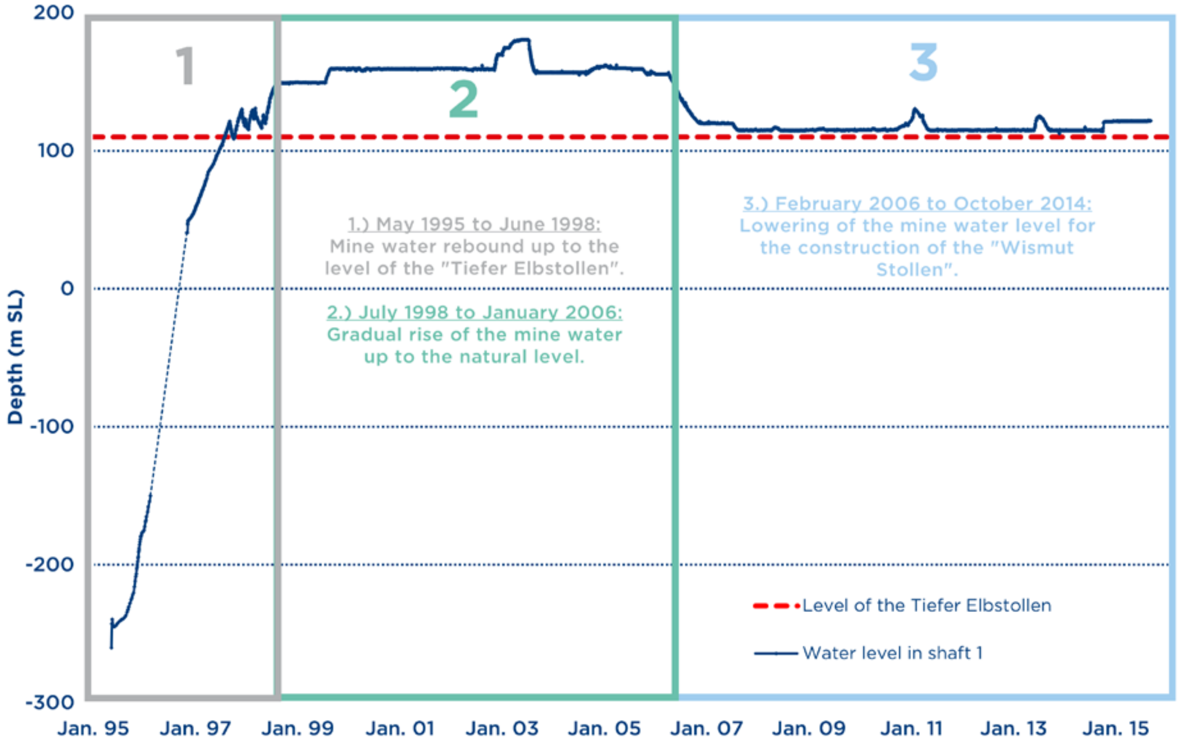


Fig. 40: Development of the mine water rebound in the Burgk mining region, mining field Gittersee Döhlen basin; data: Wismut GmbH.

the vicinity of the so-called Elbezone, a part of the NW-SE striking Elbe lineament (Reichel & Schauer 2007). The rift-related ore deposit was formed by *volcanogenic tectonic* processes during the Permian-Carboniferous (see info box on 'Stratigraphy of Hard-Coal Deposits'). Essentially, the Döhlen basin is filled with *terrigeneous sediments* with a high proportion of *pyroclastics* (Pälchen & Walter 2011; Franke 2019). The sediment strata deposited within the Döhlen basin is up to 800 m thick.

Mining and Mine Dewatering

Coal was mined in the Döhlen basin in the mining districts of Zaukerode and Burgk; these two mining regions are confined from each other by the river Weißeritz (Fig. 39). In the mining region Zaukerode, west of the Weißeritz, mining was finally abandoned in 1959, and the mine water rebound was initiated; since then, the mine water has been discharged via the adit Tiefer Elbstollen.

The mining region Burgk, east of the Weißeritz, consists of the coalfields Gittersee, Bannewitz and Heidenschanze. There, hard coal containing uranium was mined until 1989. Although roadways cut for mining purposes and connecting the mining regions Zaukerode and Burgk have been documented in the mine charts, nothing is known about their condition.

Mine Water Rebound

Between 1991 and 2014 Wismut GmbH kept the mine workings in the Döhlen basin safe in an environmentally compatible and sustainable manner (Mann & Wedekind 2015; Goerke-Mallet et al. 2016). The mine water rebound concept was developed in the early 1990s; this concept envisaged that the mine water from the areas east and west of the river Weißeritz should flow jointly and naturally from the mine workings and the disturbed area of the rock mass to the existing adit Tiefer Elbstollen. Whereas the western mining region Zaukerode had been discharged via Tiefer Elbstollen and its connected *lateral drifts* since the mine dewatering ceased in the 1960s, the mine water in the eastern coalfields was supposed to be kept at a level above that of Tiefer Elbstollen, close to the ground surface.

The mine water rebound in the collieries of the Döhlen basin began in 1995 (Fig. 40). This process was accompanied by an extensive monitoring programme which included a continuous monitoring of the mine water level. In summer 1997, the mine water level reached the level of Tiefer Elbstollen (+110 m NN). In order to stimulate the water flow paths in the mine workings, the water level was raised slightly several times by pulsation and subsequently lowered again by pumping over the following months.

In summer 1998 to the rebound reached a level of +150 m NN (Fig. 40). The mine water level was kept stable at that level for one year by pumping. Despite the rising mine water level, the outflow volume at the discharge of Tiefer Elbstollen remained the same. In summer 1990, the mine water level reached the level of +160 m NN and was kept at that level until the end of 2002. It became increasingly obvious that Tiefer Elbstollen only discharged a part of the additional mine waters incurred, and that it was not possible to discharge the complete mine waters of all mining regions via Tiefer Elbstollen.

In collaboration with the responsible authorities, Wismut GmbH developed a concept of how the rebound in the Döhlen basin could proceed.

This concept envisaged the restoration of the original hydrogeological conditions in the Döhlen basin at large by letting the mine water level rise up to the top aquifer horizon at a level of approx. +180 m NN.

In summer 2003, water logging and soil wetness induced by mine water, which at that time was at a level of +180.5 m NN, were identified at the ground surface. As a consequence, Wismut GmbH reduced the water level by pumping to +160 m NN which resulted in drying out of the water loggings. In conclusion, the natural discharge at a level of +180 m NN turned out to be impossible.

Therefore, Wismut GmbH came back to an earlier plan which anticipated the crosscutting of connecting mine openings (the drift Wismut Stollen) at an elevation of approx. +120 m NN. Wismut Stollen connects the mine workings of Gittersee with Tiefer Elbstollen, thus creating a sufficient water flow path to ensure a safe and sustainable discharge of the mine waters into the river Elbe. The approx. 3 km length of Wismut Stollen was driven between April 2007 and June 2014. After the drivage was done and the pumps were switched off, the mine water rose to a level of +121 m NN. Since then, the mine water of the eastern coalfields has been properly discharged into the river Elbe using both pathways, Wismut Stollen and Tiefer Elbstollen. Hence, the underground mine workings in the Döhlen basin are regarded as properly and environmentally safeguarded.

During the mine water rebound, only minor vertical ground movements of approx. 6 cm were documented (Tunger 2009; Mann & Wedekind 2010; Mann & Wedekind 2015). In 2009 Tunger reported that any rebound-induced mining damage would not occur at new buildings, but was only related to buildings that had already been previously damaged by mining activities of the past.

Conclusion

Since the early 1990s, concepts for the safekeeping of the collieries in the Döhlen basin had been developed and implemented by consulting external experts (USAKO 1991; 1993). The final concept already encompassed planning options ('backups') which had also been checked for their economics and technical feasibility; if the initial concept would not be successful.

A specialist view advocates the aim to achieve a sustainable mine water level. The mine water rebound was approved by the authorities and then implemented step by step until the level of the natural receiving water course was reached. This process was regarded as a controlled process due to a number of factors: the provision of backup variants; extensive monitoring, and the fact that the mine water level was accessible at any time. According to the current state of knowledge, this was the first time such a controlled process was implemented at a mine water rebound in a German colliery.

Considering the underground water flow paths it has to be noted that the capacity of old mine workings to receive and conduct water needs to be investigated with particular intensity and scrutiny. As experiences have observed, attempts to refill water are rather not suitable for that purpose.

How water volumes can be discharged in abandoned mines needs to be assessed obtaining all information available. Besides the analysis of the *mine plan* the results of e. g. on-site visit of open mine workings are also of special relevance. Historical documents research may also provide relevant information. In this case, it can be assumed that mud avalanches which occurred as part of the river Weißeritz floods in 1897 had significantly impacted the hydraulic conditions in parts of the mine workings. As Wolkersdorfer & Bowell (2004) were able to demonstrate using the example of the mine water flood in Nassereith (Tyrol, Austria), any neglected information cited above can lead to mine water inrushes in abandoned yet open mines which may be of disastrous consequences. The same can be applied to the mine water flood during the mine water rebound in the tin mine Wheal Jane (Devonshire, United Kingdom) which resulted in an outflow of 50,000 m^3 contaminated mine water in 1992 (Younger et al. 2002). These examples show how crucial it is to have detailed knowledge of the hydraulic conditions of all underground mine workings (Hamilton et al. 1994).

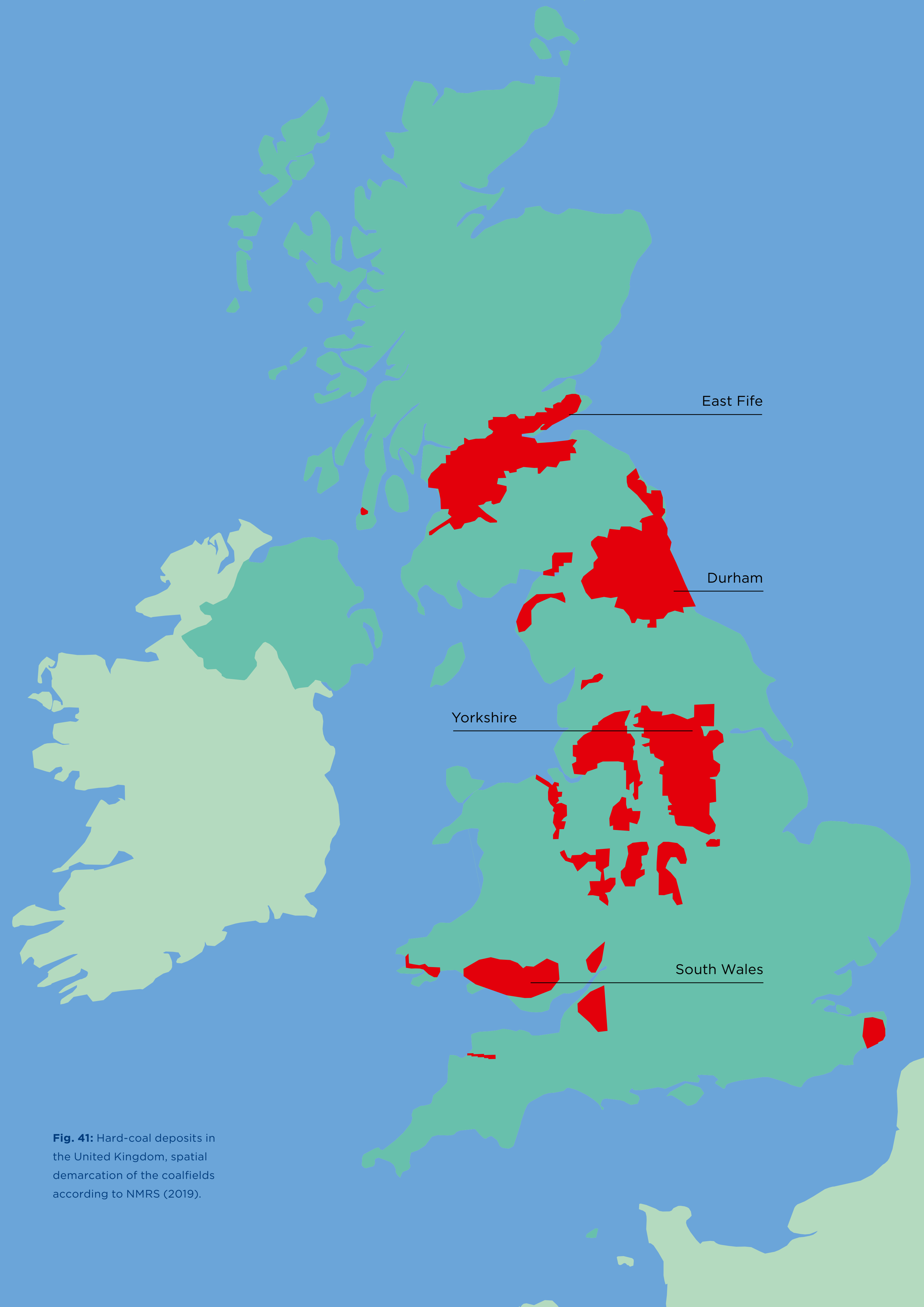


Fig. 41: Hard-coal deposits in the United Kingdom, spatial demarcation of the coalfields according to NMRS (2019).

3.2. United Kingdom

Due to its extensive and rich coal *deposits*, the United Kingdom can look back at a very long tradition of hard-coal mining (Fig. 41). Since the Middle Ages – some sources even assume since the Roman times – hard coal had been extracted both in open-cast and in underground mining operations (Hill 2001). The coalfields range from the very south-east of Kent via South Wales and the important coalfields in Yorkshire and Lancashire at the Pennine foothills up to the deposits in Scotland between Ayrshire and Fife (Fig. 41). British hard-coal industry reached its peak in the early 20th century when nearly 1.2 million workers produced up to 290 MT of hard coal in approx. 3,000 collieries per year (Hill 2012).

After World War II, the British hard-coal sector experienced a number of restructurings. In 1947 the collieries were nationalised and merged in the National Coal Board (since 1987 British Coal). Only in 1994 the existing collieries were privatised again; then, the administrative tasks were assigned to the newly founded Coal Authority and the commercial interests – together with the company RJB Mining – were transferred to UK Coal. Since 1999 the operated mines have been responsible for the impact of their excavations; as only a few mines were operating then, responsibility was delegated to the public authorities. Today, many of the post-mining challenges have been transferred to the Coal Authority. Detailed information on the history of coal mining in the United Kingdom has recently been published in Goerke-Mallet et al. (2017) and Reker et al. (2018).

3.2.1. Yorkshire

Geology and Hydrogeology

Yorkshire was one of the most significant hard-coal mining areas in the United Kingdom. This mining region is located in the east of the Pennine foothills. The coal seams dip to the east because of the uplift that occurred during the variscan orogenesis (Fig. 42). In the United Kingdom the seamy Carboniferous is divided into lower, middle and upper coal measures. In the western coalfield, the seams crop out at the surface. Further to the east, overburden consisting of Permian and Triassic strata is overlying the coal-bearing Carboniferous (see info box on 'Stratigraphy of Hard-Coal Deposits'). The basal strata of the overburden consists of marls and forms generally an *aquitard*. These are overlain by limestones which may form locally important aquifers. From a post-mining view, the overlying sandstone bearing aquifer of the Permian and Triassic in the eastern parts of the coalfield is of particular importance.

This sandstone horizon provides an important drinking water reservoir for the United Kingdom, and the aquifer is hydraulically confined from the coal seams by marlstones. However, this confinement might have been disturbed by underground hard-coal extraction. As a result, infiltrating mine water depending on hydraulic head distribution can potentially impact the hydrochemical composition of this aquifer.

Mining

Kellingley Colliery, the last worked mine in Yorkshire and thus in the entire United Kingdom, was closed down in 2015. In some parts of the mining region, however, mine water rebound started considerably earlier. First scientific observations of the rebound were carried out in the 1990s and modelled using the program GRAM (Groundwater Rebound in Abandoned Mineworkings; Burke & Younger 2000; Burke & Barber 2004; Burke et al. 2005).

More detailed descriptions on coal mining in the Yorkshire mining region have recently been published in Goerke-Mallet et al. (2017) and Reker et al. (2018).

Modelling the Mine Water Rebound

The purpose of the modelling was to forecast mine water occurrences at the ground surface. In this context, it had to be considered that the abandoned part of the mining area, consisting of the hydraulically connected collieries Treeton, Thurcroft and Silverwood, were still hydraulically connected with the operated mine Maltby (Fig. 42). However, it was not known whether and to which extent this connection was still hydraulically effective; therefore, different models needed to be created reflecting a parameter space with different hydraulic conductivity (variants 1 to 3; Fig. 43). The modelling revealed that, depending on the specific hydraulic conductivity of the connecting adit between the collieries Silverwood and Maltby, the occurrence of first mine water discharges is to be expected from a timeframe of 2004 up to well after 2030. The graph in Figure 43 indicates the modelled curve of the mine water rebound of the three options at Thurcroft Colliery before the mine water level was regularly monitored and measured.

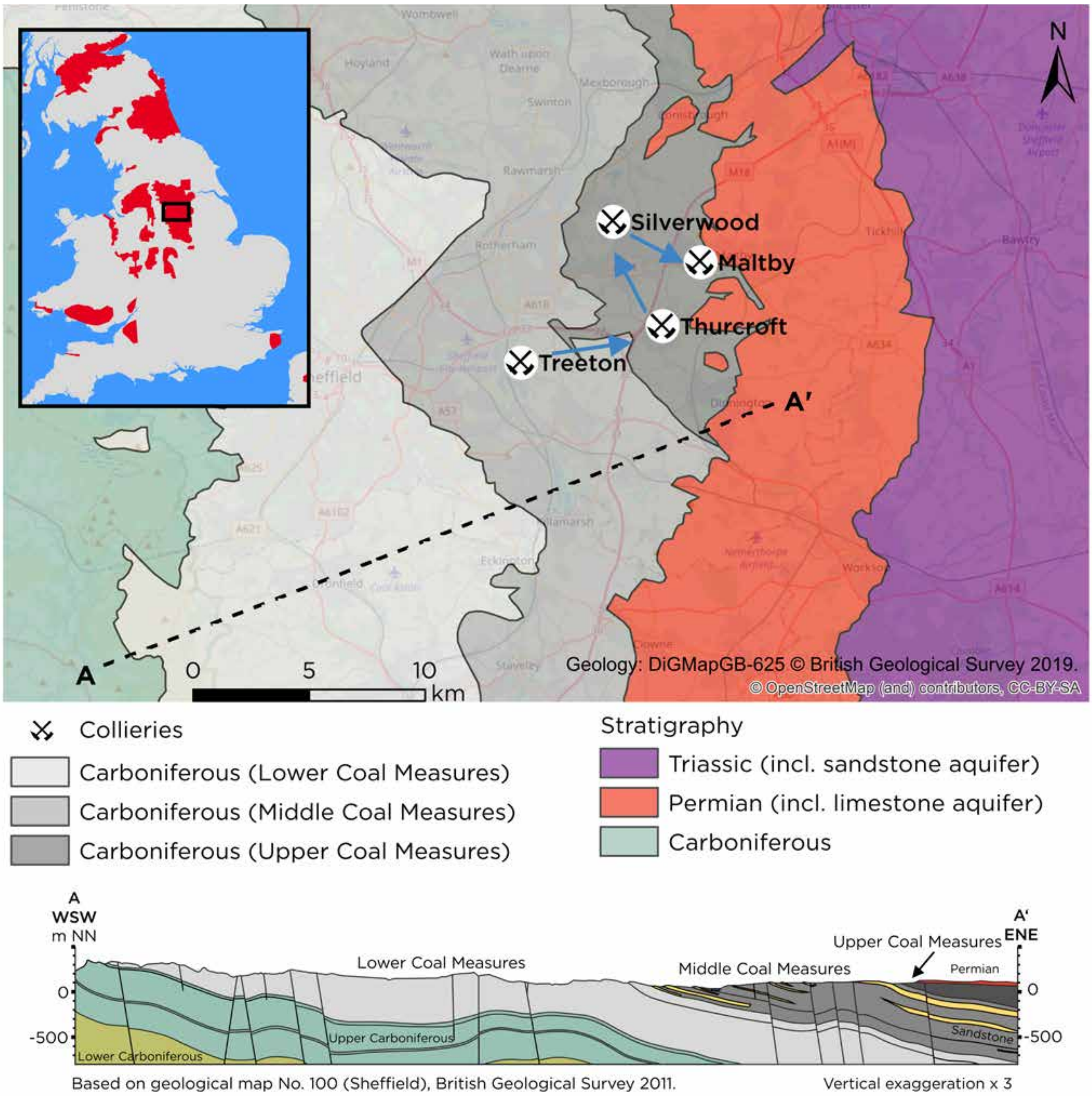


Fig. 42: Geographical and geological overview of selected collieries in the Yorkshire coalfield (United Kingdom). Geology according to British Geological Survey (2011). The flow direction of mine water is marked with blue arrows, according to Gandy & Younger (2007).

Since 2001, the mine water levels have been measured at regular intervals. After Burke (pers. comm. in 2017) an incidental measuring of the mine water level in Thurcroft Colliery revealed that this level was considerably higher than expected (Burke 2017). Subsequent examinations (Burke & Barber 2004; Burke et al. 2005; Gandy & Younger 2007) considered the mine water levels measured, the history matching helped to update the models and make them more accurate. Now it was possible to consider a hydraulic conductivity between the assumptions of variants 2 and 3. This knowledge enabled Gandy & Younger (2007) to consider the impact of changing precipitation rates and to refine the model accordingly. This model still exhibits a factor of uncertainty regarding the closure of the Maltby mine and the associated mine water rebound management. A call for a modelling study of the entire Yorkshire coalfield initiated by the Coal Authority (2015) demonstrates that this issue continues to be a point of interest for the Coal Authority to provide the appropriate procedures, measures and infrastructure needed for future mine water management.

Conclusion

The modelling results of the mine water rebounds in Thurcroft Colliery and adjacent mines illustrates that one parameter can lead to a significant uncertainty in the outcome of the modelling. Depending on the hydraulic effectiveness of the hydraulic

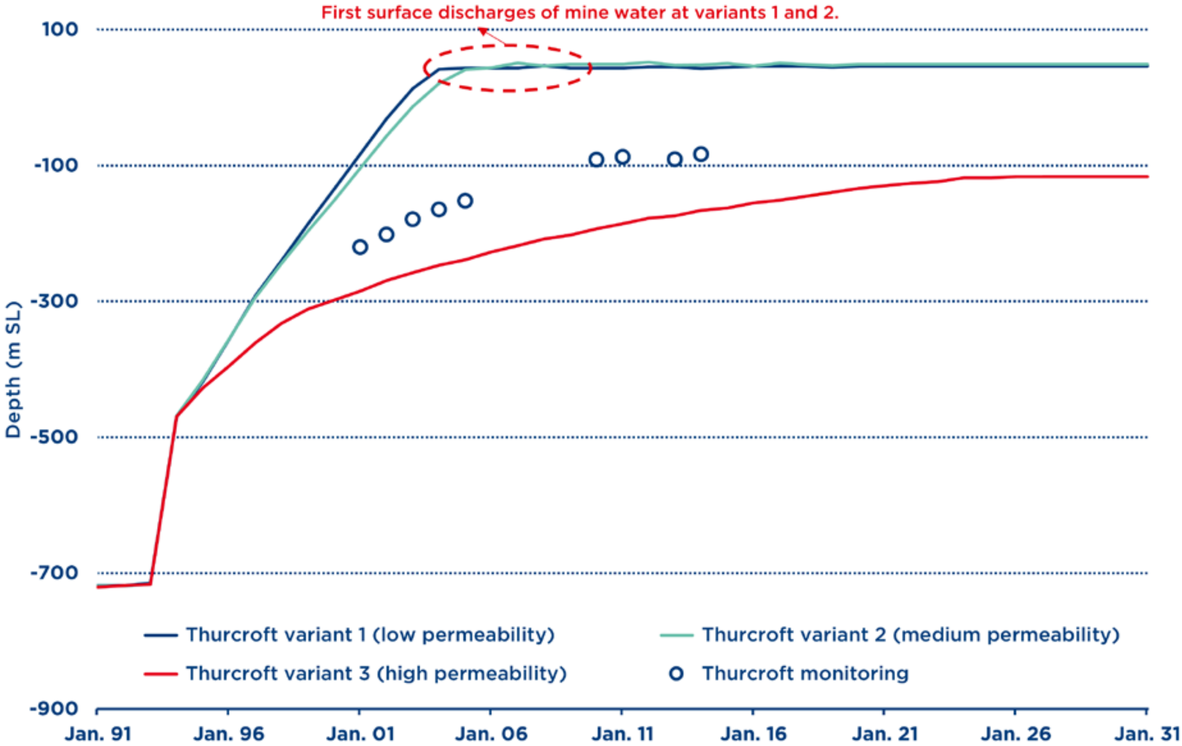


Fig. 43: Modelled courses of the mine water rebounds in Thurcroft Colliery for three different variants plus the mine water levels measured. Data reproduced according to Burke & Younger (2000); Burke & Barber (2004); Burke et al. (2005); Burke (2017); Gandy & Younger (2007).

drifts connecting the collieries, the timeframe of the first occurrence of mine water discharges at the ground surface ranges between the year 2004 and well after the year 2030, i.e. a period of more than 25 years.

As conducted in the modelling of Burke & Younger (2000), it is advisable to consider different probability distributions, i. e. a worst-case scenario as well as a base-case and a best-case scenario. Regarding the mine water rebound this implies that suitable measures have to be identified and ready for implementation in advance considering the worst-case option, in other words, the point of time of the earliest possible occurrence of surface related mine water discharge. To further minimise uncertainties in the modelling, a continuous monitoring system needs to be established which can be used to continuously adapt the model to the actual conditions.

3.2.2. Durham

Geology and Hydrogeology

Compared to the Yorkshire coalfield, the western part of the Durham coalfield similarly exhibits no overburden while its eastern part is overlain by younger strata (Fig. 44; Bearcock & Smedley 2009). Embedded in this overburden, a limestone succession forms an important aquifer in the north-east of England (Younger 1995).

Mining

Coal extraction was continued offshore, under the North Sea, following the east-dipping coal seams. In the coalfield of South Butterknowle, the last collieries were already closed at the end of the 1960s, and in the coalfield East of Wear in the early 1990s. Associated with the closure of the mines, the discontinuation of the mine dewatering has resulted in elevated mine water levels over a large area. A more detailed view of the coal extraction history in the Durham mining region has been published in Reker et al. (2019a).

Mine Water Rebound in South Butterknowle Mine District

The southern mining area of the Durham coalfield is also known as South Butterknowle; this area is separated from the northern mining area East of Wear by a major fault, i. e. the Butterknowle fault. This region is known as one of the few known European examples where rising mine water was able to infiltrate and subsequently pollute the groundwater. When the last colliery of this mining area closed, the mine water began to rise in the early 1970s. Although the risk of groundwater contamination had been known, and the mine water rebound had been initially monitored (Cairney & Frost 1975), the entire mine dewatering was ceased in the middle

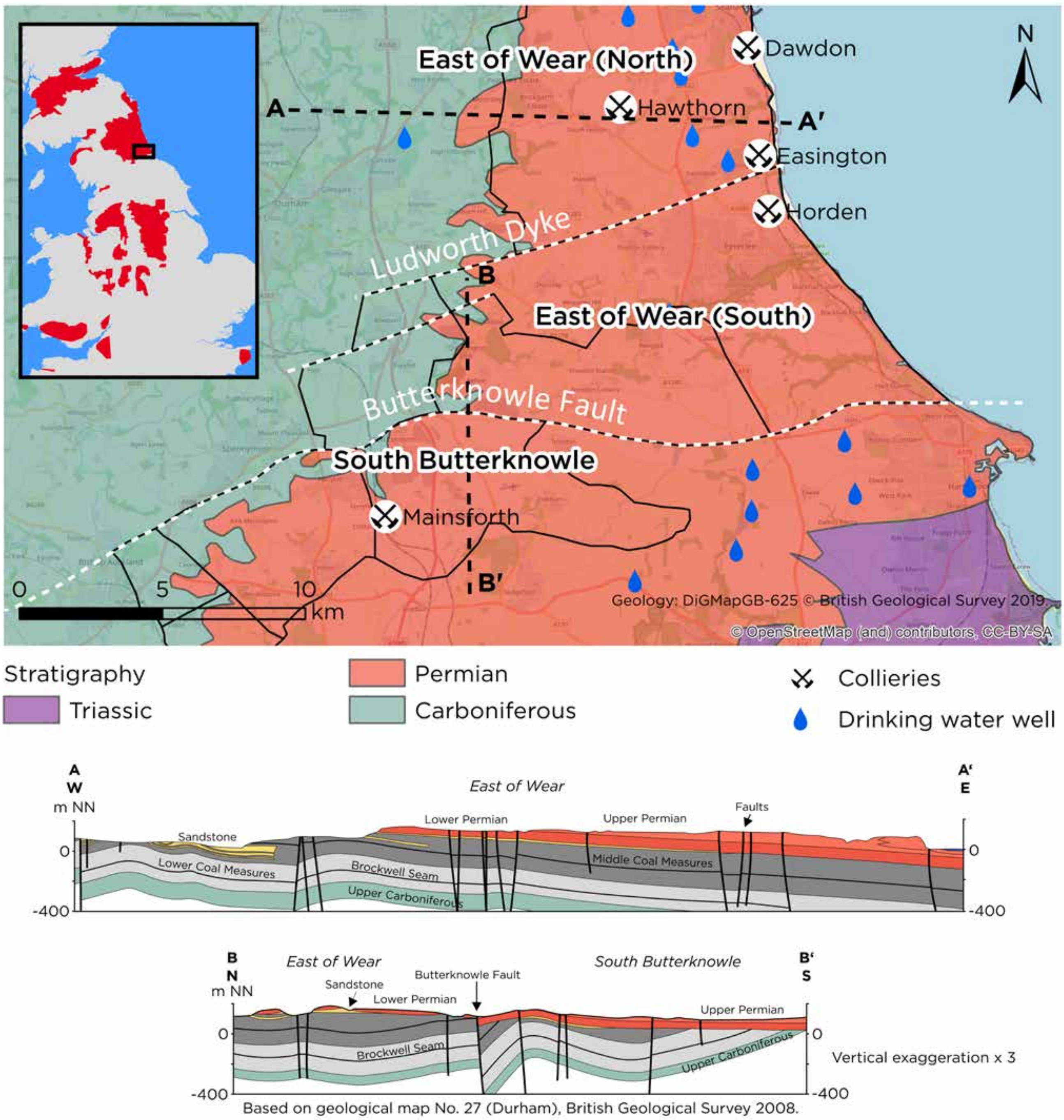


Fig. 44: Geographical and geological overview of selected collieries in the Durham mining region (United Kingdom); geology according to British Geological Survey (2008); mining areas according to Pastor et al. (2008).

of the 1970s. Hence, the mine water was able to rise in an uncontrolled manner. As the mine water is fed by precipitation waters that enter the coal seam Brockwell which outcrops at a height of approx. +125 m NN, associated hydraulic heads are significantly higher compared to the groundwater reservoir with a potentiometric surface of approx. +90 m NN (Younger & Adams 1999; Fig. 45). Due to this difference in heads, the mine water was able to lead to an impoundment in the overburden of Mainsforth Colliery as early as 1974/75 (Fig. 46). The groundwater pollution could be detected in the mid to late 1970s by a sudden rise of sulphate concentrations. It is expected that the concentration limit of sulphates will be exceeded at individual wells of public drinking water supply between 2019 and 2024 (Neymeyer et al. 2007). What is interesting in this context is the circumstance that no increased concentration of dissolved iron could be evidenced in the groundwater: this circumstance can be explained by the fact that the in total acidic mine water (see info box on 'Chemical Definitions') has been neutralised by the limestone host rock of the aquifer, and that the iron precipitated as a hydroxide coating on the limestone (Younger & Adams 1999).

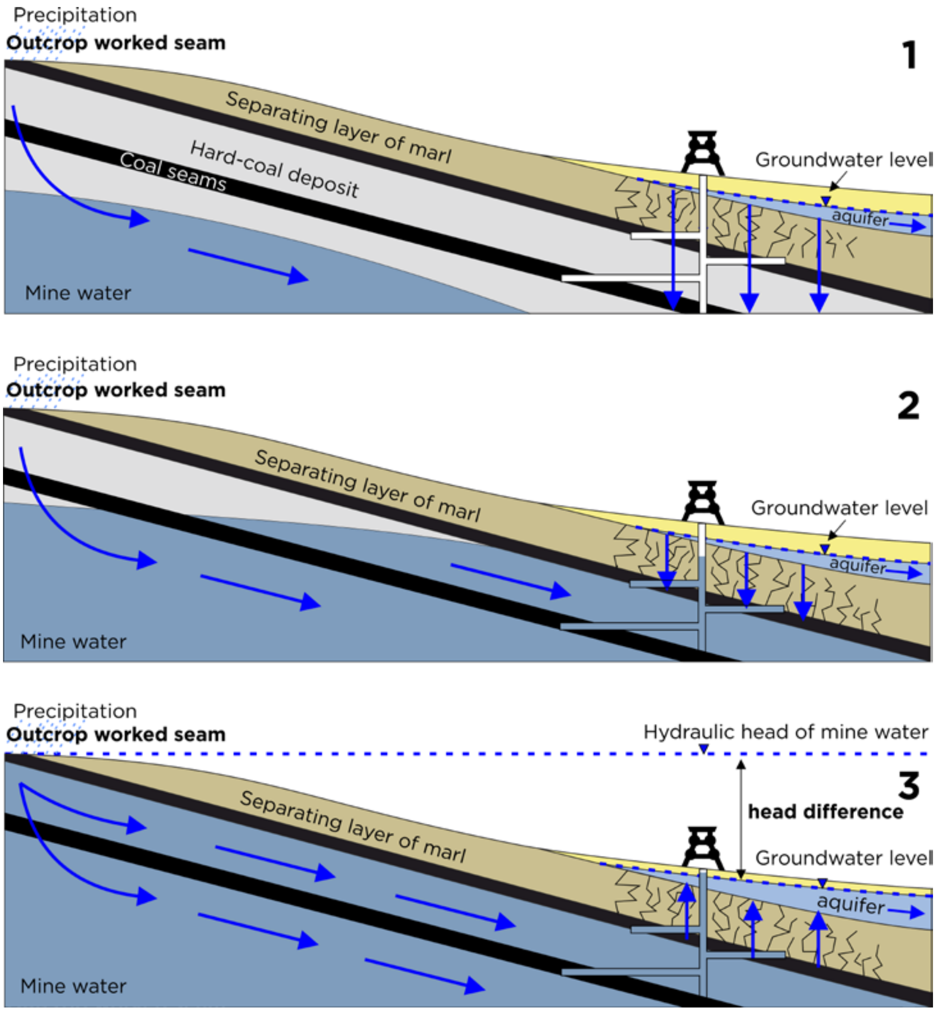


Fig. 45: (1) Outflow of the groundwater into the hard-coal deposits (hydraulic head of the mine water lies significantly below the groundwater level); (2) reduced outflow of the groundwater into the deposits (hydraulic head of the mine water lies below the groundwater level); (3) mine water infiltrating the groundwater (hydraulic head of the mine water lies significantly above the groundwater level); schematic drawing, not to scale; please note the increased groundwater level in the bottom drawing.

Conclusion

The fact that the aquifers in the South Butterknowle mining area could be contaminated by rising mine water was owed to an erroneous assessment of the anticipated hydraulic head of the mine water. This incident demonstrates again that knowledge of geological, hydrogeological and, in particular, topographic characteristics of the mining regions interact is of decisive importance in order to assess and prevent hazards to aquifers. Moreover, it is obvious that prior to the rebound neither an adequate monitoring system nor suitable backup solutions had been provided.

Optimising the Mine Water Management in the East of Wear Mining Area

The mining area East of Wear is located north of South Butterknowle. It is extensively covered by an overburden of 140 m to 180 m thickness in which a fractured aquifer is embedded (Fig. 44); this aquifer is also used as a reservoir for public drinking water supply.

Based on the experience made in the South Butterknowle mining area, the mine water rebound was monitored after the mine dewatering ceased in this mining area in the mid-1990s. An interpolation of the water levels measured helped to estimate the timing of impact on the fractured aquifer (Fig. 47; Watson 2011). From that point on (mid-2004) mine dewatering has been reactivated to keep the hydraulic head of the mine water a few metres below the corresponding hydraulic head of the groundwater. The pumped water was then purified by means of an active treatment plant (see info box on 'Mine Water Treatment'). Here, different pumping rates were set to examine the impact of the pumped water rate on the water chemistry. The observation revealed that a lower pumping rate yielded lower concentrations of iron and chloride in the mine water (Pastor et al. 2008). A high pumping rate would lead to an increased inflow of highly mineralised waters, thus impairing both the overall quality of the pumped water and the long-term stability of a density stratification (Ch. 2.5.). For that reason the pumping rate was reduced to a level that kept the hydraulic head of the mine water just below that of the hydraulic head of the groundwater. As a consequence, the quality of the pumped mine water was improved, the pumping costs minimised, and the groundwater was protected from mixing with mine water.

In this context, the chloride concentration of the mine water is an essential parameter: chloride cannot be removed using passive remediation methods, and it therefore limits the use of wetland technology. Initially, the mining area around Horden Colliery was hydraulically confined from the collieries Easington and Dawdon by an igneous intrusion called the Ludworth dyke. A hydraulic connection was only given by a sealed drift, i. e. a dam installation according to records of the mine plan. All mine water rebounds exhibit similar

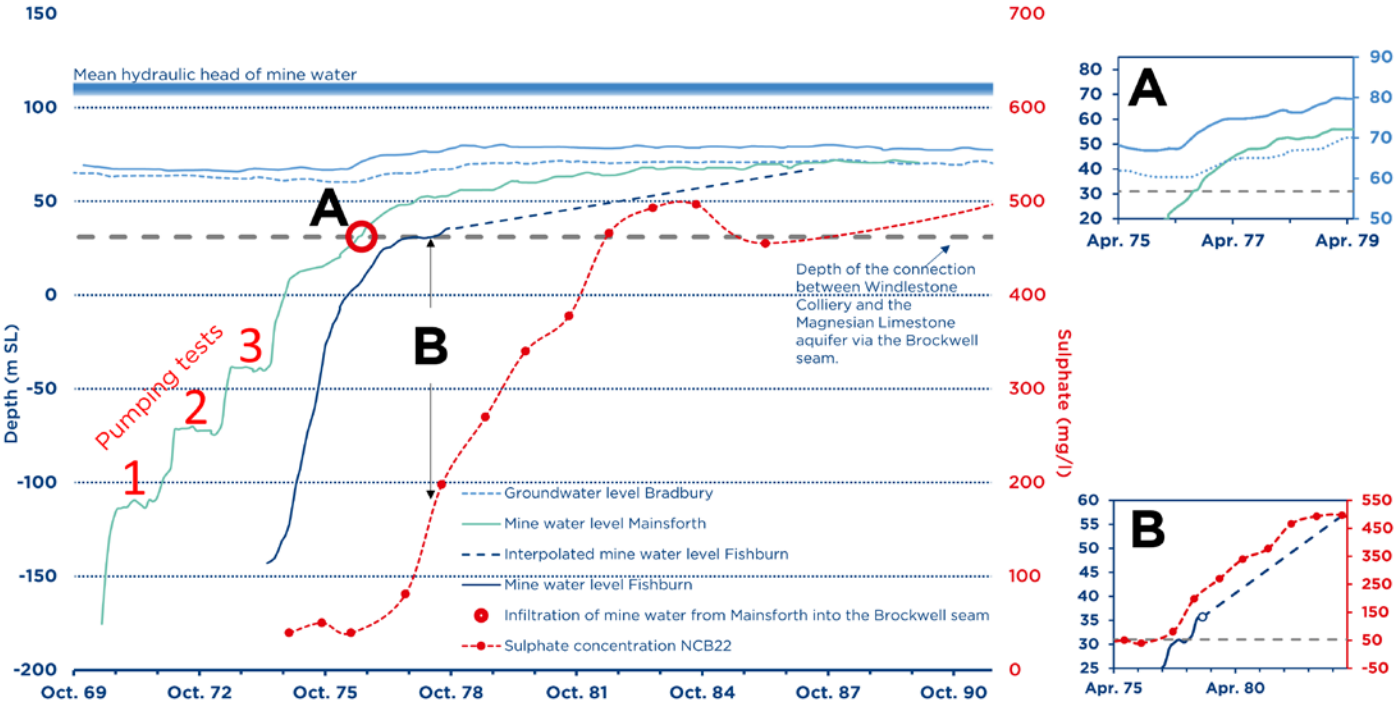


Fig. 46: Plots of the historic water levels of mine water rebounds in selected collieries and monitoring points in the Durham coalfield for the mining areas south of the Butterknowle fault between 1969 and 1991; the contamination of the overlying aquifer starting in summer 1976 is reflected in the increasing sulphate concentration (green line); modified data after Cairney & Frost (1975); Kortas & Younger (2007); Pastor et al. (2008).

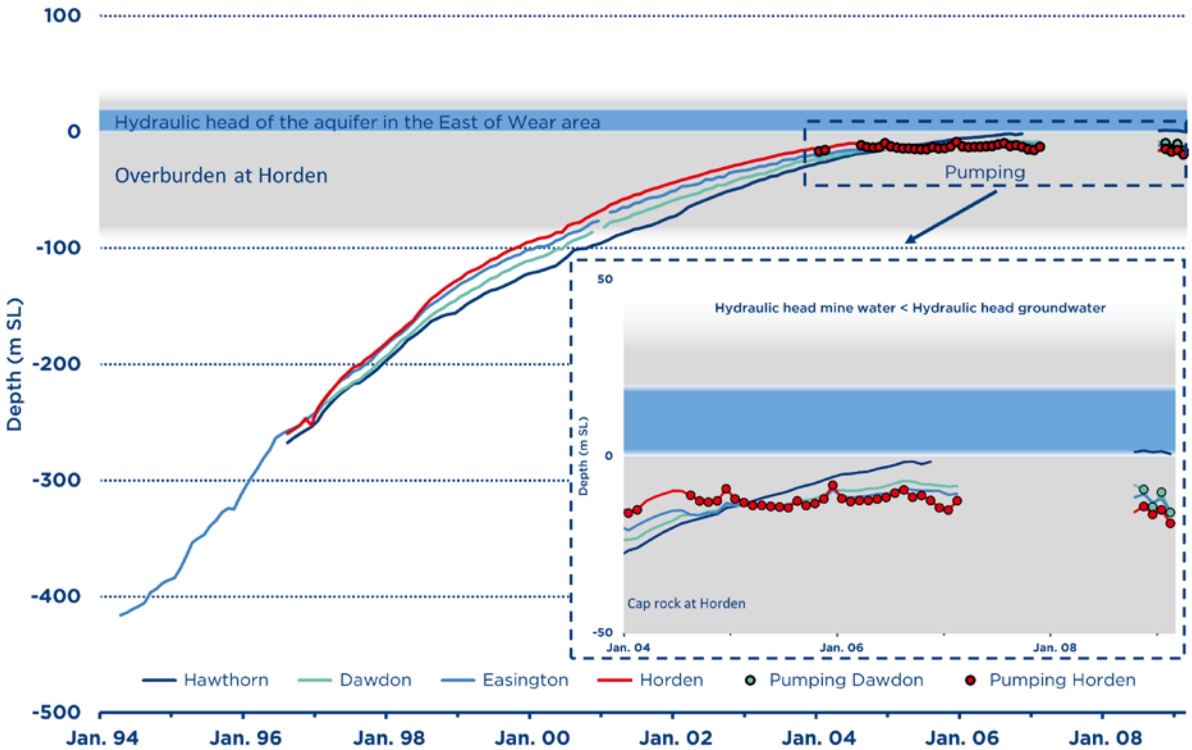


Fig. 47: Plots of historical mine water rebound data from the collieries Dawdon, Easington and Horden in the East of Wear mining area. The depth of the overburden in the East of Wear-mining area is highlighted in grey. The inlet illustrates that the mean hydraulic head of the groundwater is situated only a few metres above the mine water level which has been lowered by the mine dewatering measures. Data modified after Whitworth (2002); Pastor et al. (2008); Watson (2011). No data is publicly available for the years 2007 and in parts 2008.

characteristics which indicated that there seem to be no seals between the mining areas; instead an open hydraulically effective connection has to be assumed. It remains unclear how long this connection will stay open (Watson 2011). As the hydraulic gradient in this mining area – for both the mine water and the groundwater flows – is directed from west to east, i. e. towards the coast and located collieries, the treatment capacities at Horden Colliery would be exceeded if mine workings cannot act as hydraulic conduits. An uncontrolled contamination of the groundwater would be the result. To prevent this scenario, an active treatment plant of identical capacity was soon installed at Dawdon Colliery. As the shaft of Dawdon Colliery is situated deeper than that of Horden Colliery, a poorer water quality containing higher quantities of e. g. chloride and iron was expected. When the treatment plant at Dawdon Colliery was completed end of 2008, the water withdrawal rate at Horden Colliery could be reduced from 6 – 9 m^3/min to approx. 3 m^3/min (Watson 2011). A reduced withdrawal rate resulted in the expected reduction of the chloride concentration; as a consequence, the active treatment plant at Horden Colliery could be dismantled and, by 2011, replaced by a passive treatment system of a size of 1.7 ha including a ventilation system, settling pond and a constructed wetland (Watson 2011). Since then, the treated water has been discharged into the adjoining North Sea where the higher chloride concentration is no longer important due to the dilution effects.

Conclusion

The experience gained from the contamination of the aquifer in the South Butterknowle mining area helped to protect the aquifer in the northern adjacent East of Wear mining district by providing mine dewatering stations and appropriate pumping measures. Therefore, the mine water rebound was continuously monitored in several mines to estimate the point of time at which the mine water would reach the base of the aquifer. By maintaining a comparably low potential difference of a few metres between the groundwater and the mine water, an infiltration of the mine water into the aquifer could be prevented. Hence, pumping costs and energy consumption could be reduced, resulting in a lower environmental impact. Another advantage of this sustainable mine dewatering concept in the East of Wear mining area is that the composition of the mine water could be modified to such a level (i. e. contaminant species were reduced) that a change from active to passive mine water treatment was possible. This reduction of contaminations was most certainly also due to the fact that the lower pumping rates provided favourable conditions for the formation of a stable density stratification in the mine water.

To summarise, it can be deduced that a higher piezometric surface of the groundwater compared to the mine water prevents the mine water from infiltrating the aquifer. This conclusion applies even if the hydraulic head of the mine water has already reached the level of the water-filled area of the aquifer. To maintain this difference in the hydraulic potential it must be ensured that suitable backup locations of water pumping stations are continously provided.

3.2.3. East Fife

Geology and Hydrogeology

The East Fife mining region is located at the coast opposite the city of Edinburgh within the county of Fife. The hard-coal deposits outcrop at the surface. Many of the collieries are in close vicinity to the coast. As the coal seams dip towards the North Sea, undersea mine workings were installed far out at sea (Fig. 49).

Tidal Influence

Such undersea mines recorded mine water levels which exhibit a cyclical pattern of rise and fall in the order of several decimetres. According to Younger et al. (2002), tidal forces are responsible for this cyclical nature: when the sea is at high tide, the pressure of the seawater column on the underlying rocks increases; the additional load of the water column results in higher compression of the underground void spaces (Fig. 50-1), which forces water out of these voids yielding a higher water level within the shaft (Fig. 50-2). When the sea is at low tide, there is a pressure relief from the underlying rocks. The sea water recedes, and, as a result, the voids expand again and the moveable water flows back into the voids. Accordingly, the water level at the observed measuring point decreases, too (Fig. 50-3). Especially in Scotland's coastal East Fife mining region one can observe this phenomenon (Whitworth 2002; Nuttall et al. 2002; Younger et al. 2002; Wyatt et al. 2014); the mine water level responds with a retention time

Mine Water Treatment

If water does not meet the requirements of a certain purpose or pertinent standards, it can be treated using different purification methods and systems. Mine water treatment (or mine water processing) can be designated in a passive or active way (Wolkersdorfer 2013).

An active mine *water treatment plant* involves a continuous application of energy and/or chemicals during the purification process to change the chemical composition and physical properties of the water; examples of active systems are the popular methods using low-density sludge and high-density sludge, filtration methods or electrochemical procedures such as electrocoaglation.

However, passive mine water treatment systems are less clearly defined. According to Wolkersdorfer (2013), they involve systems which only use natural forms of energy such as potential energy (difference in altitude in cascades or similar), solar energy (heat, photosynthesis, UV radiation) or biological energy provided by bacteria. In other words, natural processes are utilised to purify the mine water. Examples of passive systems are aerobic and anaerobic wetlands which are often set up particularly in the Anglo-Saxon world, the use of oxic limestone channels (OLCs) or anoxic limestone drains (ALDs) and RAPS, Reducing and Alkalinity Producing Systems.

Hybrid forms containing passive and active 'devices' occur as passive systems often combine active elements like ventilation systems (Fig. 48) or dosing of nutrients and fertilisers for promoting growth of plants and bacteria. In addition, passive systems also need regular cleaning and servicing to remain stable over a long time and be able to provide the necessary purification capacity.

More detailed information on the topic of active and passive mine water purification can be found in Hedin et al. (1994), Wolkersdorfer (2013) and the Global Acid Rock Drainage Guide (INAP 2014).

Fig. 48: Ventilation system of the mine water treatment plant at Caphouse Colliery in Yorkshire (United Kingdom; photo: Bastian Reker).

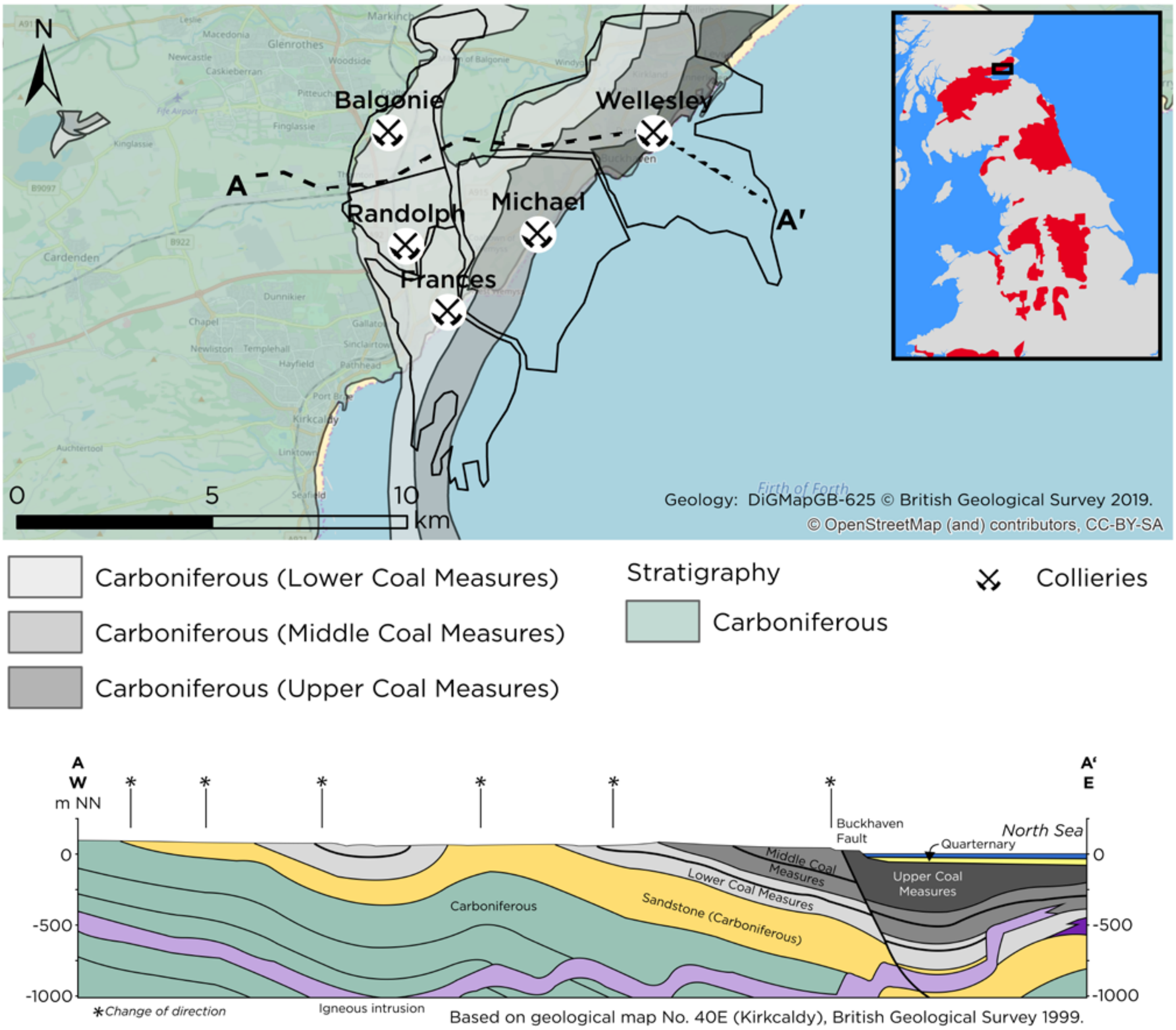


Fig. 49: Geographical and geological overview of selected collieries in the East Fife coalfield (Scotland); geology according to British Geological Survey (1999); mining areas according to Sherwood (1997).

of approx. two hours to the high tides of the sea.

In their examinations Younger et al. (2002) assume that the mine water rebound and the fluctuations in the water levels could not be linked to a direct inflow of the seawater into the mine workings. Analysing stable isotopes, however, Nuttall et al. (2002) and Nuttall & Younger (2004) could detect a seawater proportion up to 30 % in the mine water budget. But they also pointed out that the mine workings which in some spots were built for kilometres under the sea, were assumed to be mostly dry and no indication of seawater intrusion could be found.

Besides the tidal influence on the mine water levels, the tides have also been reported to be an (at least indirect) factor of influence on the mine water chemistry (Wyatt et al. 2014). At Frances Colliery maximum values of electric conductivity are recorded in the mine water during the tidal range. The electric conductivity data correlates with the measured iron concentrations (of approx. 30 mg/L up to 247 mg/L during a cycle): thus, this factor is of fundamental importance for the subsequent water treatment. This dependency can be best explained by the formation of a distinctive density stratification of the water which occurred in this depth region: whereas the highly

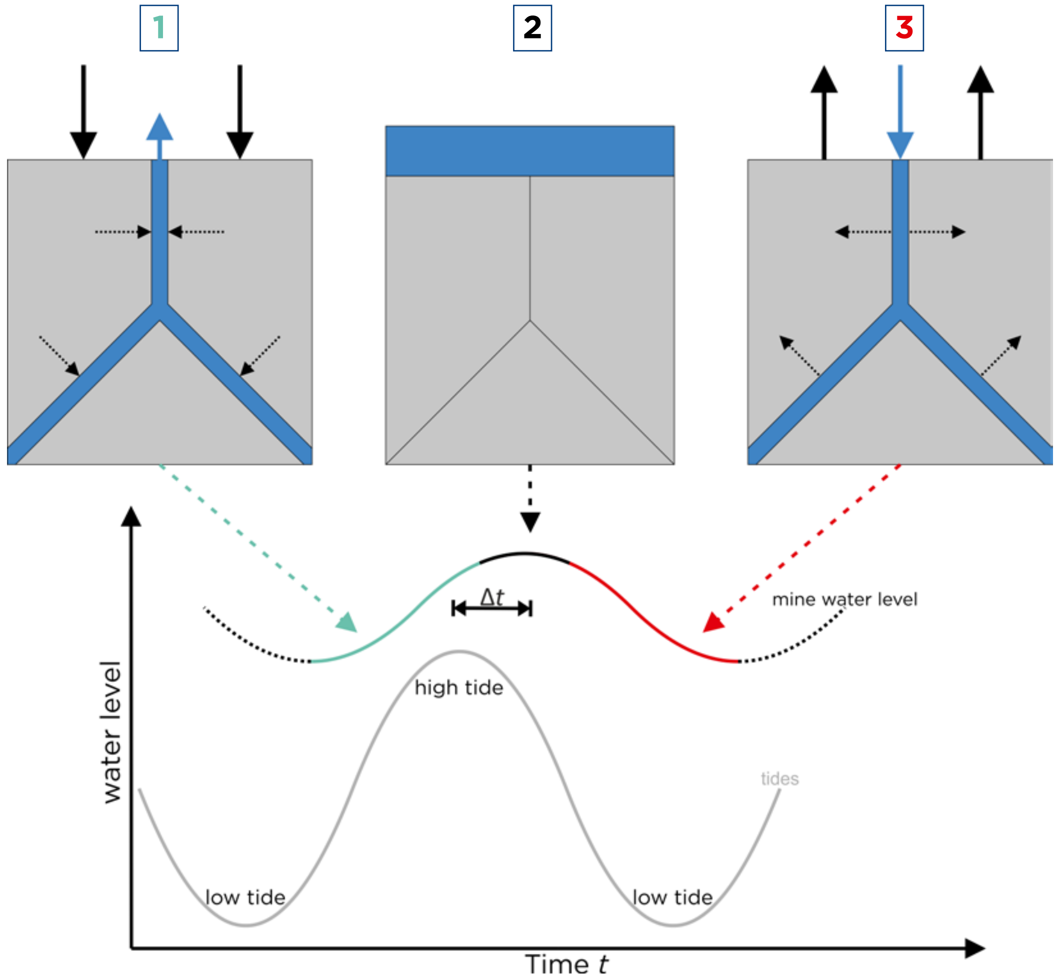


Fig. 50: Tidal influence on the porous voids in the underlying rock mass and the mine water level.

mineralised waters are located in the deep proportion of the water column, the upper water body consists of less mineralised waters. During the tidal range the interface boundary between these two water bodies fluctuates at an amplitude of approx. 10 m. Regarding the monitoring location at Frances Colliery, one of the pumps is lifting the mine water from the upper part of this fluctuation zone so that higher mineralised waters are pumped when the tide is high – containing an iron concentration of up to 247 mg/L – and lower mineralised waters are pumped when the tide is low – containing an iron concentration of approx. 30 mg/L. The mine water removed by the pump – which is mounted above this fluctuation area inside the shaft – does not show significant variations of iron concentrations. The variation in depth of the interface layer by more than 10 m during the tidal range is considerably larger than the fluctuation of the mine water level in the shaft by approx. 0.4 m and also significantly higher than the tidal range itself of approx. 4 m (Fig. 51). What exactly causes the upward movement of the interface layer is still not well understood, but it can be assumed that it is likely due to a combination of the differences in density of the two types of water, the pumping rates and the tidal forcing (Wyatt et al. 2014).

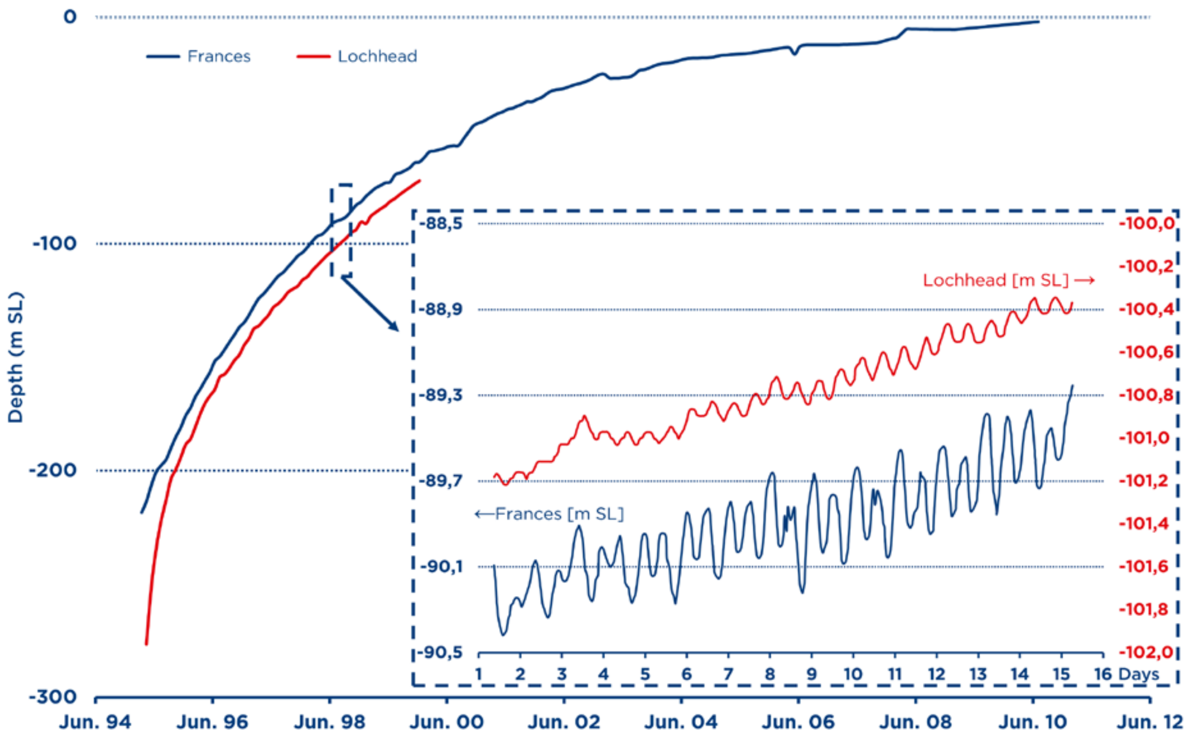


Fig. 51: Courses of mine water rebounds in the collieries Frances and Lochhead in the East Fife mining region. The inlet shows the tidal impact on the course of the rebound; data reproduced according to Whitworth (2002) and Wyatt et al. (2013).

It needs to be emphasised that the tides do not have any direct impact on the mean mine water chemistry, but that the fluctuations in the water quality can be traced back to the fluctuation in height of the stratification boundary layer.

Conclusion

At coastal collieries, tidal forcing can largely influence the stratification and, indirectly, the quality of the pumped mine water. Fluctuations of the interface in the range of up to 10 m have been reported although the cyclical changes in the mine water level were only in the decimetre range. From a scientific point of view, the reasons for these fluctuations are not fully understood; several factors of influences such as differences in density, pumping rates and tidal forcing are being discussed. At Frances Colliery the shift in the altitude of the stratification boundary layer led to one of the pumps abstracting high conductivity water and partly in lower conductivity water; thus, the water quality fluctuated notably. When planning the installation of mine dewatering systems and mine water treatment plants in the respective mining areas, the depths of the pumps need to be automatically adjusted in order to vary the dosing of chemicals in the treatment scheme.

Fig. 52: Hard-coal deposits in France. Boundaries of the mining areas according to Direction of the Mines (1963) and Daniel & Jamieson (1992).

3.3. France: Lorraine and Warndt

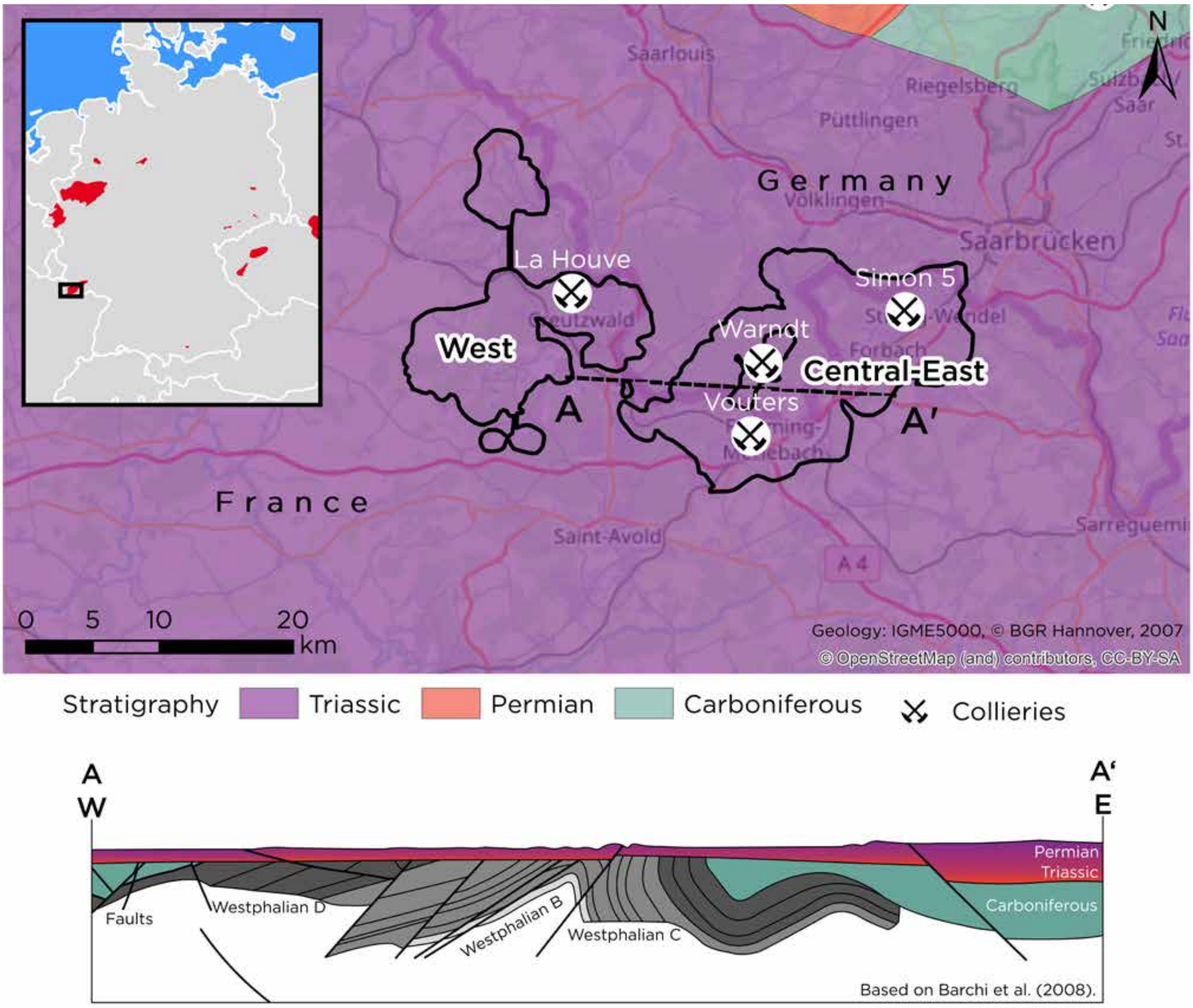


Fig. 53: Geographical and geological overview of the Lorraine mining region (France; Warndt Colliery [Germany] included); geology according to Asch (2005); mining areas according to Corbel et al. (2017).

Geology and Hydrogeology

Within the Lorraine mining region as French part and the Warndt area of the Saar mining region as German part the Lower Triassic sandstones (red sandstone) provide the regional joint and porous type aquifer (see info box on 'Stratigraphy of Hard-Coal Deposits'). This aquifer is used for industrial purposes and the public drinking water supply (Fig. 52 and Fig. 53). Although the intercalated claystones ('Grenzletten') layers between the aquifer and the Carboniferous are regarded as sealing for water, they can be disturbed due to the mining activities and thus do not act as a geohydraulic barrier between the Carboniferous and the Triassic strata anymore.

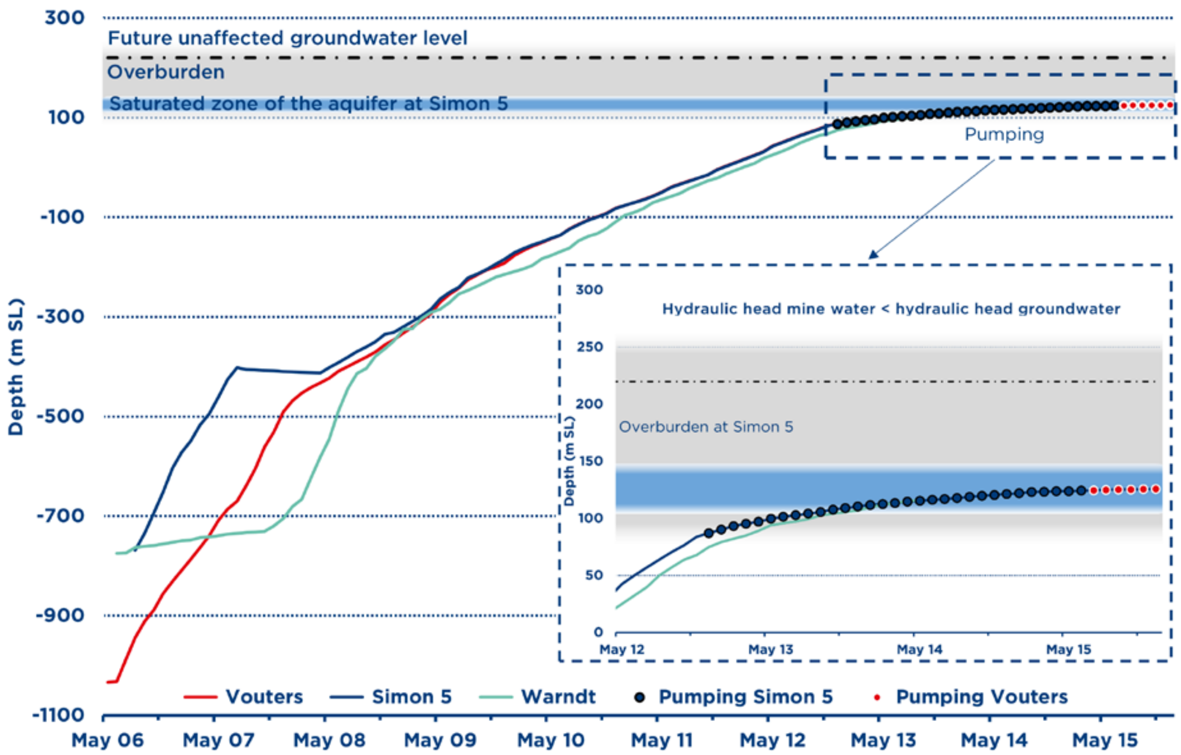


Fig. 54: Courses of mine water rebounds in the collieries Vouters and Simon in Lorraine (France) between 2006 and 2016 (data according to Cosquer [2016]) and Warndt (Germany; data according to Schäfer [2016]). The overburden is shaded in grey; the current as well as the future natural groundwater level in Simon Colliery are highlighted as blue area and as a broken white line above (data according to BRGM [2016]). The inlet illustrates how the hydraulic head of the mine water is kept just below the groundwater level during the pumping stage in order to prevent mine water from infiltrating the aquifer.

In particular the mining on the French side has disturbed this geological seal extensively (Wagner 2010).

Mining and Mine Water Management

In the Lorraine mining region, hard coal was extracted at depths of -150 m NN down to -1,250 m NN. The disruptions and fracturing of the overburden strata led to significant volumes of water entering the hard-coal deposit including mine workings from the regional aquifer. As a result, large cones of depression developed (Koeberlé et al. 2013). In parts, drawdowns of up to 160 m were measured for the groundwater levels (Wagner 2010).

The issues associated with the rising mine water are very similar to those in the Durham mining region (United Kingdom):

- large-scale underground extraction of hard coal,
- mining close to the basis of the overburden,
- *disintegration zones* above the worked fields as potential water conduits between the deposit and the overburden,
- aquifers in the overburden which are relevant for the regional water management,
- groundwater infiltrating into the deposit,
- rebounding mine water causing a hazard to the overlying aquifers.

During operations water inflow from the aquifer into the deposit was timely pumped so that the waters remained in the deposit only for a short time. Therefore, they were not enriched with dissolved ions (Blachere & Lefort 2003) and could be used for industrial purposes; any excess water could be promptly discharged into the environment (Koeberlé et al. 2013). After the mine dewatering was discontinued, such a procedure is no longer appropriate: significantly longer residence time of mine water leads to higher mineralisation of the waters. If mine water rebound continues unabated, the contaminants in the mine water will pollute the aquifer; before entering the receiving waters, mine water needs to be treated. Another problem in this mining area is the fact that the former operator of the Lorraine collieries, Charbonnages de France (CdF), left all facilities underground (i. e. machinery, electric and hydraulic installations); the pertinent operating supplies (e. g. fluids) provide a particular risk factor (Corbel et al. 2017).

In order to protect not only the groundwater, but also the buildings located in the areas of mining sub-

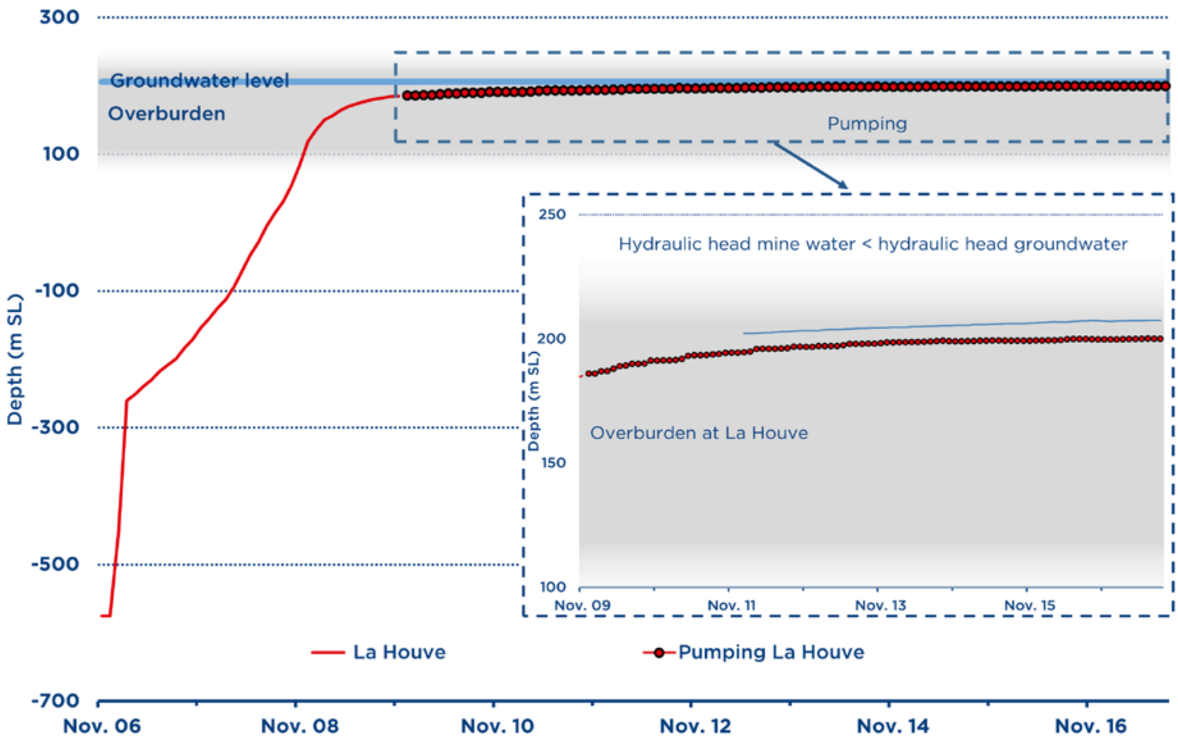


Fig. 55: Course of mine water rebound at La Houve Colliery in Lorraine (France) between 2006 and 2017 (data according to Corbel et al. [2017] and BRGM [2017]). The overburden is shaded in grey, the groundwater level in light blue. The inlet illustrates how pumping measures keep the mine water level almost constant at 7.5 m below the slowly rising groundwater level.

sidence and thus partly below the natural groundwater level, the rise of the mine water, which had been going on since 2006, was continually monitored in the beginning (collieries Vouters, Simon and Warndt: June to August 2006; La Houve Colliery: December 2006). The position of the monitoring locations and the division of the mining regions into a western and a central-eastern mining area are shown in Fig. 53. Warndt Colliery is hydraulically confined by a high-pressure dam, located at a depth of approx. –840 m NN (i. e. 1,000 m below ground level), from the Saar collieries in its northeast (Wagner 2010; RAG AG 2015).

Mine Water Rebound in the Central-eastern Mining Area

The mine dewatering measures at the collieries Vouters, Simon and Warndt were discontinued between June and August 2006 (Wagner 2010; Schäfer 2016; Corbel et al. 2017). The continuous mine water rebound process is shown for all three collieries in Fig. 54. In all collieries, the rise can be divided into three stages: the initial stage, marked by a very high level increase of up to almost 50 m per month. Later on values quickly lowered to up to 30 m per month in the first year. In July 2007 the mine water rise levelled off at Simon Colliery, became stable and even was sinking slightly (i. e. monthly rebound velocities went down to 0 m and even to slightly negative values); meanwhile rebound velocities at Vouters Colliery reached again values of 42 m per month. This difference can be traced back to the hydraulic connection between the three sites. The water was overflowing at Simon Colliery into the lower levels of the collieries Vouters and Warndt that had not been filled up so far. Close to the spill points of the three interconnected mine workings, the second stage of the mine water rebound commenced (intermediate stage). The mine water at shaft Simon 5 resumed its rise at values of around 10 m per month, and the rebound velocities at the collieries Vouters and Warndt dropped to almost identical values. The difference between the water levels reduced from previously up to 270 m in July 2007 (shaft Simon 5: –402 m NN; shaft Vouters: –670 m NN) to approx. 20 m in April 2008 (shaft Simon 5: –413 m NN; shaft Vouters –433 m NN). During 2008 and 2009 the water levels continued to approach each other until all water levels equilibrated in mid-2009. Water level increase continued with a range of 6 m to 11 m per month until the Carboniferous hard-coal bearing rock was fully saturated; infiltration of overburden strata consisting of Permian and Triassic aged rocks began at the end of 2012. That point marked the beginning of the third stage of the mine water rebound (final stage) in which mine dewatering measures helped to lower the rebound velocity to 1 – 2 m per month, thus creating almost stationary conditions. More detailed descriptions of the mine water rebound and its respective concepts in the Lorraine mining region have been published in Reker et al. (2019b).

Mine Water Rebound in the Western Mining Area

The mine dewatering measures at La Houve Colliery, hydraulically isolated from the collieries Vouters and Simon, was discontinued in December 2006; The three-stage approach for the rebound pattern can also be applied here (Fig. 55). The first stage lasted from December 2006 to February 2007 and was defined by a steep increase of the water level up to 190 m per month. During that time, the water rose from approx. –580 m NN to –250 m NN. This pattern can probably be explained by the difference of rather small void volume compared to the existing reservoir volume (Koeberlé et al. 2013). The transition to the second stage is observed by a drop in the rebound velocities to values of 10 m per month. At that depth, hard coal had been mined most extensively, therefore, the largest floodable void volumes exist in this depth range. At the end of stage 2, rebound velocity values rose again to values between 20 m and nearly 35 m maximum per month. This development is interpreted as a mine water rebound within the (mining-induced) disturbed strata above the highest working level. Shortly after the local maximum rise of 35 m per month was reached, the seepage into the overburden was observed. At first, mine water level increased to less than 10 m per month, and successively to values of around 1 m per month. On the one hand, this is due to a decrease of inflow as the difference in hydraulic potential between the mine water and surrounding aquifers decreases; on the other hand, the sandstones of the overburden (Triassic) act as an aquifer horizon which is already fully saturated. Since November 2009 the mine water level has been kept at a constant level of 7.5 m below the groundwater level as a new mine dewatering system was installed.

Comparison with the Durham Mine Water Management (United Kingdom)

In the Lorraine mining region, a concept similar to that of Durham mining district in Great Britain was implemented to protect the aquifers (Ch. 3.2.2.). At Lorraine, the mine dewatering systems were reactivated at the following collieries: La Houve Colliery in November 2009, at Simon Colliery in November 2013, and finally at Vouters Colliery in July 2015. The system was implemented in order to keep the mine water level a few metres below the piezometric surface of the groundwater (Fig. 54 and Fig. 55). The potential gradient between 5 m and 10 m was kept stable (Wagner 2010) and in combination with a stratified water column ensures that mine waters won't mix with Triassic groundwater (Koeberlé et al. 2013). The Triassic groundwater will discharge into the mine water due to its higher potential, and consequently hinders mine water to infiltrate the groundwater. Due to the narrow potential gradient between the two waters, the groundwater volume infiltrating the mine water is almost negligible (similar to the Durham mining region). As a result, the groundwater level rises successively together with the rising mine water. However, if the mine water is kept at a constant level, the groundwater level will be influenced as well and water logging of mining areas affected by mining subsidence will be prevented. Usually, a distance of 3 m between the ground surface and the groundwater level is targeted; nevertheless, in the western mining area (La Houve Colliery) water logging and the formation of ponds occurred in some towns, and basements in urban areas were intruded by water as well (Ernst & Mailasson 2018). Even in some places on the German side water logging can be expected (Wagner 2010). However, there had been wetlands in this area before groundwater levels were lowered during mine operations; these wetlands will now be restored to its original condition.

In the eastern mining region, no uncontrolled gas releases or damages to infrastructure or environment – including the groundwater – are known (Schleuning 2018). Although large-scale upheaval on the scale of up to 20 cm was registered, that occurred evenly and did not impair the infrastructure in any way.

Conclusion

Like in the East of Wear mining area, Durham mining region, the mine water in the Lorraine mining region rose until it reached the water saturated area of the aquifer. By maintaining a hydraulic head difference of 5 – 10 m, it was possible to protect the Lorraine groundwater from infiltration with mine water, too. As a hydraulic contact between groundwater and mine water also leads to a reduced outflow of groundwater into mine water filled compartments, it results in a larger yield of groundwater and a potential rise of the groundwater level on a regional scale. Accordingly, appropriate polder monitoring measures must be investigated and planned to ensure the protection of the environment, nature and infrastructure. In addition, spare pumps must be provided for pump failure alerts to ensure that mine water cannot infiltrate the groundwater.

Geothermal Systems: Open-Loop and Closed-Loop

In general, geothermal systems use two ways underground heat usage:

An open-loop system pumps water to the ground surface where a heat exchanger is installed to transfer the heat to a heating network. The (mine) water, which is cooled when it leaves the heat exchanger, can either be discharged at the surface or reinjected to the groundwater using an injection well. Where high conductivity mine water is involved (in particular with high dissolved iron loads), *ochre iron* precipitates *('scales')* and can cause scaling or even clogging issues thus lowering the performance of the heat exchanger (Fig. 56) and increasing maintenance costs.

In a closed-loop system (in terms of geothermal heat so called 'heat probes'), pipes are installed in a drill hole or shaft in which heat is transferred from the mine water to the water cycle in the loop. That means that the heat exchanger is located within the shaft, i. e. the warm water column. The advantage of this system is that no ochre iron scales can occur as no mine water pumping is involved. More detailed information and a comparison of the two systems can be found in Banks et al. (2019).

Fig. 56: Disadvantage of open-looped systems: ochre iron at the heat exchanger (ochre-coloured areas on the metal plate; photo: Bastian Reker).

Fig. 57: Hard-coal deposits in Spain; spatial demarcation of the mining areas according to IGME (1985).

3.4.
Spain: Asturias

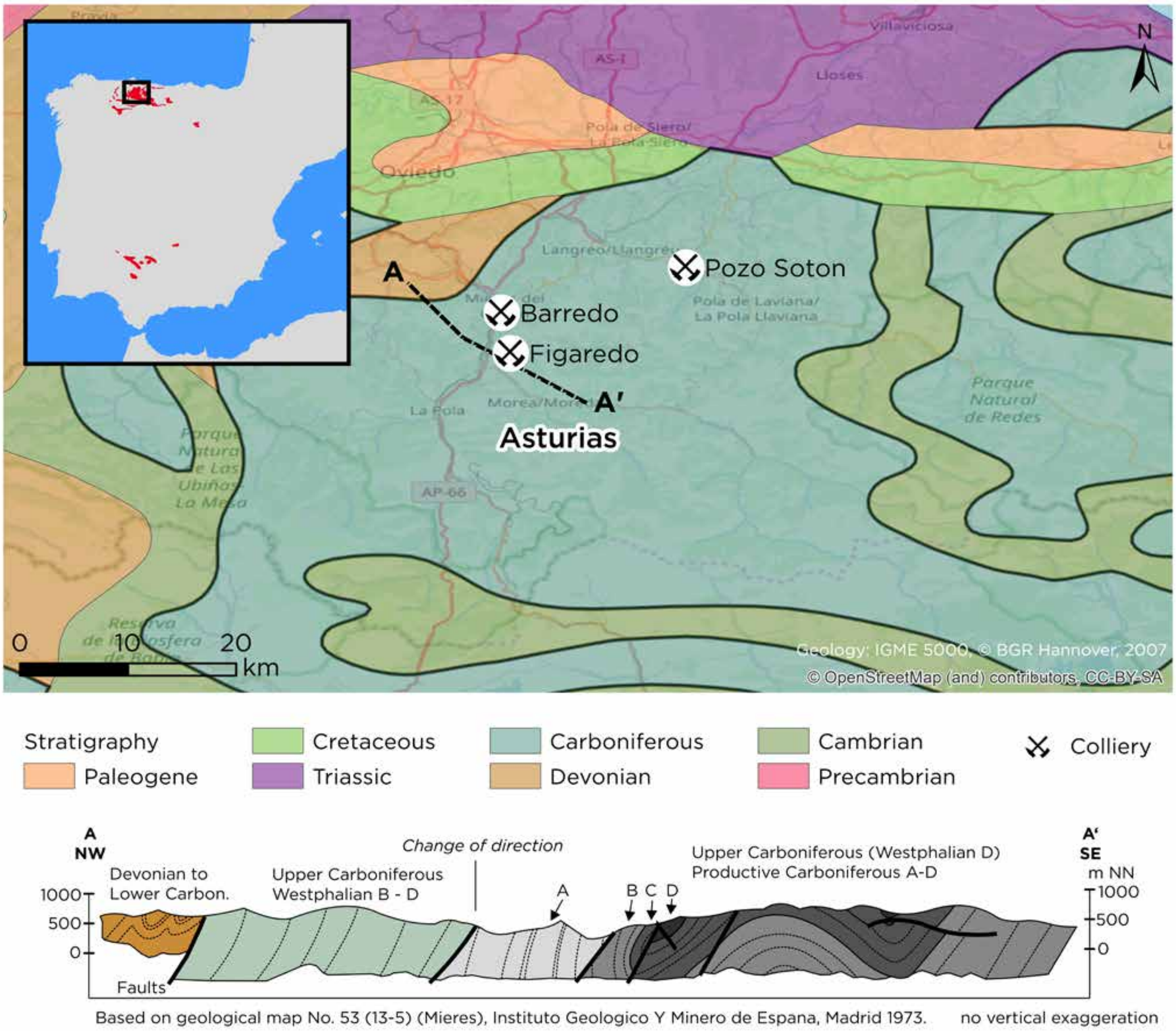


Fig. 58: Geographical and geological overview of selected collieries in the hard-coal mining region of Asturias (Spain); geology according to IGME (1973).

In Spain multiple hard-coal mining regions exist: the Sur Occidental 'combined' coalfield in the south-west with its eastern mining area Puertollano, the Sierra de la Demanda coalfield in the north, and the region of Asturias – by far the most important and extensive (Fig. 57). Since the mid-19th century, between 50 % and 70 % of the entire Spanish hard coal was extracted at Asturias (Ordóñez et al. 2012). At Asturias several coalfields are merged and form the Central Coal basin.

Until 1967, hard coal was mostly extracted by smaller collieries; in total, there were 131 coal mines. In 1967, the fifteen most important mines were merged in the organisation HUNOSA which onwards was responsible for around 50 % of the entire Spanish hard-coal production (Busch 1974). However, when compared to other EU hard-coal operations, in particular in the United Kingdom and Germany, the maximum yearly output rate in Spain in the 1980s with 16 MT was rather low.

In Spain hard-coal mining came to an end in 2018 as subsidies were discontinued. Unlike to Germany, there are some small and privately-run companies which continued their hard-coal mining operations even after 2018 without being subsidised.

Geology and Hydrogeology

In the Asturian deposit, the coal-bearing Carboniferous strata outcrop directly to the surface. Due to several tectonic processes the coal-bearing strata have been heavily

Fig. 59: Headframe at Barredo Colliery near the newly-built HUNOSA research centre and Oviedo University (photo: Bastian Reker).

deformed and are in parts almost vertically dipping which makes automated mining operations with high throughput rather difficult. The sedimentary succession in Asturias starts with Namurian limestones (Carboniferous) followed up by a series of limestones, sandstones and claystones of the *barren Carboniferous*, which is up to 3,500 m thick (Cienfuegos & Loredo 2010). Overlying the barren rocks, coal seam-bearing sediments are up to 3,000 m thick.

A special feature of the Asturian hydrogeology is that there are almost no considerable aquifers. The Carboniferous rocks mostly consist of clay- and siltstones with very low porosity and permeability. Interbedded layers of higher permeability and porosity (in particular sandstones) can form individual and confined aquifers; however, mining activities may disturb the surrounding rocks to such an extent that the sealing capacity of the clay layers is reduced and vertical conduits formed.

Mining

The two collieries Barredo and Figaredo are located in the Asturian coalfield, only a few kilometres south of the city of Oviedo (Fig. 58). At Barredo Colliery, hard coal was mined until 1993 (Fig. 59), at Figaredo Colliery mining continued until 2007. Both mine workings are hydraulically connected by several drifts. A more detailed description of the mining in the Asturian mining region has been published in Reker et al. (2019b).

Modelling the Mine Water Rebound

Mine water rebound in the region was modelled in Ordóñez et al. (2012). First of all, the total inflow volume was determined; this included not only water volumes transported during the mine dewatering but also the hydrogeological catchment area, the monthly precipitation and the water infiltrating from the river Turon. It needs to be emphasised that any groundwater entering the mine percolates vertically; there are no lateral inflows compared to most other mining regions. Accordingly, the inflow rate can be seen as constant irrespective of the mine water level as no lateral inflowing waters contribute to the mine water budget or could be inundated during an increasing mine water level. As a next step, the remaining void volumes in the mines were determined for the various depth intervals using *mine plans*, extracted tonnes of coal and the different mining methods applied. Combining the flow rate and the depth-related remaining void volumes allowed for computer-aided modelling using the GRAM program; this modeling could display the actual history of the mine water rebound (Fig. 60).

Subsequent Uses

In large parts of Asturias there are no considerable aquifers in place that can be used for public drinking water supply – this supply is mostly done using water from the Rioseco reservoir. Therefore, there is an opportunity to 'reclaim' the remaining working levels as regional artificial aquifers. Especially related to climate change this method would provide an alternative to secure and regulate the drinking water supply in hydrological difficult regions around the world. Ordóñez et al. (2012) and Jardón et al. (2013) suggest the use of the two collieries as artificial drinking water reservoirs. Assuming an average inflow of around 4 million m³ per year into the collieries Barredo and Figaredo, and proper regulating of the daily outtake, calculations anticipate that another 60,000 people could be supplied with drinking water every year (at an average consumption of approx. 185 L per person per day). The regulation would be necessary to ensure that the rate of the groundwater recharge – subject to seasonal fluctuations – and the potable and non-potable uses will be balanced over the year.

In addition to securing the public water supply, another added value could be to provide riverine systems with enough water during dry periods to ensure an ecologically needed minimum run-off. In relation to the long drought period of summer 2018 and 2019 in Europe, this method would be an interesting option for smaller watersheds.

Especially in the early 2010s, extensive studies were carried out for Barredo Colliery to estimate the geothermal potential of this mined coal deposit (Loredo et al. 2011; Ordóñez et al. 2012; Jardón et al. 2013). Meanwhile, the first pilot

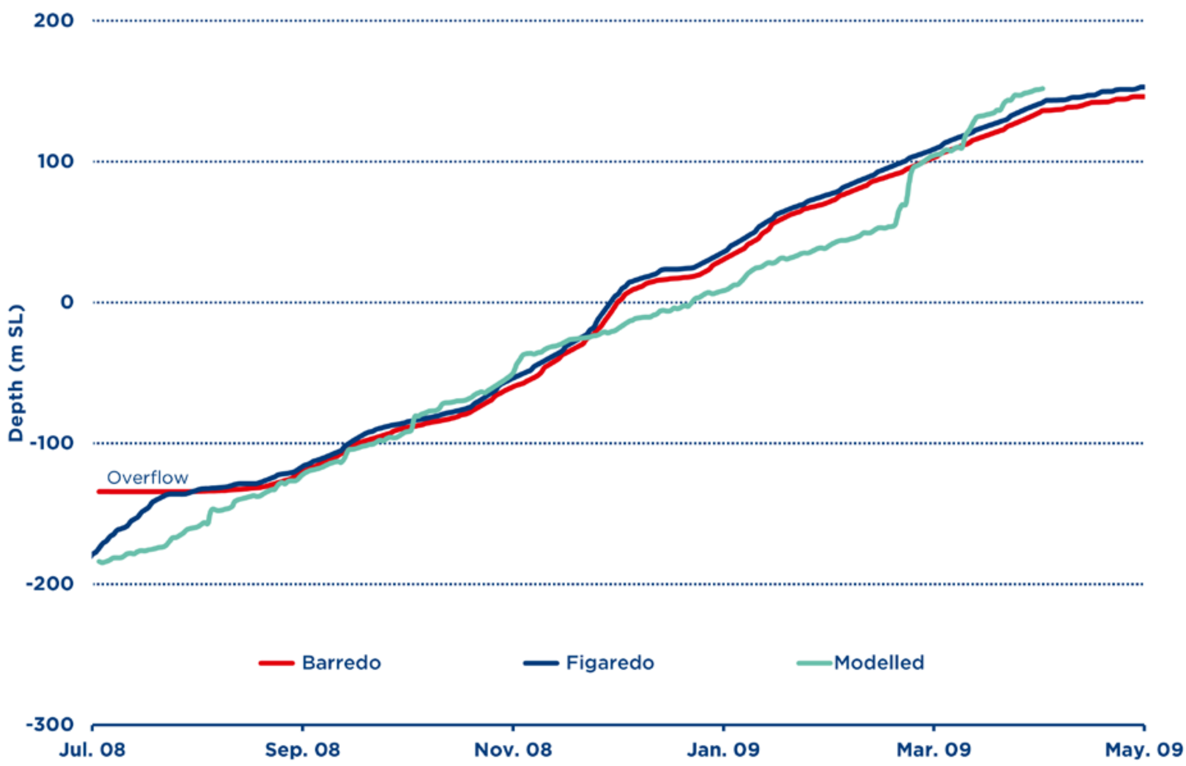


Fig. 60: Courses of the mine water rebound measured at Barredo Colliery (red curve) and Figaredo Colliery (blue curve) plus the modelled course (black curve). The depths of the worked main level are marked as horizontal red lines (Barredo) and horizontal blue lines (Figaredo).

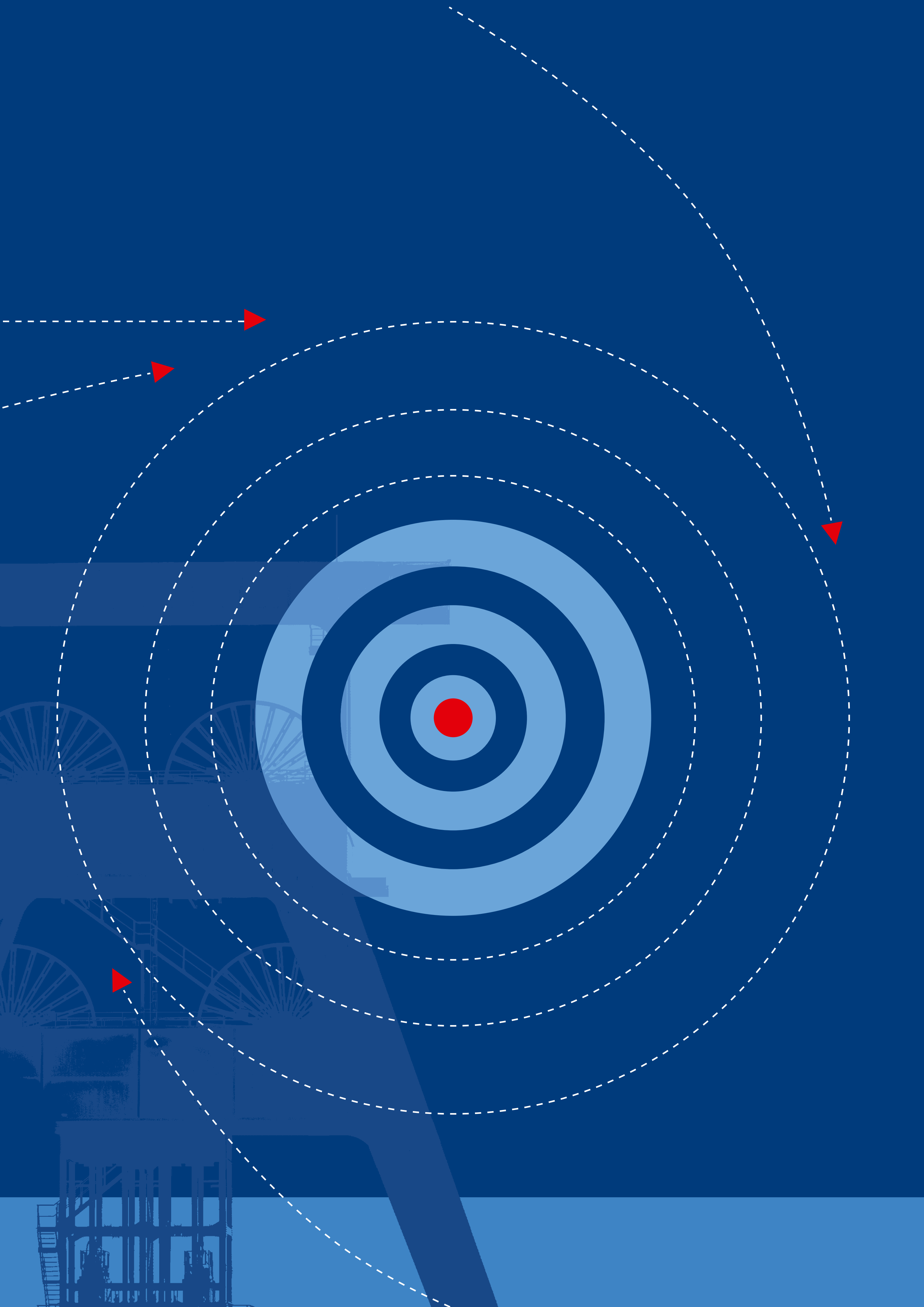
plants providing heat with capacities in the high-kilowatt to low-megawatt range have been installed in the building of the Campus de Mieres of Oviedo University (accommodating a HUNOSA research centre and a students' hall of residence) and the adjacent hospital Álvarez Buylla. For both plants, the water is lifted directly in the Barredo shaft with the winding tower still in place. Air conditioning of the Campus de Mieres is provided by an open-loop system (see info box on 'Geothermal Systems Open-Loop and Closed-Loop') with a power of 2 × 362 kW; for the hospital, a closed-loop configuration was chosen with a power of 3.5 MW which means that this system is now one of the largest geothermal air-conditioning systems in Europe (Gutiérrez Colinas et al. 2018).

Conclusion

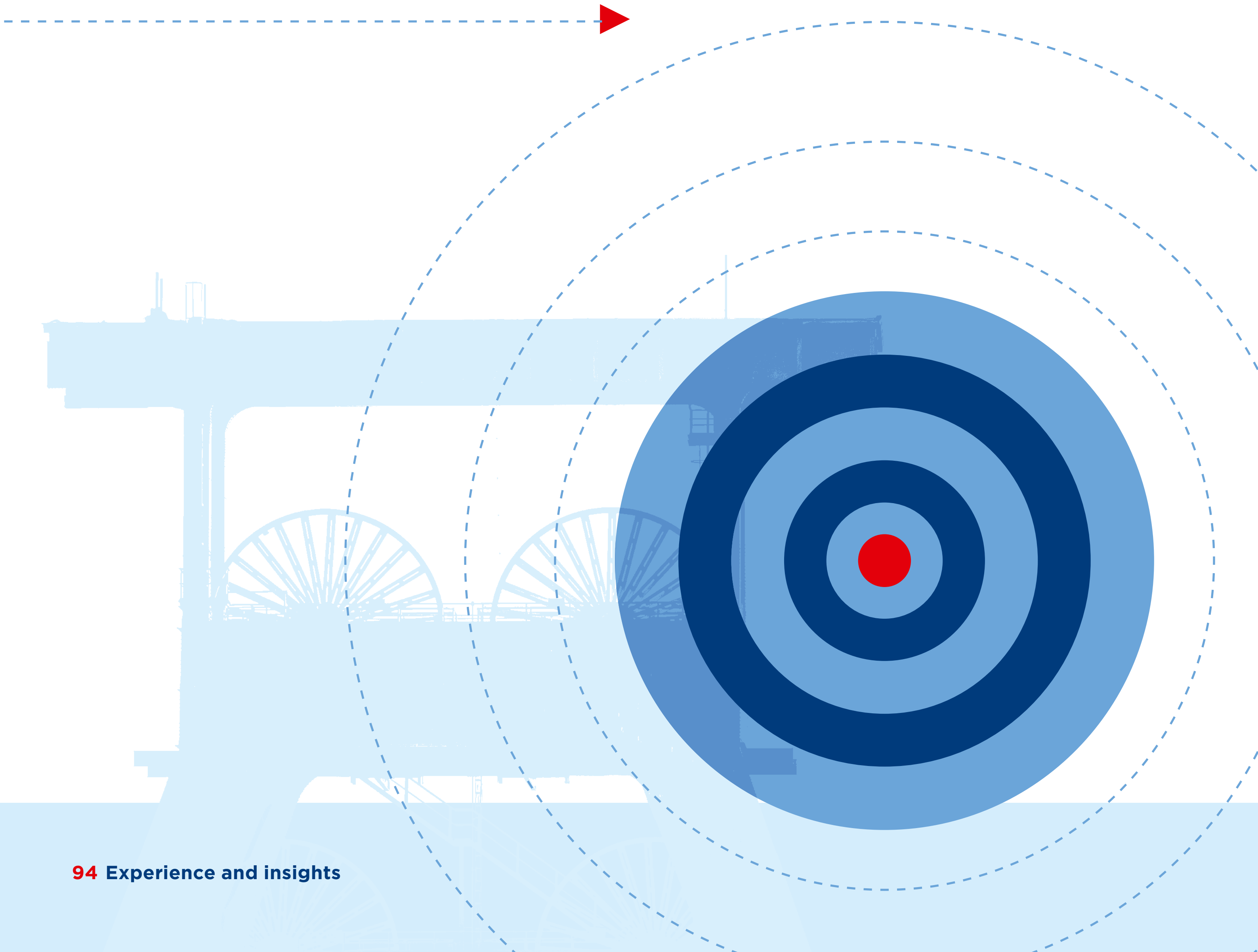
The mine water research results gained in Spain demonstrate that the determination of flow rates and void volumes are fundamental parameters of any mine water rebound modelling approach. Especially the insights based on mine related hydrogeological investigations provide the foundation to precisely record all inflows contributing to mine water budget. The evaluation of all existing mine plans, even historical ones, is of vital importance to be able to calculate the remaining void volumes available to be saturated during a mine water rebound. Both factors provide the modelling framework to accurately predict mine water rebound.

For the post-mining period in the Spanish mining districts, there are several utilisation concepts regarding mine water. On the one hand, there is the idea to use the abandoned mines as artificial reservoirs for drinking water; this idea would be a reasonable option in particular for dry climate conditions where drinking water supply is difficult. On the other hand, water could be supplied to intermittent streams during dry periods in order to maintain the ecological balance. This option would be an interesting added value especially with regard to the European Water Framework Directive. Moreover, the sustainable use of geothermal heat provided by mine water in large-scale heat exchanger systems, which are currently among the largest in Europe, is accompanied and examined by scientists. To sum up, there are numerous different approaches regarding a post-mining utilisation of mine water, and all of them underline that a mine water rebound should not only be seen as a threat, but also as an opportunity for reclamation .

4. Experience and Insights



This project on the Evaluation of Mine Water Rebound Processes in the German Coalfields of Ruhr, Saar, Ibbenbüren, and the adjacent European Countries carried out a systematic evaluation of mine water rebounds. Factors and processes were identified which influenced the pattern of mine water rebounds and the chemical composition of the mine water. Strategies and measures of current mine dewatering projects in European hard-coal mining regions have been evaluated. Thus, in-depth scientific knowledge has been developed that enables a profound understanding of the processes taking place during a mine water rebound in underground mine workings. The fundamental insights are summarised in this chapter.



Mine Water Rebound

- The history of mine water rebounds is influenced by numerous natural and anthropogenic causes; the main factors are the following:

Natural Factors

- intrinsic hydraulic conductivity of surrounding rocks,
- volumes of pores and joints,
- groundwater inflow rates,
- rate of groundwater recharge,
- thickness and lithology of the overburden,
- post-mining regulated level of the water level (anthropogenic influence possible),
- groundwater levels in the catchment area of the mine water rebounds.

Anthropogenic Factors

- mining-induced void volumes,
- intrinsic hydraulic conductivity of the mine workings,
- monitoring system with targeted control measures,
- mine drainage-induced cone of depression.

- To ensure a controlled mine water rebound, these factors need to be reviewed as precisely as possible; in an ideal case, the monitoring begins already during the exploration phase; in any case, it needs to be taken into account during and after the extraction stage. Once the mine has been decommissioned, such monitoring will be very difficult.

- Each course of mine water rebound is individual due to the specific on-site conditions. However, the underlying processes and interdependencies are comparable. Accordingly, the courses of mine water rebounds can generally be divided into three stages: the initial stage, the intermediate stage and the final stage.

- The velocities of mine water rebounds fluctuate between a few metres (e. g. at Lugau-Oelsnitz, Germany, with approx. 10 m/a) and several hundred metres per year (e. g. at Ibbenbüren Colliery, Westfeld, Germany, around 500 m/a; and at Lorraine, France, around 200 m/a).

- In a large number of German collieries (e. g. south-eastern Ruhr, Erkelenz, South Bavarian bituminous coal) the mine water has already reached its naturally equilibrated water level.

- Only in exceptional cases, the mine water rebounds evaluated here had adverse impact on the environment; specific examples are the mining regions of Durham (United Kingdom), where mine water infiltrated the groundwater and hence caused an impairment of the groundwater, and Erkelenz (Germany), where mine water rebound led to non-uniform ground upheaval in the vicinity of large tectonic fault zones which caused damages to buildings. Other impacts of that scale are not known to the authors in the reviewed mining region.

- Forecasts on the duration of historic mine water rebounds often assumed too short time intervals. Often these deviations in time are due to simplified assumptions or insufficient information on certain evaluated parameters within modelling approaches. When modelling the mine water rebound, two factors need to be considered in particular: the void volumes in relation to the specific depths and the groundwater inflow rate which should be monitored comprehensively.

- Uncertainties of the input data of a forecast can often be considered as a best-case, a base-case and a worst-case scenario. The forecast can be continually updated and adjusted by means of a monitoring programme that accompanies the mine water rebound. Courses of action and planning measures should always be based on the shortest period of the forecast.

Mine Water Chemistry

- A mine water rebound leads to a quantitative improvement and, in the medium to long term, also to a qualitative improvement at the mine water discharge points to receiving water courses. A higher mine water level leads to reduced discharge volumes. Deep groundwater of higher mineralisation is inundated and hindered to percolate further with a rising mine water level; this process mostly helps to attenuate the brine-type waters.

- During mine water rebound many cases exhibit an initial increase in the ionic composition of the mine water, a phenomenon also known as ‘first flush’; empiric data has demonstrated that this process lasts about four times as long as the rebound process itself. During a fast rebound, the initial concentrations of ionic species can be significantly higher compared to a slow rebound, but its duration of the first flush is shortened. The absolute number of moles of ions transported over time remains the same.

- When abandoned worked areas are inundated, further (di)sulphide oxidation (e. g. pyrite, marcasite, pyrrhotite) and the acidity from those oxidation products are attenuated .

- If a first flush levels off quickly in mines where water treatment is required, it will be optional to change from ‘complex’, i. e. continuously maintained, and costly systems (active systems) to systems which are technically still feasible and thus of economic and ecological advantage (passive systems).

- In a lot of hard-coal mining regions in the United Kingdom and in France (Lorraine mining region) as well as in Germany (Ibbenbüren) mine water treatment is currently being used to reduce potential contaminants, mostly those of dissolved iron concentrations. The majority of treatment systems applied are passive mine water purification plants which combine aeration with a settling pond as well as aerobic and anaerobic constructed wetlands. These wetlands offer not only economic benefits, but also ecological ones, as the area receives valuable habitats to develop a high biodiversity. The people often uses these wetlands which require in general a lot of space as local recreation areas.

- In the mining region of Upper Silesia (Poland) a pilot project is being undertaken to remove chloride from the mine water. For that purpose, the mine water is treated at several steps, from pre-treament extracting via membrane technology (reverse osmosis) and finally removal as concentrated brine.

- In Germany, feasibility studies are being carried out in the Ibbenbüren mining region on how to treat sulphate-containing mine waters.

- Currently, mine waters are treated in the German mining regions of Ruhr (collieries Robert Müser and Haus Aden) and Saar (Camphausen Colliery). Hydrogen peroxide (H_2O_2) is added to chemically oxidise hydrogen sulphide to elemental sulphur in order to eliminate *organoleptic* peculiarities (H_2S odour) where possible.

- While hard coal was being extracted at Auguste Victoria Colliery (Ruhr, Germany), sodium sulphate was added to the barium-containing mine water to precipitate barite (barium sulphate, $BaSO_4$) in order to remove high barium ion loads from the mine water.

- The inundation of lower mine areas significantly reduces the flow velocities; as a result, less suspended particles can be transported which reduces the mobilisation potential of pollutants.

- In many mines, even globally speaking, which experienced a mine water rebound in the past, stratifications formed in the mine waterbody. Density stratification is caused by separated convection streams and prevents a dilution of the involved water bodies, i. e. it separates the often highly conductive deep water from the less mineralised groundwater close to the surface and thus forms a natural hydrogeochemical barrier.

- A hydraulic potential difference between mine water and groundwater levels also prevents a dilution of the two adjacent waterbodies. In the United Kingdom (Durham mining region) and in France (Lorraine mining region) the potentiometric surface of the mine water has been maintained at just a few metres below the potentiometric surface of the groundwater for years, and there has been no infiltration of the groundwater so far.

Ground Movements

- The mine water rebound causes upheaval of the ground surface.

- Reasons for this are the hydrostatic pressure of the rising mine water, and the water percolation in the host rock which results in a swelling process of clay minerals (interstitial water).

- The ground upheaval only starts at a certain delay after the mine dewatering has been ceased. This delay depends on the conditions of each coalfield, mostly on the geological prerequisites in the deposit and the mine water rebound volume that was reached in total.

- The ground upheaval ranges from centimetres to a few decimetres and thus is diminishing compared to the mining-induced subsidence. According to the current state of knowledge, the inundation induced ground upheaval can be up to 0.5 m depending on the excavation volume.

- The ground upheaval usually occurs extensively and evenly and does not lead to any major terraces, shearing or compression at the surface. Damages to buildings are therefore not to be expected.

- Damages to buildings only occur if they are linked to geological large fault structures that are hydraulically sealing and outcrop to the ground surface or to mining-induced terraces where different hydraulic potentials are in place on both sides which consequently leads to ground upheaval differences. So far, evidence and indications of ground upheaval differences that caused damages to buildings have been documented in the mining regions of Erkelenz, Aachen and the Döhlen basin (all Germany) and in the coalfield of South Limburg (Netherlands).

- There are causal links between the pattern of the mine water rebounds and the ground upheaval in which the mine water rebound velocities correspond with the dimensions of the ground upheaval.
- The inundation-induced ground upheaval may reinforce once it reaches the overburden (e. g. the Dutch mining region of South Limburg).
- The catchment area of the mine water rebound can exceed that of the mining-induced subsidence area.
- A linear continuous history of the damage to buildings is seen as a good indicator of inundation-induced damages to buildings (Erkelenz mining region, Germany).

Gas Release

- The rising mine water mobilises free gases in the mine workings and in the porosity of the host rock; this is a prerequisite for gas migration.
- The quantity of the gas which is mobilised during the rebound corresponds with the volume of the mine water inflow .
- Due to the void space of the mine workings in its initial rebound phase, the proportion of the gas displaced by the mine water rebound is low compared to the proportion of the barometric degassing potential.
- The barometric degassing potential of the mine workings is successively reduced during the ongoing mine water rebound.
- After the inundation of the mine workings as well as the hard-coal deposit, it is to be expected that the gas release rate reaches a minimum and that the mine water-induced degassing process can be regarded as finished.
- As tests in Lorraine (France) have shown, small volumes of methane in the mine water continue to be dissolved and released over a long term even after the mine water rebound is finished. However, this process is most likely related to bacterial methanogenesis.
- No critical gas escapes caused by mine water rebound have been documented in any of the hard-coal mining regions evaluated.

Conceptualisation

- Safekeeping a mine, and in particular dealing with the mine water rebound, requires diligent planning ahead. During conceptualisation all sources of information available (historic files, expert opinions, mine plans, contemporary witnesses) should be taken into account.
- Where possible, there should be intensive thorough on-site inspection of the accessible mine workings before the mine water rebound is initiated in order to identify and record any potential hydraulic conduits.
- Alternative contingency plans should always be provided as options in any case of verified deviations from the forecast
- During the mine water rebound the initially developed concepts and plans should be continually optimised and aligned to the current state of knowledge and technology.

Monitoring

- Monitoring refers to a systematic programme that allows the observation, control and assessment of intrinsic processes in time and space in order to enhance process safety. Monitoring is used to control and check the performance linked to processes and developments, verify measurements and compare them with the forecast.

- Monitoring provides a reliable awareness system and the possibility to intervene and prevent or mitigate consequences where needed.

- Any mine water rebound must be accompanied by a monitoring programme that provides accurate information on the mine water level and its composition at any time.

- Monitoring goals need to be identified, suitable methods be selected, and inspection routines and control systems be defined up front; furthermore, baselines and threshold values have to be specified for conformance monitoring; additionally, monitoring tasks and appropriate control measures have to be installed.

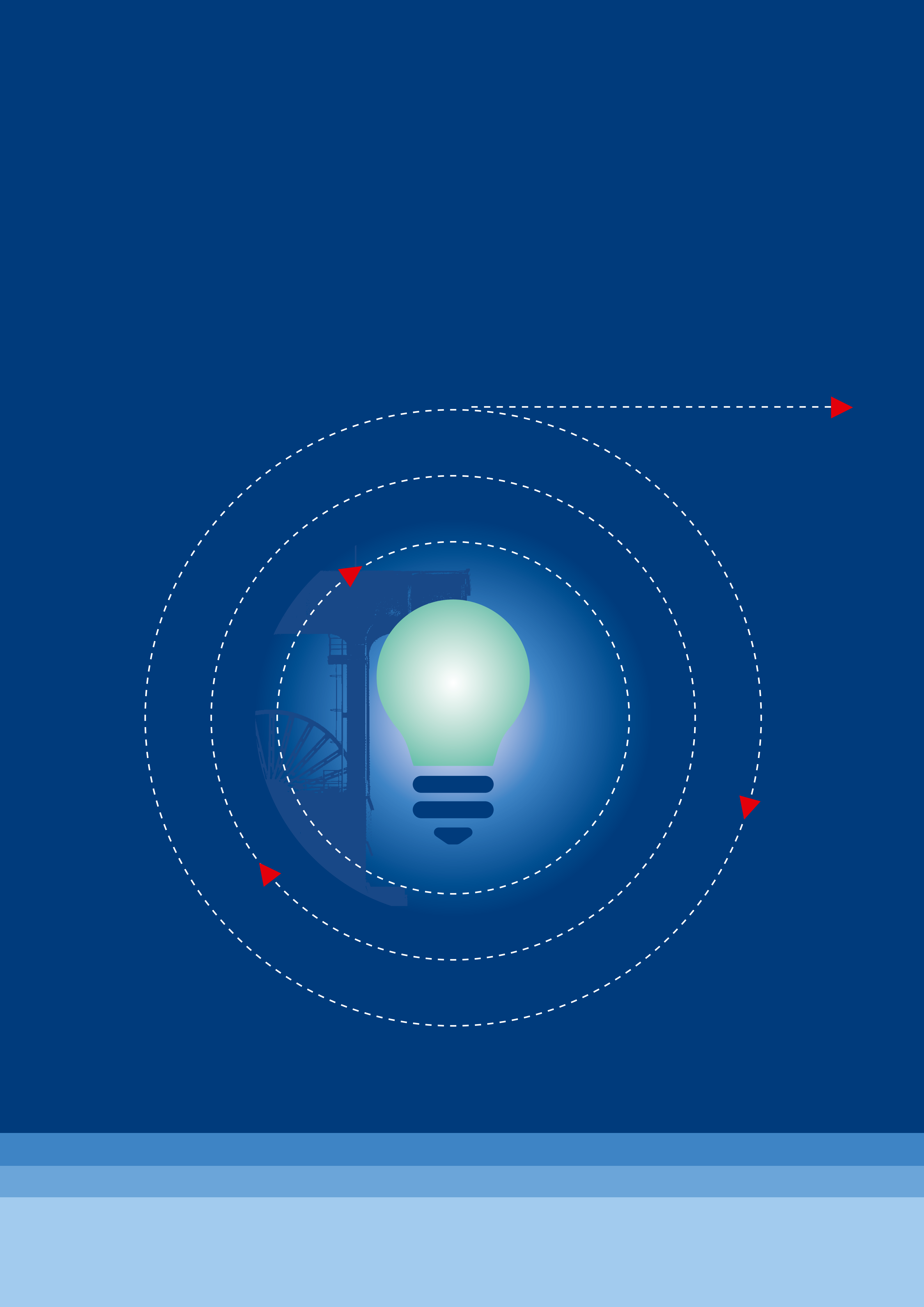
- In an ideal case, monitoring should cover the entire mining life cycle in alignment to the specific requirements.

- Monitoring also enables to enhance the understanding of the intrinsic processes and gain insights into their interdependencies

Conclusion

Sustainable mine water management is one of the paramount tasks of post-mining endeavours. Although a mine water rebound encompasses certain risks, it also offers a whole range of opportunities. A key future challenge will be to identify these opportunities, to assess them and to find ways of utilising them. This challenge is one to be tackled by the mining companies, but also by politics, the economy, the general public and, in particular, science.

5. Summary and Assessment



Mine Water Rebound

Mine water rebound is the common process after mining activities have been discontinued.

As a general rule, the mine water rebound in the mine workings and in the deposit provides significant advantage regarding mine water quality and its quantity in the long run.

Mine Water Chemistry

The mine water quality is particularly determined by the deposit (host rock), the geogenic inflows and the reaction products of the discharged areas of deposit and mine workings.

Furthermore, the mine water quality may be influenced due to manmade operating and backfilling materials (i. e. solids and fluids).

Ground Movements

The mine water rebound may lead to ground movements because of the induced hydrostatic pressure of the waters involved.

The scope of damage caused by mine-water induced ground movement is rather small compared to mining-induced subsidence rates.

Further research needs to be conducted regarding the interdependencies between the mine water rebound and the pattern of ground movements.

Gas Releases

Hazardous gas releases caused by the mine water rebound have not been documented in any of the hard-coal mining areas reviewed. As a result, the volume of mine gas mobilised during the mine water rebound is comparably low in relation to the mine gas release during operations.

Conceptualisation

To ensure a controlled mine water rebound diligent planning is necessary; it is a reasonable way forward to plan and implement the mine water rebound stepwise.

For each rebound stage, control values need to be set for the targets as well as for the warning and alarm signals; monitoring tasks and appropriate control measures have to be installed.

Monitoring

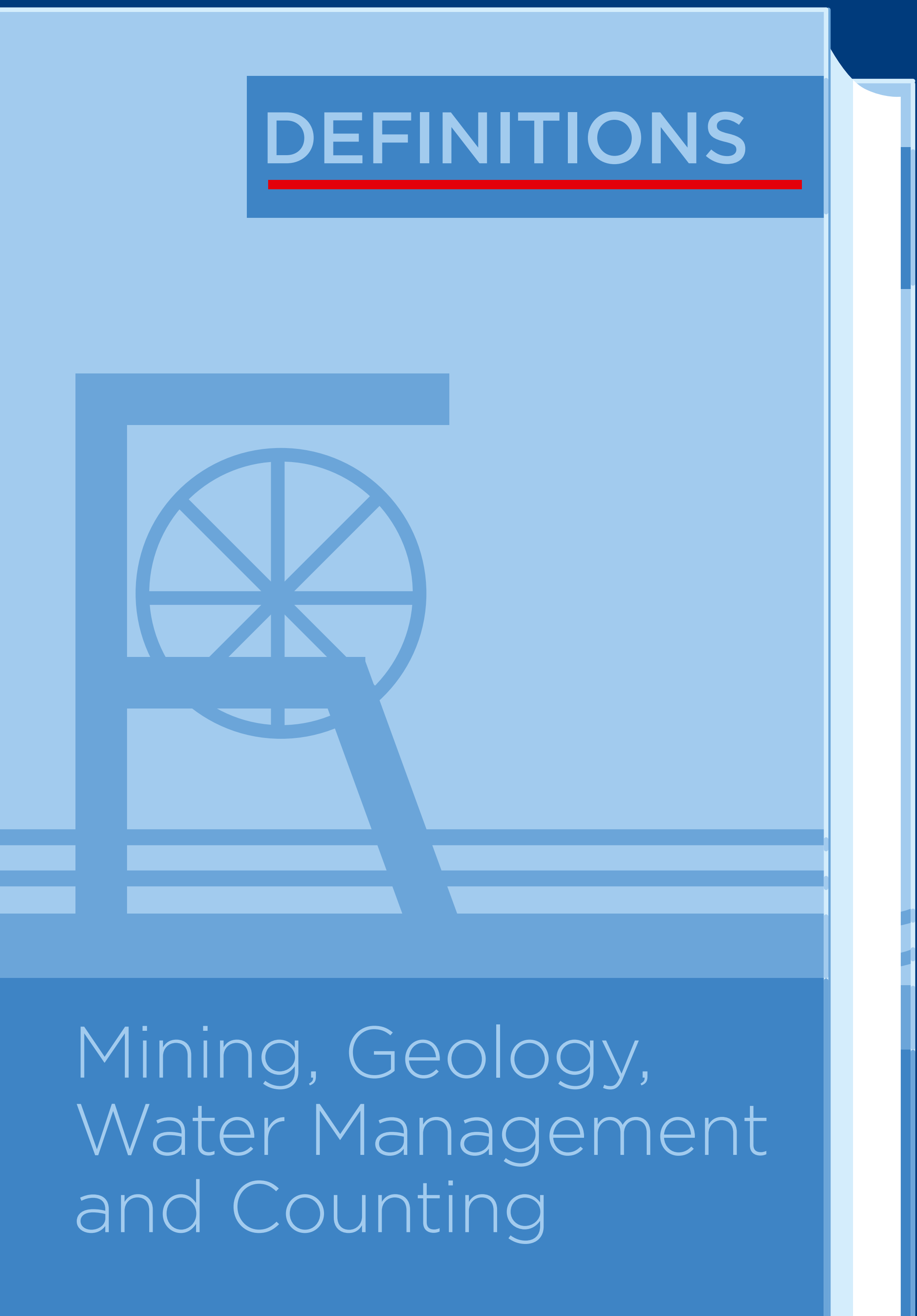
Monitoring is the key element to allow supervision and performance control of the mine water rebound, and it helps to better understand the intrinsic processes acting on the rebound.

Conclusion

The risks of a mine water rebound, i. e. the probability that damage will actually occur and the consequences to be expected, are comparably low in relation to the threat, i. e. possible adverse impact.

Based on the well-documented and evaluated experiences made in German and European hard-coal mining regions it can be concluded that the mine water rebound process can be technically managed.

6. Glossary


DEFINITIONS
Mining, Geology, Water Management and Counting

The definitions provided in this glossary have been taken from standard reference works of science and mining. The individual contributions are as follows: Bischoff (1998), Fellner (1999), Kentucky Coal Education (2011) and Kratzsch (2013) for mining terms; Burghardt et al. (2017) for terms of mine water management; Allaby & Allaby (1991), Gossauer (2006) Murawski & Meyer (2010), Press & Siever (1986) and Ramdohr & Strunz (1980) for terms of geology, geoengineering and mineralogy; Adam & Henke (1979) and Adam et al. (2000) for hydrogeological terms; Mortimer & Müller (2003) and Schmidt (2006); for chemical terms, and Brockhaus (1980) and Martin et al. (2002) for several other terms. Individual citations are not given.

acidity
The content of acid in a substance.

adhesive water
Water in the unsaturated zone which forms a thin film around solid particles and is resisting gravity, for example, adsorptive water and capillary water.

adit
An approximately horizontal mine tunnel as part of the mine workings, which permits access from the ground surface, to ensure free discharge of water, ventilation and the transport of ore and coal.

anion
An atom or group of atoms carrying a negative charge.

aquifer
A rock body suitable for the infiltration of water.

aquifuge
A completely impermeable rock layer that does not allow groundwater to flow through.

aquitard
A zone within the subsurface that restricts the flow of groundwater, comprising layers of clay or other low-permeable rocks.

barren Carboniferous
Carboniferous rocks where mineable coal deposits, i. e. no seams, are embedded.

bottom
The lower boundary of a cut roadway, a seam or a geological unit (stratum, rock body).

capillary water
Water above the water level that is lifted or held by surface tension forces (capillary action).

Carboniferous horst
A part of Carboniferous strata – a horst is a raised fault block bounded by normal faults.

carbonification
The process in which organic matter is transformed from peat to different types with increasing carbon content, i. e. soft coal and hard coal to anthracite coal.

catalysis
The process of increasing the rate of a chemical reaction by adding a substance known as a catalyst which is not consumed in the catalysed reaction and can continue to act repeatedly.

cation
An atom or group of atoms carrying a positive electric charge.

claystone
A clastic sedimentary rock consisting mostly of clay and silt grain sizes (less than 0.0625 mm); refers also to thin layers of fine-grain clay materials in the hard-coal bearing rock.

coal mine methane
Refers to methane released from the coal and surrounding rock strata due to mining activities. In underground mines, it can create an explosive hazard to coal miners, so it is removed through ventilation systems. In abandoned mines and surface mines, methane might also escape to the atmosphere through natural fissures or other diffuse sources.

cone of depression
Depression in the shape of a cone of the piezometric groundwater surface which defines the area of influence of a well.

convergence
The reduction in length from the approximation of the roof and floor part of the seam caused by lithostatic (i. e. confining) pressure.

deep water
A synonym of deeply seated groundwater.

deposit
Any natural accumulation of usable minerals, rocks, petroleum, natural gas and other gases in the soil or underground.

depression
A vertical displacement of points at the ground surface or in the rock mass because of mining activities.

depression null boundary
A line of all points which separates

the mining-induced catchment area from the non-operating area at the ground surface.

disintegration zone
Rock formations which have been intensively folded or which have been fragmented by curved sliding or crushing surfaces.

dook workings
Carrying out extraction works below the main working level.

fault
Tectonic faults are sites of localised motion both at the earth surface and subsurface – as a consequence the two adjacent blocks separated by the fault are displaced.

goaf
Abandoned, blocked, filled or collapsed part of the mine workings, also known as gob.

(un-)got
Synonym of (not) worked, e. g. in a rock mass where mine workings have already been established; also known as (un)disturbed.

ground movement
Any deformation or displacement (movement, translation) of the ground surface.

groundwater
Underground water contained in the void space between rocks (lithosphere) or percolating and whose possibilities to move are solely determined by gravity.
The following distinctions are made:

- unconfined groundwater whose water level and hydraulic head are identical in the area examined,
- confined groundwater whose water level and hydraulic head are not identical in the area examined,
- artesian groundwater whose hydraulic head lies above the ground surface in the area examined.

hard-coal bearing rock
The entity of all strata in which hard-coal seams are interbedded.

hydraulically inundated
Refers to an increase of hydrostatic pressure on an inflow point due to rising mine water.

hydraulic head
Specific measurement of hydrostatic pressure above a vertical datum, measured as liquid surface elevation using a piezometer and expressed in unit of length.

inclination
Inclined angle of the surface to be measured with regard to the horizontal level.

in situ
Synonym of on-site (Latin).

lateral drift
Side openings from the mine workings which are cut to allow for an examination of this rock part.

leaky aquifer
Large-scale percolation of groundwater through a groundwater aquitard from one groundwater stockwork into another.

level
Bottom of mine workings.

levelling line
Accumulation of several successive levelling points.

limestone
Sedimentary rock composed of up to 50 % of $CaCO_3$ (calcium carbonate) or $CaMg(CO_3)_2$ (dolomite).

limnic
Refers to processes, products and settlements in freshwater lakes.

main working level
The level of mine workings in which the major extraction takes place.

marl
Sedimentary rock composed of limestone and clay; contains up to 65 % $CaCO_3$ (calcium carbonate) and 35 % clay.

Mesozoic Era
A stratigraphic time interval also referred to as the middle ages of the Earth including the Triassic, Jurassic and Cretaceous periods (251 – 65 million years ago).

mine dewatering
All measures that can be taken to discharge or keep water away from the mine workings and all technical equipment used for this purpose.

mine dewatering location
A location from which the mine water is pumped to the ground surface.

mine methane
Refers to methane released from the coal and surrounding rock strata due to mining activities. In underground mines, it can create an explosive hazard to coal miners, so it is removed through ventilation systems. In abandoned mines and surface mines, methane might also escape to the atmosphere through natural fissures or other diffuse sources.

mine plan
Contains all draft, charts and maps which are needed for the planning, operation, and the technical, economic and safety-related monitoring of a mine.

mine water
Any water that has come or comes into contact with underground or open-cast mining operations.

mine water drainage
Pumping of the mine water.

mine water inrush
Sudden outflow of large water volumes from inundated mine areas or water-conducting fractures into the mine workings.

mine water rebound
The rise of the water levels in the mine workings resulting from 1.) the reduction or cessation of mine dewatering or 2.) the addition of water.

mine working
The entire system of openings in a mine for the purpose of exploitation.

mining damage
Deformation at the ground surface causing damages to buildings based

on it caused by mining-induced subsidence, non-uniform tectonics comprising sloping, shearing or compression.

mining region
Region in which mining and smelting is or was done at a notable scale.

mining subsidence
Mining-induced depression of the rock formations visible at the surface due to convergence of anthropogenic void space in the subsurface.

ochre iron
A natural earth pigment of yellowish to deep orange/brown colour consisting mainly of iron oxides or oxyhydroxides (goethite, limonite) with various amounts of clay. It precipitates from mine water due to the partial or full oxidation of dissolved bivalent iron to trivalent iron; the process can be a chemical one or microbially mediated (e. g. ferric bacteria).

organoleptic
Refers to sensory perception.

oscillation
A repetitive regular variation in magnitude or position about a mean value.

overburden strata
In mining, the entity of all strata overlying the economically exploitable strata, e.g. above a coal seam or an ore deposit (economic geology).

oxidation
The loss of electrons during a reaction by a molecule, atom or ion; its oxidation number is therefore raised; historically it is associated with the reaction involving oxygen because atmospheric oxygen as a strong oxidant gains electrons and will be reduced in a so called redox reaction.

Persistent Scatterer Interferometry (PSI)
A method to display a test area using two or more different sensor positions. The information gained can be used for generating digital elevation models, detecting changes in position at centimetre range, multitemporal classifications or detecting movable scatterers.

polder
An area in mining regions that has lost its receiving water courses due to mining subsidence and must be artificially drained.

process water
Water used in mining operations for cooling, cleaning, binding dust, explosion protection and purging wells.

pyrite oxidation
The oxidation of iron disulphides (FeS_2) where an oxidant is present (O_2, Fe^{3+}, NO_3^-).

pyroclastic
Generic terms for all clastic products of volcanic origin (e. g. ashes, volcanic breccia).

receiving water course
A river, ocean, stream, or other watercourse into which wastewater or treated effluent is discharged.

roadway
A horizontal or nearly horizontal part of the mine workings of a regular, more or less steady cross section. Contrary to a drift, a roadway does not lead to the ground surface but to a shaft or commences in other mine workings. Depending on the type of use, there are different types of roadways: main roadways, bottom roadways, top roadways, gate roadways or panels, ventilation roadways, water roadways or gates.

roof
The upper boundary of a roadway, a seam or a geological unit (stratum, rock body).

safety distance
A protective area in mining where no mineral is mined for safety purposes.

sagging
Vertical displacement of the surface due to a collapse of the granular structure caused by compaction; groundwater saturation of the pores in the unconsolidated soil facilitates the movement of grains due to gravitational forces as it reduced frictional forces between the grains.

salinity
Total concentration of dissolved solids (i. e. ions) in brines and seawater, mostly sodium chloride (NaCl).

salt freight
The mass of dissolved solids or certain individual ions transported in an effluent or waterway and determined in a defined cross section of the water.

sandstone
Clastic sedimentary rock made up of grains with a grain size between 0.02 mm and 2 mm.

seepage water
Underground water which percolates in the unsaturated zone due to gravity.

settlement
Perpendicular deformation of the building ground due to external loads imposed or to ground motion induced by compaction of the unconsolidated sediment.

shaft
Usually upright, sometimes also inclined, part of the mine workings which connects the underground workings with the ground surface or two or more levels with each other. Shafts which don't reach the surface are called inside or blind shaft.

shrinkage
Volume reduction due to capillary tensions which occur in cohesive soils as the water content reduces and pores become increasingly smaller. The scope of depressions caused by shrinkage depends on the volume at which the water content reduces as well as on how thick the soil is and how fine the pores of the soil are.

siltstone
Clastic sedimentary rock consisting of grains with a grain size in between 0.002 mm and 0.02 mm.

sorption process
A selective process in which one substance incorporates another

substance it is in contact with. Adsorption refers to the collecting of molecules by the external surface or internal surface (walls of capillaries or crevices) of solids or by the surface of liquids. Absorption, with which it is often confused, refers to processes in which a substance penetrates into the actual interior of crystals, of blocks of amorphous solids, or of liquids. Sometimes the word sorption is used to indicate the process of the taking up of a gas or liquid by a solid without specifying whether the process is adsorption or absorption.

stagnant water
1.) The accumulation of water in natural or artificial voids which can lead to uncontrolled and thus dangerous inrushes of water. 2.) Standing water in old abandoned mines.

stratigraphy
The geological subscience of description, correlation, and classification of strata in sedimentary rocks, using all of their inorganic and organic features including the interpretation of the depositional environment of those strata in order to set out a timeline of geological processes and events.

sulphates
The salts of sulphuric acid.

surface collapse
The collapse funnel at the ground surface caused by the underground mines.

tectonic process
The scientific study of the deformation of the rocks that make up the Earth's crust and the forces that produce such deformation, i. e. thrusts, folds, fractures, faults etc.

terrace
Geomorphologic expression of a discontinuity at the ground surface which has been formed by uneven subsidence.

terrigeneous sediment
Any sediment that is derived from terrestrial environments (e. g. the erosion of rocks on land).

thermodynamics
The science of the relationship between heat, work, temperature, and energy. In broad terms, thermodynamics deals with the transfer of energy from one place to another and from one form to another. The key concept is that heat is a form of energy corresponding to a definite amount of mechanical work.

ventilation
The systematic supply of mines and mine workings with fresh air from the surface.

ventilation system
All of the equipment and measures taken to bring atmospheric air into the mine workings.

volcanogenic-tectonic
Volcano tectonics is a scientific field that uses the techniques and methods of structural geology, tectonics, and physics to analyse and interpret physical processes and the associated deformation in volcanic areas, at any scale.

water treatment plant
A plant used for the physical or physico-chemical processing of resources into saleable or technically usable products .

7. References

Adam, C., Glasser, W. & Hölting, B. (2000): Hydrogeologisches Wörterbuch. – 311 p.; Stuttgart (Thieme).

Adam, C. & Henke, J. (1979): Hydrogeologische Untersuchungen. – 1st ed: 69 p.; Leipzig (VEB Deutscher Verlag für Grundstoffindustrie).

Allaby, A. & Allaby, M. (eds.) (1991). The Concise Oxford Dictionary of Earth Sciences; Oxford (OUP).

Asch, K. (2005): IGME 5000. 1 : 5 Million International geological map of Europe and adjacent areas; Hannover (BGR).

Bässler, R. (1970): Hydrogeologische, chemische und Isotopen-Untersuchungen der Grubenwässer des Ibbenbürener Steinkohlenreviers. - Z. dt. geol. Ges., Sonderheft Hydrogeologie und Hydrogeochemie: 209–286.

Baglikow, V. (2003): Bergschäden nach Beendigung der Grubenwasserhaltung im tiefen Bergbau. – Markscheidewesen, **110**(2): 45–49.

Baglikow, V. (2010): Schadensrelevante Auswirkungen des Grubenwasseranstiegs im Erkelenzer Steinkohlenrevier. – Dissertation, RWTH Aachen: 121 p.; Herne (Blömeke). – [Schriftenreihe / Institut für Markscheidewesen, Bergschadenkunde und Geophysik im Bergbau an der Rheinisch-Westfälischen Technischen Hochschule Aachen, **2010**,1].

Baglikow, V. (2019): Belange von Grundstückseigentümern im Rahmen eines Grubenwasseranstiegs. – [presentation at the conference NACHBergbauzeit in NRW at THGA Bochum on 7.3.2019]. – 9 p. – available online at: https://www.vbhg.de/images/downloads/Dr_Baglikow/Baglikow_-_Belange_von_Grundeigentümern.pdf (retrieved on 17.04.2019).

Baltes, B. (ed.) (1998): Entwicklung und Anwendung analytischer Methoden zur Eignungsuntersuchung der Verbringung bergbaufremder Rückstände in dauerhaft offene Grubenräume im Festgestein – Abschlussbericht (Hauptband). – VI + 126 p.; Köln (Gesellschaft für Anlagen und Reaktorsicherheit (GRS) mbH). – [GRS / Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, **140**]. – available online at: https://www.grs.de/sites/default/files/pdf/GRS-140.pdf (retrieved on 17.04.2019).

Bamler, R., Adam, N., Hinz, S. & Eineder, M. (2008): SAR-Interferometrie für geodätische Anwendungen. – Allg. Vermess.-Nachr., **115**(7): 243–252.

Banks, D. (2001): A variable-volume, head dependent mine water filling model. – Ground Water, **39**(3): 362–365.

Banks, D., Athresh, A., Al-Habaibeh, A. & Burnside, N. (2019): Water from abandoned mines as a heat source: practical experiences of open- and closed-loop strategies, United Kingdom. – Sustainable Water Resources Management, **5**(1): 29–50.

Bearcock, J. & Smedley, P.L. (2009): Baseline groundwater chemistry: the Magnesian Limestone of County Durham and north Yorkshire. – 63 p. – [British Geological Survey Open Report, **OR/09/030**]. – available online at: http://nora.nerc.ac.uk/id/eprint/8147/ (retrieved on 01.05.2019).

Bekendam, R. (2017): Abschätzung der Bodenhebungen in Folge des Grubenwasseranstiegs über stillgelegten Kohlegruben im Südlimburger Revier. – In: Meier, G., Benndorf, J., Löbel, K.-H., Butscher, C., Tondera, D. & Busch, W. (eds.): 17. Altbergbau-Kolloquium 16. bis 18. November 2017 in Freiberg: 118–130; Nossen (Wagner).

Benson, S. (1999): Coal in Hungary. – 37 p.; London (IEA Coal Research). – [CS, **07**].

Bernard, B., Brooks, J.M. & Sackett, W.M. (1977): A geochemical model for characterization of hydrocarbon sources in marine sediments. – 9th Annual Offshore Technology Conference, Preprints, **3**: 435–438.

Berthold, S. (2009): Geophysikalischer Nachweis freier Konvektion in Grundwassermessstellen und Bohrungen. – Dissertation, TU Dresden: XVI + 230 p.; Dresden (DGFZ). – [Proceedings of DGFZ e. V., **39**, dissertation].

Binnewies, M., Finze, M., Jäckel, M., Schmidt, P., Willner, H. & Rayner-Canham, G. (2016): Allgemeine und Anorganische Chemie. – 3., completely revised ed.: XXIII + 965 p.; Berlin (Springer Spektrum).

Bischoff, W. (1998): Das kleine Bergbaulexikon. – 8., unchanged ed.: 404 p.; Essen (Glückauf publ.).

Bluma, L., Farrenkopf, M. & Przigoda, S. (2017): Geschichte des Bergbaus. – 1st ed.: 272 p.; Berlin (L & H Verlag). – [Publication by the German Mining Museum Bochum, **225**].

Blume, H.-P., Brümmer, G. W., Horn, R., Kandeler, E., Kögel-Knaber, I., Kretzschmar, R., Stahr, K. & Wilke, B.-M. (2010): Scheffer / Schachtschabel – Lehrbuch der Bodenkunde. – 16. ed.: XIV + 569 p.; Heidelberg (Spektrum, Akademischer Verlag).

Branchet, M. & Kaiser, R. (2001): Die Einwirkungen der Grubenwasserflutung des Bergwerkes Faulquemont auf die Stabilität der Erdoberfläche. – In: Deutscher Markscheiderverein/ Bezirksgruppe Saar/Arbeitsgruppe Fachvorträge, Schramm, H.-G., Kloy, G., Oberbergamt Saarland, Oberbergamt Rheinland-Pfalz, Uhl, O. & DSK AG (Bergwerk Ensdorf) (eds.): Markscheidewesen, quo vadis? – Mensores fodinarum Augustae Treverorum (in urbe opulentissima) – 43. Wissenschaftliche Tagung des Deutschen Markscheider-Vereins e. V., 26.–29. September 2001 in Trier: 141–154; Dillingen (Krüger). – [Das Markscheidewesen in der Rohstoff-, Energie- und Entsorgungswirtschaft, **43** = Scientific series of publication in mine surveying, **20**].

Brockhaus (1980): Brockhaus ABC Naturwissenschaft und Technik. – 13., revised and ext. ed.: 1441 p.; Leipzig (F.A. Brockhaus).

Büttgenbach, F. (1898): Geschichtliches über die Entwicklung des 800 jährigen Steinkohlenbergbaues an der Worm (1113 - 1898) – Nebst Situationskarte des Wormreviers. – 29 p.; Aachen (Schweitzer).

Büttner, R., Brede, M., Lübken, F.-J. & Leder, A. (2012): Experimentelle Untersuchung zur Ausbreitung und Transition interner Wellen. – In: Leder, A., Brede, M., Ruck, B. & Dopheide, D. (eds.): Lasermethoden in der Strömungsmesstechnik. – 20. Fachtagung, 4.–6. September 2012, Rostock. Tagungsband: 39/1–39/11; Karlsruhe (Dt. Gesellschaft für Laser-Anemometrie GALA e. V.).

Buntzel, A. (1911): Über die in Oberschlesien beim Abbau mit Spülversatz beobachteten Erdsenkungen. – Berg-, Hütten- und Salinenwesen, **59**: 293–334.

Burchard, H., Craig, P.D., Gemmrich, J.R., van Haren, H., Mathieu, P.-P., Meier, H.E.M., Nimmo Smith, W.A.M., Prandke, H., Rippeth, T.P., Skyllingstad, E.D., Smyth, W.D., Welsh, D.J.S. & Wijesekera, H.W. (2008): Observational and numerical modeling methods for quantifying coastal ocean turbulence and mixing. - Progress in Oceanography, **76**: 399-442.

Burghardt, D., Coldewey, W.G., Melchers, C., Messer, J., Paul, M., Walter, T., Wesche, D., Westermann, S., Wieber, G., Wisotzky, F. & Wolkersdorfer, C. (2017): Glossar Bergmännische Wasserwirtschaft. – 1st ed.: 78 p.; Neustadt/Wstr. (Arbeitskreis Grubenwasser der Fachsektion Hydrogeologie e.V. in der DGGV e.V. [FH-DGGV]).

Burke, S. & Barber, J. (2004): An overview of mine water rebound in the South Yorkshire Coalfield. – In: Jarvis, A. P., Dudgeon, B.A. & Younger, P.L. (eds.): International Mine Water Association Symposium – proceedings of the symposium: Mine Water 2004 – process, policy and progress. Newcastle upon Tyne, United Kingdom, 20-25 September 2004, **1**: 1. Aufl.: 61–66; Newcastle-on-Tyne (University of Newcastle upon Tyne).

Burke, S.P. (2017): Informations from personal discussions and messages during the survey of the Yorkshire coal field (United Kingdom) in April 2017.

Burke, S.P., Potter, H.A.B. & Jarvis, A. (2005): Groundwater rebound in the South Yorkshire Coalfield: a review of initial modelling. – In: Loredo, J. & Pendàs, F. (eds.): 9th International Mine Water Association Congress – proceedings of the Congress - Mining Clossure; 5.–7. September 2005: 223–227; Oviedo (Dep. de Explotación y Prospección de Minas, Univ. de Oviedo).

Burke, S.P. & Younger, P.L. (2000): Groundwater rebound in the South Yorkshire Coalfield: a first approximation using the GRAM model. – Quarterly journal of engineering geology and hydrogeology, **33**(2): 149–160.

Busch, K. (1974): Spanien. – IX + 160 S.; Stuttgart (Schweizerbart). – [Rohstoffwirtschaftliche Länderberichte, **4**].

Busch, W., Coldewey, W. G., Walter, D., Wesche, D. & Tielmann, I. (2012): Analyse von Senkungserscheinungen außerhalb prognostizierter Einwirkungsbereiche des Bergwerks Prosper-Haniel. – Gutachten der TU Clausthal und der WWU Münster vom 31.8.2012 im Auftrag der Bezirksregierung Arnsberg (Abt. 6), 140 p.; Clausthal-Zellerfeld. – available online at: https://www.bezreg-arnsberg.nrw.de/presse/2012/09/160_12/gutachten.pdf (retrieved on 03.05.2019).

Cairney, T. & Frost, R.C. (1975): A case study of mine water quality deterioration, Mainsorth Colliery, County Durham. – Journal of Hydrology, **25**(3/4): 275–293.

Christensen, J. (2007): Explosionsfähigkeit von Methan in Luft nach Coward (1938). – Prüfstelle für Grubenbewetterung der DMT, Essen. – [unpubl. expert opinion].

Cienfuegos, P. & Loredo, J. (2010): Coalbed methane resources assessment in Asturias (Spain). – International Journal of Coal Geology, **83**(4): 366–376.

Clarke, L.B. & McConville, A. (1998): Coal in the Czech Republic. – 36 p.; London (IEA Coal Research). – [CS, **03**].

Coal Authority (2014): Outline for scope of works Yorkshire Coalfield – Rising Mine Water Assessment. – [Ausschreibung CA18/2311 Instr. 121 and CA08/20/3/239/3 the Coal Authority in June 2014].

Cohen, K.M., Finney, S.C., Gibbard, P.L. & Fan, J.-X. (2013): The ICS International Chronostratigraphic Chart. Episodes 36: 199–204. – available online at: http://www.stratigraphy.org/ICSchart/ChronostratChart2017-02.pdf (retrieved on 31.05.2019).

Coldewey, W.G., Hewig, R., Richter, R., Rüterkamp, P. & Wedewardt, M. (1999): Abschlussbericht zum Untersuchungs- und Entwicklungsvorhaben: Mittelfristige Entwicklung des Chemismus und der Dichte-Schichtungen von Grubenwassern in Bergwerken und ihre Auswirkungen auf nutzbares Grund- und Oberflachenwasser – Vorhaben, gefördert mit den Mitteln des Landes Nordrhein-Westfalen aus dem Technologieprogramm Bergbau. – 83 p. – [unpubl. expert opinion].

Corbel, S., Kaiser, J. & Vicentin, S. (2017): Coal mine flooding in the Lorraine-Saar basin: experience from the French mines. – In: Wolkersdorfer, C., Sartz, L., Sillanpää, M. & Häkkinen, A. (eds.): Proceedings 13th International Mine Water Association Congress - Mine water & circular economy – Lappeenranta, Finland, June 25 - 30, 2017, **Vol. 1**: 161–166; Lappeenranta (LUT Scientific and Expertise Publications). – [LUT Scientific and Expertise Publications: Research Reports, **63**].

Cosquer, R. (2016): Compterendu d'activités DPSM – Année 2015 / Lorraine – Rapport final. BRGM/RP-65651-FR, Mars 2016. – 143 p.; Orléans (BRGM). – available online at: http://infoterre.brgm.fr/rapports/RP-65651-FR.pdf (retrieved on 24.05.2019).

Couch, G., Hessling, M., Hjalmarsson, A.-K., Jamieson, E. & Jones, T. (1990): Coal prospects in Eastern Europe. – 117 p.; London (IEA Coal Research). – [IEACR, **31**].

Cravotta, C.A. (1993): Secondary ironsulfate minerals as sources of sulfate and acidity. – In: Alpers, C.N. & Blowes, D.W. (eds.): Environmental geochemistry of sulfide oxidation – developed from a symposium sponsored by the Division of Geochemistry, Inc., 204th National Meeting of the American Chemical Society, Washington, DC, August 23 - 28, 1992: 345–346; Washington, DC (American Chemical Society). – [ACS Symposium Series, **550**].

Daniel, M. & Jamieson, E. (1992): Coal production prospects in the European Community. – 78 p.; London (IAE Coal Research). – [IEACR, **48**].

Darcy, H. (1856): Les fontaines publiques de la ville de Dijon – Exposition et application des principes a suivre et des formules a employer dans les questions de distribution d'eau; ouvrage terminé par un appendice relatif aux fournitures d'eau de plusieurs villes au filtrage des eaux et a la fabrication des tuyaux de fonte, de plomb, de tole et de bitume. – 627 p.; Paris (Dalmont).

Denneborg, M., Berk, W. van, König, C.M., Schwarzbauer, J., Rüde, T.R. & Preusse, A. (2017): Gutachten zur Prüfung möglicher Umweltauswirkungen des Einsatzes von Abfall- und Reststoffen zur Bruch-Hohlraumverfüllung in Steinkohlenbergwerken in Nordrhein-Westfalen, Teil 1. Endbericht. – XVII + 217 p.; Aachen (ahu GmbH). – available online at: http://www.umweltauswirkungen-utv.de/gutachten_1_Apr_2017/Versatzgutachten_April_2017.pdf (retrieved on 14.02.2019).

De Vent, I. & Roest, H. (2012): Neue Indizien für nachträgliche Einwirkungen des Steinkohlenabbaus in Südlimburg (NL)?. - In: Meier, G., Sroka, A., Löbel, K.-H., Klapperich, H., Tondera, D., Busch, W., Moser, P. & Mayer, G. (eds.): 12. Altbergbau-Kolloquium, 04. bis 06. November 2010 in Goslar: 273–287; Essen (VGE Verlag).

DIN 2000 (2017): Zentrale Trinkwasserversorgung-Leitsätze für Anforderungen an Trinkwasser, Planung, Bau, Betrieb und Instandhaltung der Versorgungsanlagen. – 9 p.; Berlin (Beuth).

DIN 2001-1 (2019): Trinkwasserversorgung aus Kleinanlagen und nicht ortsfesten Anlagen – part 1: Kleinanlagen – Leitsätze für Anforderungen an Trinkwasser, Planung, Bau, Betrieb und Instandhaltung der Anlagen; Berlin (Beuth).

DIN 2001-2 (2018): Trinkwasserversorgung aus Kleinanlagen und nicht ortsfesten Anlagen – part 2: Nicht ortsfeste Anlagen – Leitsätze für Anforderungen an Trinkwasser, Planung, Bau, Betrieb und Instandhaltung der Anlagen. – 40 p.; Berlin (Beuth).

DIN 2001-3 (2015): Trinkwasserversorgung aus Kleinanlagen und nicht ortsfesten Anlagen – part 3: Nicht ortsfeste Anlagen zur Ersatz- und Notwasserversorgung – Leitsätze für Anforderungen an das abgegebene Wasser, Planung, Bau, Betrieb und Instandhaltung der Anlagen. – 43 p.; Berlin (Beuth).

DIN 4049-1 (1992): Hydrologie – part 1: Grundbegriffe. – 12 p.; Berlin (Beuth).

DIN 4049-3 (1994): Hydrologie – part 3: Begriffe zur quantitativen Hydrologie. – 80 p.; Berlin (Beuth).

DIN 18130-1 (1998): Baugrund - Untersuchung von Bodenproben; Bestimmung des Wasserdurchlässigkeitsbeiwerts – part 1: Laborversuche. – 20 p.; Berlin (Beuth).

Direction des Mines (DM; Bureau de documentation Miniere) (1963): Carte des ressources Minerale de la France. – 1 : 1.000.000.

DMT GmbH (1994): Kurzstellungnahme zum Anstieg des Grubenwassers im Bereich der stillgelegten Schachtanlage Königsborn und zu möglichen Auswirkungen auf das oberflächennahe Grundwasser. – 5 p.; Bochum. – [unpubl. expert opinion commissioned by Ruhrkohle Bergbau AG].

DMT GmbH (2011): Ermittlung der Auswirkungen des Grubenwassereinstaus in den Deckgrundwasserleiter im Bereich Königsborn. – 46 p.; Essen. – [unpubl. expert opinion commissioned by RAG AG].

DMT GmbH (2017): Evaluierung von Grubenwasseranstiegsprozessen. Kurzdokumentation zum Bergwerk Ibbenbüren Westfeld. – 15 p.; Essen. – [unpubl. expert opinion commissioned by RAG AG].

Drozdzewski, G., Hiss, M., Lehmann, F., Michel, G., Skupin, K., Staude, H., Thiermann, A., Dahm-Arens, H. & Finke, W. (1995): Geologie im Münsterland. – 195 p.; Krefeld (GLA).

Ernst, N. & Maillasson, H. (2018): In Lothringen sind die Gruben längst geflutet. – [online article in Saarbrücker Zeitung of 31.07.2018]. – available online at: https://www.saarbrueckerzeitung.de/saarland/blickzumnachbarn/frankreich/in-lothringen-sind-die-gruben-laengst-geflutet_aid-24159007 (retrieved on 31.01.2019).

Euracoal (2010): Coal and lignite in Europe. – Thematische Karte der European Association for Coal and Lignite.

Evangelou, V.P. (1995): Pyrite oxidation and its control – solution chemistry, surface chemistry, acid mine drainage (AMD), molecular oxidation mechanisms, microbial role, kinetics, control, ameliorates and limitations, microencapsulation. – 1st ed.: 293 p.; Boca Raton (CRC press).

Fellner, A. (1999): Bergmännisches Handwörterbuch. – 1st ed.: 697 p.; Vienna (Fellner).

Fenk, J. (1997): Zeitreihenanalyse für Hebungsprozesse über stillgelegten Steinkohlenbergwerken. – In: Deutscher Markscheider-Verein (ed.): Neue Technologien und Aufgaben in den Geowissenschaften – 41. Wissenschaftliche Tagung des Deutschen Markscheider-Vereins e. V., Bad Neuenahr-Ahrweiler, 10.–13. September 1997: 117–122; Aachen (Mainz). – [Das Markscheidewesen in der Rohstoff-, Energie- und Entsorgungswirtschaft, **41** = Scientific series of Publication in mine surveying, **17**].

Fenk, J. (2000): Eine analytische Lösung zur Berechnung von Hebungen der Tagesoberfläche bei Flutung unterirdischer Bergwerksanlagen. – Markscheidewesen, **107**: 420–422.

Fernandez-Rubio, R. (1979): Drainage of coal and lignite mines. – In: Argall, G.O. & Brawner, C.O. (eds.): Mine drainage – Proceedings of the First International Mine Drainage Symposium, Denver, Colorado, May 1979: 492–506; San Francisco (Freeman).

Franke, D. (2019): Regionale Geologie von Ostdeutschland – Ein Kompendium (Sachsen, Thüringen, Sachsen-Anhalt, Brandenburg, Mecklenburg-Vorpommern) – Wörterbuch stratigraphischer und regionalgeologischer Begriffe. – as of: 21.05.2019: 2.346 p.; Glienicke/Nordbahn (Franke). – available online at: www.regionalgeologie-ost.de (retrieved on 29.05.2019).

Gandy, C.J. & Younger, P.L. (2007): Predicting groundwater rebound in the South Yorkshire Coalfield, UK. – Mine Water Env, **26**(2): 70-78.

Garling, F. & Dittrich, G. (1979): Gesteinsbemusterung. – 1st ed.: 54 p.; Leipzig (VEB Deutscher Verlag für Grundstoffindustrie). – [Hydrogeology].

Geinitz, H.B., Fleck, H. & Hartig, E. (1865): Die Steinkohlen Deutschlands und anderer Lände Europas – Ihre Natur, Lagerungs-Verhältnisse, Verbreitung, Geschichte, Statistik und technische Verwendung. – 2 vols: X + 420 p. with a map book of 28 maps and XIII+ 423 p.; München (Oldenbourg).

Goerke-Mallet, P. (2000): Untersuchungen zu raumbedeutsamen Entwicklungen im Steinkohlenrevier Ibbenbüren unter besonderer Berücksichtigung der Wechselwirkungen von Bergbau und Hydrologie. – Dissertation, RWTH Aachen: 226 p.; Aachen (Mainz).

Goerke-Mallet, P., Reker, B., Westermann, S. & Melchers, C. (2017): Nachbergbau in Großbritannien: das Steinkohlenrevier South Yorkshire. – Markscheidewesen, **124**(1): 13–21.

Goerke-Mallet, P., Westermann, S. & Melchers, C. (2016): Die Verwahrung der Bergwerke im Döhlener Becken durch die Wismut GmbH – Eine Evaluierung des Grubenwasseranstiegsprozesses. – In: Sroka, A. (eds.): 17. Geokinematischer Tag des Institutes für Markscheidewesen und Geodäsie am 12. und 13. Mai 2016 in Freiberg: 123–130; Nossen (Wagner). – [Schriftenreihe des Institutes für Markscheidewesen und Geodäsie an der Technischen Universität Bergakademie Freiberg, **2016**, 1].

Gossauer, A. (2006): Struktur und Reaktivität der Biomoleküle – Eine Einführung in die organische Chemie. – 1st ed.: XIX + 650 p.; Zürich (Helvetica Chimica Acta publ.).

Gross, U. & Wedekind, C. (2006): Auswirkungen der Flutung auf die Tagesoberfläche im Bereich des Wismut-Bergbaus im Döhlener Becken. – In: Niemeyer, I., Sroka, A. & Wittenburg, R. (eds.): 7. Geokinematischen Tag des Institutes für Markscheidewesen und Geodäsie am 11. und 12. Mai 2006 in Freiberg: 96–110; Essen (VGE, Verlag Glückauf). – [Schriftenreihe des Institutes für Markscheidewesen und Geodäsie an der Technischen Universität Clausthal, **2006**, 1].

Gutíerrez Colinas, I., Lara Gómez, L.M., Hernández Battez, A.E. & Viesca Rodríguez J.L. (2018): La innovación geotérmica – nuevos usos del Agua de Mina. – 2nd ed.: 48 p.; Oviedo (Universidad de Oviedo).

Hamilton, R.M., Bowen, G.G., Postlethwaite, N.A. & Dussek, C.J. (1994): The abandonment of Wheal Jane, a tin mine in South West England. – In: Reddish, D.J. (eds.): 5th International Mine Water Congress, Nottingham, U.K., 18-23 September 1994 – Proceedings, 2: 543–551; Nottingham (University of Nottingham; IMWA).

Hammarstrom, J.M., Seal, R.R., Meier, A.L. & Kornfeld, J.M. (2005): Secondary sulfate minerals associated with acid drainage in the eastern US: recycling of metals and acidity in surficial environments. – Chemical Geology, **215**(1–4): 407–431.

Hedin, R.S., Nairn, R.W. & Kleinmann, R.L.P. (1994): Passive treatment of coal mine drainage. – 35 p.; Pittsburgh, PA. (US Department of the Interior, Bureau of Mines). – [Information Circular, **9389**].

Heitfeld, M., Denys, F., Schouwstra, M., Klünker, J., Rosner, P. & Spaans, J. (2017): Spätfolgen des Steinkohlenbergbaus in Südlimburg/Niederlande – Bestandsaufnahme und Prognosen. – In: Sroka, A. (ed.): 18. Geokinematischer Tag des Institutes für Markscheidewesen und Geodäsie am 11. und 12. Mai 2017 in Freiberg: 146–165; Nossen (Wagner). – [Schriftenreihe des Institutes für Markscheidewesen und Geodäsie an der Technischen Universität Bergakademie Freiberg, **2017**, 1].

Heitfeld, M., Rosner, P. & Mühlenkamp, M. (2012): Untersuchungen zu den Ursachen von Geländehebungen bei der Flutung von Steinkohlenbergwerken sowie Bearbeitung von Prognosen für das Ruhrrevier. 3. Bericht. Detailbericht Bergwerk Königsborn. – II + 52 p.; Aachen. – [unpubl. expert opinion commissioned by RAG AG].

Henscheid, S. (2012): Methanausgasung an der Oberfläche. Behördliche Datengrundlagen und Darstellung in www.gdu.nrw.de. – presentation of AK Methan at an event of EnergieAgentur NRW on 29.11.2012, 27 p.

Heydenreich, H. (1970): Über großflächige Entlastungs- und Hebungsvorgänge bei Grundwasserstandsänderungen. – Bergbautechnik, **20**(4): 180–185.

Hill, A. (2001): The South Yorkshire Coalfield – A history and development. – 251 p.; Charleston (Tempus publ.).

Hill, A. (2012): Coal – A chronology for Britain. – 272 p.; Northern Mine Research Society. – [British Mining, **94**].

Hillegaart, A. (1910): Untersuchungen über den Einfluss des Bergbaus auf die Erdoberfläche im Zwickauer Steinkohlenrevier. – Zeitschrift für Vermessungswesen, **39**: 229–334.

Hölting, B. & Coldewey, W.G. (2013): Hydrogeologie – Einführung in die Allgemeine und Angewandte Hydrogeologie. – 8. ed.: XXXVII + 438 p.; Heidelberg (Springer Spektrum).

Hülsmann, K.H. (1997): Probleme bei der Aufgabe von Steinkohlenbergwerken in Verbindung mit dem Grundwasseranstieg. – In: Coldewey, W. G. & Löhnert, E. P. (eds.): Grundwasser im Ruhrgebiet – Probleme, Aufgaben, Lösungen. Lecture and poster summary of the conference of german montan technology – Bochum, October 1997: 115–125; Cologne (von Loga). – [GeoCongress, **3**].

Huyssen, A. (1855): Die Soolquellen des Westfälischen Kreidegebirges, ihr Vorkommen und muthmaasslicher Ursprung. – Z. dt. geol. Ges., **7**: 17–252.

International Network for Acid Prevention (INAP) (2014): Global Acid Rock Drainage Guide (GARD Guide). – Version Rev. 1 of 21.10.2014. – 473 p. – available online at: http://www.gardguide.com/images/5/5f/TheGlobalAcidRockDrainageGuide.pdf (retrieved on 14.03.2019).

Instituto Geologico Y Minero España (IGME) (1985): Actualización del inventario de recursos nacionales de carbon. – 217 p.; Madrid (Servicio de Publicaciones, Ministerio de Industria y Energía).

Jardón, S., Ordóñez, A., Álvarez, R., Cienfuegos, P. & Loredo, J. (2013): Mine water for energy and water supply in the central coal basin of Asturias (Spain). – Mine Water Env, **32**(2): 19–151.

Job, B. (1987a): Inrushes at British collieries: 1851 to 1970 (Part 1). – Colliery Guardian, **235**(5): 192–199.

Job, B. (1987b): Inrushes at British collieries: 1851 to 1970 (Part 2). – Colliery Guardian, **235**(6): 232–235.

Johnson, D.B. & Hallberg, K. B. (2003): The microbiology of acidic mine waters. – Research in Microbiology, **154**(7): 466–473.

Karrenberg, H. (1981): Hydrogeologie der nicht verkarstungsfähigen Festgesteine. – XIII + 284 p.; Vienna (Springer).

Keller, G. (1968): Zur Geologie des Piesberges bei Osnabrück. – Z. dt. geol. Ges., **117**: 743–748.

Kelly, D.P. & Wood, A.P. (2000): Reclassification of some species of Thiobacillus to the newly designated genera Acidithiobacillus gen. nov., Halothiobacillus gen. nov. and Thermithiobacillus gen. nov. - International Journal of Systematic and Evolutionary Microbiology, **50**: 511–516.

Kentucky Coal Education (2011): Glossary of Mining Terms. – available at http://www.coaleducation.org/glossary.htm#S (retrieved on 29.08.2019).

Kerkis, E.-E. (1955): Opredelenie radiusa vlijanija pri rasčete vodopritokov. – 1st ed.: 99 p.; Moskva (Ugletekhizdat).

Klinger, C., Eckart, M., Charmoille, A., Le Gal, N., Bueno, J., Gzyl, G., Kura, K. & Garzon, B. (2013): Flooding management for underground coal mines considering regional mining networks (Flominet) – Final report. – 72 p.; Luxembourg (Publications Office of the European Union). – [EUR, **25905**].

Koeberlé, N., Levicki, R., Kaiser, J. & Heitz, S. (2013): Treating mine waters in the Lorraine coal field – Feedback from the La Houve treatment plant. – Mine Closure 2013, Sep 2013, Cornwall, United Kingdom: Australien Centre for Geomechanics: 11 p. – <hal-00849990>. – available online at: https://hal-brgm.archives-ouvertes.fr/hal-00849990 (retrieved on 01.05.2019).

Koetter, G. (2001): Bergbau im Muttental – Geologie und Geschichte des Wittener Bergbauwanderwegs. – 198 p.; Witten (Koetter).

Kortas, L. & Younger, P.L. (2007): Using the GRAM model to reconstruct the important factors in historic groundwater rebound in part of the Durham Coalfield, UK. – Mine Water Env, **26**(2): 60–69.

Kotarba, M.J., Clayton, J.L., Rice, D.D. & Wagner, M. (2002): Assessment of hydrocarbon source rock potential of Polish bituminous coals and carbonaceous shales. – Chem. Geo., **184**: 11–35.

Kratzsch, H. (2013): Bergschadenkunde. – 6. ed.: XII + 950 p.; Bochum (Deutscher Markscheider-Verein e. V.). – [Markscheidewesen, **5**].

Kusakin, I.P. (1935): Iskusstwennoje ponischenije urownja gruntowyh wod. – 2nd ed.: 248 p.; Moskva, Leningrad (Onti, Glawnaja redakzija stroiteljnoii literatury).

Lahner, L., Wellmer, F.-W., Pasternak, M., Thielemann, T., Wagner, H., Dill, H., Schütte, H. & Weinmann, W. (2004): Geowissenschaftliche Karte der Bundesrepublik Deutschland 1 : 2.000.000 – Wichtige Lagerstätten (ohne Massenrohstoffe). – Hannover (Bundesanstalt für Geowissenschaften und Rohstoffe).

Löbel, K.-H. & Döhner, S. (2010): Bergbaubedingte Senkungen und Hebungen in Oelsnitz/E. – In: Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie (ed.): Geologie und Bergbaufolgen im Steinkohlenrevier Lugau/Oelsnitz: 55–69; Dresden (Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie). – [Geoprofil, **3**].

Loredo, J., Ordóñez, A., Jardón, S. & Álvarez, R. (2011): Mine water as geothermal resource in Asturian coal mining basins (NW Spain). – In: Rüde, T.R., Freund, A. & Wolkersdorfer, C. (eds.): Mine water - managing the challenges – Proceedings of the 11th International Mine Water Association Congress, RWTH Aachen, Aachen, Germany, 4–11 September 2011: 177–182; Aachen (RWTH).

Lottermoser, B.G. (2010): Mine wastes – Characterization, treatment and environmental impacts. – XIV + 400 p.; Berlin (Springer).

Lotze, F., Semmler, W., Kötter, K. & Mausolf, F. (1962): Hydrogeologie des Westteils der Ibbenbürener Karbonscholle. – 113 p.; Köln (Westdeutscher Verlag). – [Forschungsber. Landes Nordr.-Westfalen, **999**].

Mann, S. & Wedekind, C. (2010): Die Flutung des Wismut-Bergbaus am Standort Dresden-Gittersee unter Berücksichtigung des historischen Steinkohlenbergbaus sowie vorhandenen Altlasten – ein Rückblick. – In: Meier, G., Sroka, A., Löbel, K.-H., Klapperich, H., Tondera, D., Busch, W., Moser, P. & Mayer, G. (eds.): 10. Altbergbau-Kolloquium, 04. bis 06. November 2010 in Freiberg: 177–188; Essen (VGE publ.).

Mann, S. & Wedekind, C. (2015): Der Wismut-Standort Dresden-Gittersee nach Sanierungsabschluss. Ein Review mit Blick auf die Nachsorgephase. – In: Institut für Markscheidewesen und Geodäsie, Institut für Bergbau und Spezialtiefbau, Ring Deutscher Bergingenieure e. V. & Deutscher Marscheider-Verein e. V. (eds.): Tagungsband Bergbau, Energie und Rohstoffe 2015 – Gemeinsame Tagung Energie und Rohstoffe 2015, 7. Bergbaukolloquium, 07.–09. Oktober 2015, Freiberg: 30–43; Nossen (Wagner). – [Wissenschaftliche Schriftenreihe im Markscheidewesen].

Martin, C., Bischof, N., & Eiblmaier, M. (2000–2002): Lexikon der Geowissenschaften – In sechs Bänden. – 2711 p.; Heidelberg (Spektrum, Akademischer Verlag).

McConville, L., Broadbent, J. & Rousaki, K. (1999): Coal in Bulgaria. – 38 p.; London (IEA Coal research). – [CS, **04**].

Melchers, C. (2008): Methan im südlichen Münsterland. Genese, Migration und Gefahrenpotenzial. – Dissertation, Westfälische Wilhelms-Universität Münster: XVI + 153 p.; Münster.

Melchers, C., Bendrat, M., vom Berg, B., Kruse, S. & Witthaus, H. (2017): Entwicklung eines Grubenwassermonitoring-Systems für das Bergwerk Auguste Victoria in Marl. – In: Meier, G., Benndorf, J., Löbel, K.-H., Butscher, C., Tondera, D. & Busch, W. (eds.): 17. Altbergbau-Kolloquium. 16. bis 18. November 2017, Freiberg: 303–309; Nossen (Wagner).

Melchers, C., Cebula, L., Jasnowski-Peters, H. & Wiegelmann, H. (2019): Ermittlung der Kinematik der Dichteschichtungen im Grubenwasser des Ruhrgebietes. – Abschlussbericht. – 83 p.; Bochum. – [unpubl. expert opinion commissioned by RAG AG].

Melchers, C., Michel, I., Hoppe, U., Isaac, M. & Goerke-Mallet, P. (2016): Methoden zur Ermittlung eines Einzugsgebietes wasserführender Stollen am Beispiel des Franziska Erbstollens in Witten. – In: Meier, G., Benndorf, J., Löbel, K.-H., Tondera, D. & Busch, W. (eds.): 16. Altbergbau-Kolloquium im Hotel- und Tagungszentrum „Der Achtermann“ in Goslar vom 10. bis 12. November 2016: 107–117; Nossen (Wagner).

Mortimer, C.E. & Müller, U. (2003): Chemie – Das Basiswissen der Chemie. – 8., fully revised and ext. ed.: XVIII + 766 p.; Stuttgart (Thieme).

Mühlenbeck, H. (2015): Hebungen nach Einstellung von Wasserhaltungen im Ruhrgebiet. – Bergbau, **8**: 346–349.

Murawski, H. & Meyer, W. (2010): Geologisches Wörterbuch. – 12., revised and ext. ed.: 220 p.; Heidelberg (Spektrum, Akademischer Verlag).

Neymeyer, A., Williams, R.T. & Younger, P.L. (2007): Migration of polluted mine water in a public supply aquifer. – Quarterly Journal of Engineering Geology and Hydrogeology, **40**(1): 75–84.

Noddack, I. (1936): Über die Allgegenwart der chemischen Elemente. – Angewandte Chemie, **49**(47): 835–841.

Northern Mine Research Society (NMRS) (2019): Coal mining in British Isles. – online map available at: https://www.nmrs.org.uk/mines-map/coal-mining-in-the-british-isles/ (retrieved on 03.06.2019)

Nuttall, C.A., Adams, R. & Younger, P.L. (2002): Integrated-hydraulic hydrogeochemical assessment of flooded deep mine voids by test pumping at the Deerplay (Lancashire) and Frances (Fife) Collieries. – In: Younger, P.L. & Robins, N.S. (eds.): Mine water hydrogeology and geochemistry: 315–326; London (Geological Society London). – [Geological Society London, Special Publication, **198**].

Nuttall, C.A. & Younger, P.L. (2004): Hydrochemical stratification in flooded underground mines: an overlooked pitfall. – J Contam Hydrol, **69**(1–3): 101–114.

Oberste-Brink, K. (1940): Die Frage der Hebungen bei Bodenbewegungen infolge Bergbaues. – Glückauf, **76**(18): 249–256.

Ordóñez, A., Jardón, S., Álvarez, R., Andrés, C. & Pendás, F. (2012): Hydrogeological definition and applicability of abandoned coal mines as water reservoirs. – J. Environ. Monit., **14**(8): 2127–2136.

Paas, N. (1997): Untersuchungen zur Ermittlung der geochemischen Barriere von Gesteinen aus dem Umfeld untertägiger Versatzräume im Steinkohlenbergbau des Ruhrkarbons. – 234 p.; Bochum (DMT) – [DMT-Berichte aus Forschung und Entwicklung, **54**].

Pälchen, W. & Walter, H. (2011): Geologie von Sachsen I – Geologischer Bau und Entwicklungsgeschichte. – 2nd corr. ed.: XVI + 537 p.; Stuttgart (Schweizerbart).

Pastor, J., Klinger, C., Talbot, C., Whitworth, K. & Suso Llamas, J.M. (2008): Optimisation of mine water discharge by monitoring and modelling of geochemical processes and development of measures to protect aquifers and active mining areas from mine water contamination – Final report. – 130 p.; Luxembourg (Office for Official Publications of the European Communities.) – [EUR, **23456**].

Plotnikov, N.I. & Roginets, I.V. (1989): Hydrogeology of ore deposits. – VIII + 290 p.; Rotterdam (Balkema) – [Russian translation series, **72**].

Pöttgens, J. J. E. (1985): Bodenhebungen durch ansteigendes Grubenwasser. – Proceedings – 6th International Congress, International Society for Mine Surveying, Harrogate, 9-13 September 1985, **2**: 928–938; Rotterdam (Balkema).

RAG AG (2014a): Konzept zur langfristigen Optimierung der Grubenwasserhaltung der RAG Aktiengesellschaft für Nordrhein-Westfalen gemäß § 4 Erblastenvertrag zur Bewältigung der Ewigkeitslasten des Steinkohlenbergbaus der RAG AG im Rahmen der sozialverträglichen Beendigung des subventionierten Steinkohlenbergbaus in Deutschland vom 14.08.2007. – 29 p.; Herne.

RAG AG (2014b): Konzept zur langfristigen Optimierung der Grubenwasserhaltung der RAG Aktiengesellschaft für das Saarland gemäß § 4 Erblastenvertrag zur Bewältigung der Ewigkeitslasten des Steinkohlenbergbaus der RAG AG im Rahmen der sozialverträglichen Beendigung des subventionierten Steinkohlenbergbaus in Deutschland vom 14.08.2007. – 17 p.; Herne.

RAG AG (2015): Grubenwasser in der Diskussion. – Herne (Krüger). – available online at: https://www.bergbau-unser-erbe.de/fileadmin/user_upload/Grubenwasser_in_der_Diskussion.pdf (retrieved on 31.01.2019).

RAG AG (2016): Aufgaben für die Ewigkeit. Grubenwasserhaltung, Poldermaßnahmen und Grundwassermanagement im Ruhrgebiet. – 34 p.; Herne.

RAG AG (2017): Logistik schafft Wasserwegigkeit. – Steinkohle, **2017**(11): 24.

RAG-Stiftung (2018): Geschäftsbericht 2017. – 88 p.; Essen (RAG-Stiftung). – available online at: https://www.rag-stiftung.de/fileadmin/user_upload/RAG-Stiftung/Dokumente/geschaeftsberichte/RAG-Stiftung_GB2017_D.pdf (retrieved on 28.05.2019).

Ramdohr, P. & Strunz, H. (1980): Klockmanns Lehrbuch der Mineralogie. – 16. ed.: XI + 876 p.; Stuttgart (Enke).

Randall, B.E. & Olyphant, G.A. (1993): Acid-generating salts and their relationship to the chemistry of groundwater and storm runoff at an abandoned mine site in southwestern Indiana, USA. – J Contam Hydrol, **12**(4): 313–328.

Reichel, W. & Schauer, M. (2007): Das Döhlener Becken bei Dresden - Geologie und Bergbau. – 343 + XXVII p.; Dresden (Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie) – [Bergbau in Sachsen, **12**]. – available online at: http://nbn-resolving.de/urn:nbn:de:bsz:14-qucosa-79315 (retrieved on 06.05.2019).

Reker, B., Goerke-Mallet, P., Westermann, S. & Melchers, C. (2018): Die britische Steinkohle und der Nachbergbau: Eindrücke aus dem Revier South Yorkshire und aktuelle Entwicklungen in Großbritannien. – Bergbau, **69**(6): 269–275.

Reker, B., Goerke-Mallet, P., Westermann, S. & Melchers, C. (2019a): Protecting aquifers from rising mine waters: managing mine water in the Durham coalfields (United Kingdom) and a comparison with methods used in Lorraine (France). – Mining report, **155**(3): 272-286.

Reker, B., Goerke-Mallet, P., Westermann, S. & Melchers, C. (2019b): Die spanische Steinkohle und der Nachbergbau: Eindrücke aus Asturien. – Bergbau, **70**(4): 160–166.

Röhrs, H. (1998): Der Ibbenbürener Bergbau des 20. Jahrhunderts in Bildern. – 2. revised and ext. ed.: 232 p; Ibbenbüren (Ibbenbürener Vereinsdruckerei).

Rom, H. (1939): Grundwasserabsenkungen und Bewegungsvorgänge im Deckgebirge bei der Grundwasserentziehung. – Mitt. Markscheidewes., **50**(2): 113–148.

Rosner, P. (2011): Der Grubenwasseranstieg im Aachener und Südlimburger Steinkohlenrevier – eine hydrogeologisch-bergbauliche Analyse der Wirkungszusammenhänge. – Dissertation, RWTH Aachen: 194 p.; Aachen.

Rosner, P., Heitfeld, M., Spreckels, V. & Vosen, P. (2014): Auswirkungen von Geländehebungen im Zuge des Grubenwasseranstiegs im Ruhrrevier. – In: Schanz, T. (ed.): Ende des Steinkohlenbergbaus im Ruhrrevier – Realität und Perspektiven für die Geotechnik. Beiträge zum RuhrGeo-Tag 2014, Bochum, 27. März 2014: 153–177; Bochum (Ruhr-Universität). – [Publication series of the chair for foundation engineering, soil and rock mechanics, **50**].

Sammarco, O. (1995): Storage of water in the voids of abandoned mines and fractured rocks. – In: Hotchkiss, W.R., Downey, J.S., Gutentag, E.D. & Moore, J.E. (eds.): Water resources at risk. – A selection of the papers presented at the conference held in Denver, Colorado, May 14-18, 1995: IMWA-102-114; Minneapolis (American Institute of Hydrology).

Schäfer, A. (2016): Zur Verteilung der Bewegungen an der Tagesoberfläche nach Grubenwasseranstieg in einer Steinkohlenlagerstätte. – Markscheidewesen, **123**(1): 21–28.

Schleuning, J. (2018): Welche Auswirkungen die aktuelle Grubenflutung im Saarland hat. – [Online article of Saarbrücker Zeitung of 28. Januar 2019]. – available online at: https://www.saarbruecker-zeitung.de/saarland/saarland/welche-auswirkungen-die-aktuelle-grubenflutung-im-warndt-hat_aid-35960693 (retrieved on 31.01.2019).

Schmidt, H.-H. (2006): Grundlagen der Geotechnik. – 3. fully revised, ext. and updated ed.: 720 p.; Wiesbaden (Teubner).

Schoell, M. (1984): Wasserstoff- und Kohlenstoffisotope in organischen Substanzen, Erdölen und Erdgasen. – 164 p.; Hannover (Schweizerbart). – [Geol. Jahrb., Reihe D, **67**].

Semmler, W. (1937): Untersuchungen, Wassermessungen und Färbungsversuche zur Ermittelung der Herkunft der Wasserzuflüsse im Felde der Grube Victoria. Püttlingen-Saar. – Der Bergbau, **50**(6): 87–93.

Semmler, W. (1955): Die Grubenwasserzuflüsse im Ruhrbergbau und ihre Abhängigkeit von den Niederschlägen. – Bergbau, **6**(8): 205–214.

SICHARDT, W. (1928): Das Fassungsvermögen von Rohrbrunnen und seine Bedeutung für die Grundwasserabsenkung, insbesondere für größere Absenkungstiefen. – V + 89 p.; Berlin (Springer).

SINGER, P.C. & STUMM, W. (1970): Acidic mine drainage: the rate-determining step. – Science, **167**(3921): 1121–1123.

SHERWOOD, J.M. (1997): Modelling mine water flow and quality changes after coalfield closure. – Dissertation, University of Newcastle upon Tyne: XIII + 241 p.; Newcastle (Newcastle University). – available online at http://theses.ncl.ac.uk/jspui/handle/10443/314 (retrieved on 24.05.2019).

SPICKERNAGEL, H. (1975): Hebungen des Gebirges als Folgen des Bergbaus unter Tage. – Glückauf-Forschungshefte, **36**: 170–176.

THIELEMANN, T. (2000): Der Methanhaushalt über kohleführenden Sedimentbecken: Das Ruhrbecken und die Niederrheinische Bucht. – Methanbildung, -migration und Austausch mit der Atmosphäre. – Dissertation, RWTH Aachen: X + 350 p.; Jülich (Forschungszentrum, Zentralbibliothek). – [JÜL-Bericht, **3792**].

THIELEMANN, T. (2002): Kohleflözgas in Deutschland. – Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Commodity Top News, **17**: 4 p.; Hannover. – available online at: https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/Commodity_Top_News/Energie/17_kohlefloezgas.html (retrieved on 03.05.2019).

THIELEMANN, T., KROSS, B.M. & LITTKE, R. (2001): Induziert der Steinkohlenbergbau im Ruhrbecken Methanemissionen? – Z. dt. geol. Ges., **152**(1): 61–76.

TUNGER, K. (2009): Bodenbewegungen durch Flutung im Steinkohlenrevier Freital/Sachsen. – Markscheidewesen, **116**(1): 3–10.

USAKO (1991): Flutungskonzeption der Lagerstätte Freital/Gittersee. – 35 p.; Chemnitz (Büro für Umweltsanierungskonzepte. SDAG Wismut - Geschäftsbereich Umweltengineering). – [unpubl.].

USAKO (1993): Lagerstätte Freital/Gittersee. Flutungskonzeption mit Umweltbewertung des Wasserpfades. – 66 p.; Chemnitz (Büro für Umweltsanierungskonzepte. SDAG Wismut - Geschäftsbereich Umweltengineering). – [unpubl.]

VERVOORT, A. & DECLERCQ, P.-Y. (2018): Upward surface movement above deep coal mines after closure and flooding of underground workings. – International Journal of Mining Science and Technology, **28**(1): 53–59.

VUTUKURI, V.S. & SINGH, R.N. (1995): Recent developments in pumping systems in underground metalliferous mining. – Mine Water Env, **12**(1): 71–94.

WAGNER, J. (2010): Zukunft Warndt Wasser – Handlungsstudie zu den Chancen nach dem Anstieg des Grundwassers im Warndt. – 102 p. – [unpubl. study by Grundwasser- und Geo-Forschung, Neunkirchen].

WALKER, S. (2000): Experience from coal industry restructuring. – 73 p.; London (IEA Coal Research). – [CCC, **48**].

WALTER, R. (2010). Aachen und nördliche Umgebung – Mechernicher Voreifel, Aachen-Südlimburger Hügelland und westliche Niederrheinische Bucht. – X + 214 p.; Stuttgart (Borntraeger). – [Sammlung geologischer Führer, **101**].

Watson, I. (2011): Managing rising mine water to prevent aquifer pollution. – available online at: http://www.groundwateruk.org/Contaminated-Land-Contaminated-Groundwater.aspx (retrieved on 02.05.2019). – [presentation at the conference "Contaminated Ground, Contaminated Groundwater?" of UK Groundwater Forum on 24.05.2011 in London].

Westermann, S., Rudakov, D.V., Reker, B. & Melchers, C. (2018): Ein neuer Blick auf Grubenwasseranstiegsprozesse – ausgewählte Beispiele aus dem deutschen Steinkohlenbergbau. – In: Meier, G., Benndorf, J., Löbel, K.-H., Butscher, C., Tondera, D., Busch, W., Dziurzynski, W. & Sroka, A. (eds.): 18. Altbergbau-Kolloquium vom 8. bis 10. November 2018, IMG PAN, Wieliczka Colliery: 61–75; Nossen (Wagner).

Whitworth, K.R. (2002): The monitoring and modelling of mine water recovery in UK coalfields. – In: Younger, P.L. & Robins, N.S. (eds.): Mine water hydrogeology and geochemistry: 61–73; London (Geological Society London). – [Geological Society London, Special Publication, **198**].

Wisotzky, F., Cremer, N. & Lenk, S. (2018): Angewandte Grundwasserchemie, Hydrogeologie und hydrogeochemische Modellierung – Grundlagen, Anwendungen und Problemlösungen. – 2nd ed.: LII + 677 p.; Berlin (Springer Spektrum).

Wolkersdorfer, C. (1996): Hydrogeochemische Verhältnisse im Flutungswasser eines Uranbergwerks - die Lagerstätte Niederschlema, Alberoda. – Dissertation, TU Clausthal: 244 p.; Clausthal-Zellerfeld.

Wolkersdorfer, C. (2001): Tracer tests in flooded underground mines. – In: Seiler, K.-P. & Wohnlich, S. (eds.): New approaches characterizing groundwater flow – Proceedings of the XXXI International Association of Hydrogeologists Congress, Munich, Germany, 10.-14. September 2001, **1**: 229–233; Lisse (Balkema).

Wolkersdorfer, C. (2008): Water management at abandoned flooded underground mines. – Fundamentals, tracer tests, modelling, water treatment. – XX + 465 p.; Berlin (Springer).

Wolkersdorfer, C. (2013): Grubenwasserreinigung – Verfahren und Vorgehensweisen. – 194 p.; Pretoria (Tshwane University of Technology).

Wolkersdorfer, C. & Bowell, R. (2004): Contemporary reviews of mine water studies in Europe, Part 1. – Mine Water Env, **23**(4): 162–182.

Wyatt, L.M., Moorhouse, A.M.L., Kershaw, S., & Iwanskyj, B. (2013): Mine water: management post-closure and lessons learned, risks from poor closure and mine water management. – In: Tibbett, M., Fourie, A.B. & Digby, C. (eds.): Mine Closure 2013 - Proceedings of the 8th International Conference on Mine Closure, 18-20 September 2013, Eden Project, Cornwall, UK: 279–292; Nedlands (ACG Australien Centre for Geomechanics).

Wyatt, L.M., Moorhouse, A.M.L. & Watson, I.A. (2014): Evolution in tidal related hydrogeochemistry at a long-term coal mine water pumping and treatment scheme, former Frances Colliery, Scotland. – In: Sui, W., Sun, Y. & Wang, C. (eds.): An interdisciplinary response to mine water challenges – 12th International Mine Water Association Congress (IMWA 2014), Xuzhou, China 18-22 August 2014: 9–13; Xuzhou (China, University of Mining and Technology Press).

Younger, P.L. (1993): Possible environmental impact of the closure of two collieries in County Durham. – Water and Environmental Management, **7**(5): 521–531.

Younger, P.L. (1995): Hydrogeology. – In: Johnson, G.A.L. (ed.): Robson's geology of North East England = The geology of North East England, 2nd. ed.: 353–359; Newcastle upon Tyne (Natural History Society of Northumbria). – [Transactions of the Natural History Society of Northumbria].

YOUNGER, P.L. (1997): The longevity of minewater pollution: a basis for decision-making. – Science of the Total Environment, **194/195**: 457–466.

YOUNGER, P.L. (2000): Predicting temporal changes in total iron concentrations in groundwaters flowing from abandoned deep mines: a first approximation. – J Contam Hydrol, **44**(1): 47–69.

YOUNGER, P.L. (2002): Mine water pollution from Kernow to Kwazulu-Natal: geochemical remedial options and their selection in practice. – Geoscience in South-West England, **10**(3): 255–266.

YOUNGER, P.L. & ADAMS, R. (1999): Predicting mine water rebound. – 109 S.; Bristol (Environment Agency). – [R&D Technical Report, **W179**].

YOUNGER, P.L., BANWART, S.A. & HEDIN, R.S. (2002): Mine water – Hydrology, pollution, remedation. – XVI + 442 p.; Kluwer (Dordrecht). – [Envrionmental pollution, **5**].

ZUNKER, F. (1930): Das Verhalten des Bodens zum Wasser. – In: BLANCK, E. (ed.): Handbuch der Bodenlehre, **6**: Die physikalische Beschaffenheit des Bodens: 66–220; Berlin (Springer).

8. Publications

As part of this project, the following publications have been released:

2019

Reker, B., Goerke-Mallet, P., Westermann, S. & Melchers, C. (2019a): Protecting aquifers from rising mine waters: managing mine water in the Durham coalfields (United Kingdom) and a comparison with methods used in Lorraine (France). – Mining report, **155**(3): 272-286.

Reker, B., Goerke-Mallet, P., Westermann, S. & Melchers, C. (2019b): Die spanische Steinkohle und der Nachbergbau: Eindrucke aus Asturien. – Bergbau, **70**(4): 160–166.

Westermann, S., Rudakov, D. V., Reker, B. & Melchers, C. (2019): Ein neuer Blick auf Grubenwasseranstiegsprozesse – ausgewählte Beispiele aus dem deutschen Steinkohlenbergbau. – Markscheidewesen, **126**(1): 30-38.

2018

Reker, B., Goerke-Mallet, P., Westermann, S. & Melchers, C. (2018): Die britische Steinkohle und der Nachbergbau: Eindrücke aus dem Revier South Yorkshire und aktuelle Entwicklungen in Großbritannien. – Bergbau, **69**(6): 269–274.

Westermann, S. (2018): Analyse und Bewertung der hydraulischen, hydrochemischen und geomechanischen Grundlagen eines Grubenwasseranstiegs in untertägigen Steinkohlenbergwerken. – In: Banning, A., Frank, S., Kaufmann-Knoke, R., Niedermayr, A., Wisotzky, F. & Wohnlich, S. (eds.): Grundwasser im Umfeld von Bergbau, Energie und urbanen Räumen – 26. Fachtagung der Fachsektion Hydrologie e. V. in der DGGV e. V. Bochum, 21.–24. März 2018. Conference Proceedings: 233; Bochum (Selbstverlag Institut für Geologie, Mineralogie und Geophysik der Ruhr-Universität Bochum). – [Bochumer geoscientific work, **24**].

Westermann, S. & Melchers, C. (2018): Scientific basics of mine water rebound. – In: Sankt-Peterburgskij Gornyj Universitet (ed.): Problemy nedropol'zovanija – Meždunarodnyj Forum-Konkurs Molodych Učenych, 18-20 aprel'ja 2018 g, Sbornik naučnych trudov, Čast' II: 84–86; Sankt-Peterburg (Sankt-Peterburgskij Gornyj Universitet). – available online at: https://spmi.ru/sites/default/files/imci_images/sciens/nirs/vkladka_2_%D1%87%D0%B0%D1%81%D1%82%D1%8C%20II_%202018.pdf (retrieved on 24.01.2019).

Westermann, S., Reker, B., Goerke-Mallet, P., Wolkersdorfer, C. & Melchers, C. (2018): Hydraulics of underground mine flooding – Optimization of prediction and monitoring procedures. – In: Drebenstedt, C., von Bismarck, F., Fourie, A. & Tibbett, M. (eds.): Mine Closure 2018 – Proceedings of the 12th International Conference on Mine Closure, 3.–7. September 2018, Leipzig, Germany: 512–523; Freiberg (Technical University Bergakademie Freiberg, Institute of Mining and Special Civil Engineering). – available online at: http://mineclosure2018.com/wp-content/uploads/2017/08/Book_prev_index_complete_online.pdf (retrieved on 24.01.2019).

Westermann, S., Rudakov, D. & Melchers, C. (2018): Analytical assessment of mine water rebound – Case study Ruhr coal basin. – In: Ministerstwo Oswity i Nauky Ukrajny, Nazionaljnyj Technitschnyj Uniwersitet, "Dniprowsjka Politechnika" (ed.): Forum Girnykiw - 2018 – Materialy mischnarodnoj konferenzij, 10.-13. schowtnja 2018 r [Tagungsband des Forum of Mining Engineers an der National Technical University Dnipro Polytechnic vom 10.–13. Oktober 2018 in Dnipro]: 204–212; Dnirpo (Serednjak T.K.).

Westermann, S., Rudakov, D. V., Reker, B. & Melchers, C. (2018): Ein neuer Blick auf Grubenwasseranstiegsprozesse – ausgewählte Beispiele aus dem deutschen Steinkohlenbergbau. – In: Meier, G., Benndorf, J., Löbel, K.-H., Butscher, C., Tondera, D., Busch, W., Dziurzynski, W. & Sroka, A. (eds.): 18. Altbergbau-Kolloquium. 8. bis 10. November 2018, IMG PAN, Bergwerk Wieliczka: 61–75; Nossen (Wagner).

2017

GOERKE-MALLET, P., REKER, B., WESTERMANN, S. & MELCHERS, C. (2017): Nachbergbau in Großbritannien: das Steinkohlenrevier South Yorkshire. – Markscheidewesen, **124**(1): 13–21.

WESTERMANN, S., DOGAN, T., REKER, B., GOERKE-MALLET, P., WOLKERSDORFER, C. & MELCHERS, C. (2017): Evaluation of mine water rebound processes in European Coal Mine Districts to enhance the understanding of hydraulic, hydrochemical and geomechanical processes. – In: WOLKERSDORFER, C., SARTZ, L., SILLANPÄÄ, M. & HÄKKINEN, A. (eds.): Proceedings 13th International Mine Water Association Congress - Mine water & circular economy – Lappeenranta, Finland, June 25-30, 2017, Vol. **1**: 147-153; Lappeenranta (LUT Scientific and Expertise Publications). – [LUT Scientific and Expertise Publications: Research Reports, **63**]. – available online at: http://imwa.info/docs/imwa_2017/IMWA2017_Westermann_147.pdf (retrieved on 24.01.2019).

WESTERMANN, S., DOGAN, T., REKER, B., GOERKE-MALLET, P. & MELCHERS, C. (2017): Mine water rebound and its environmental impacts. – In: SANKT-PETERBURGSKIJ GORNYJ UNIVERSITET (ed.): Problemy nedropol'zovanija – Meždunarodnyj Forum-Konkurs Molodych Učenych, 19-21 aprel'ja 2017 g, Sbornik naučnych trudov, Čast' II: 75–77; Sankt-Peterburg (Sankt-Peterburgskij Gornyj Universitet).

WESTERMANN, S., GOERKE-MALLET, P., REKER, B., DOGAN, T., WOLKERSDORFER, C. & MELCHERS, C. (2017): Aus Erfahrungen lernen: Evaluierung von Grubenwasseranstiegsprozessen zur Verbesserung zukünftiger Prognosen. – In: MEIER, G., BENNDORF, J., LÖBEL, K.-H., BUTSCHER, C., TONDERA, D. & BUSCH, W. (eds.): 17. Altbergbau-Kolloquium vom 16. bis 18. November 2017, Freiberg: 259–273; Nossen (Wagner).

2016

GOERKE-MALLET, P., WESTERMANN, S. & MELCHERS, C. (2016): Die Verwahrung der Bergwerke im Döhlener Becken durch die Wismut GmbH – Eine Evaluierung des Grubenwasseranstiegsprozesses. – In: SROKA, A. (ed.): 17. Geokinematischer Tag des Institutes für Markscheidewesen und Geodäsie am 12. und 13. Mai 2016 in Freiberg: 123–130; Nossen (Wagner). – [Schriftenreihe des Institutes für Markscheidewesen und Geodäsie an der Technischen Universität Bergakademie Freiberg, **2016**, 1]. – available online at: http://www.qucosa.de/fileadmin/data/qucosa/documents/20541/Textbeitrag_9.pdf (retrieved on 24.01.2019).

MELCHERS, C. (2016): Ausgasung und Grubenwasseranstieg. – In: BEZIRKSREGIERUNG ARNSBERG; TECHNISCHE HOCHSCHULE GEORG AGRICOLA (eds.): Nachbergbauzeit in NRW – Beiträge 2011, 2013, 2015: 158–161; Bochum (Selbstverlag des Deutschen Bergbau-Museums Bochum). – [publications by the German Mining Museum Bochum, 217].

We would like to warmly thank our colleagues of the Research Centre of Post-Mining at the Technische Hochschule Georg Agricola – University for reading and reviewing this report and for their enriching contributions and discussions:

B. Sc. Britta Engbring
A. d. M. Prof. Dr.-Ing. Peter Goerke-Mallet
Dipl.-Geol. Henning Jasnowski-Peters
Laura Klein
M. A. (LIS) Peter Lohnert
Dr.-Ing. Stefan Möllerherm
Prof. Dr.-Ing. Ulrich Paschedag
Prof. Dr. rer. nat. Tobias Rudolph
Dipl.-Geol. Melanie Schwermann
Hendrik Wiegelmann

We would further like to thank in particular Dr. rer. nat. Bastian Reker and B. Sc. Miriam Börger for the generation and processing of the figures and illustrations.

Technische
Hochschule
Georg Agricola
University

Selbstverlag des Deutschen Bergbau-Museums Bochum 2020
ISBN 978-3-937203-89-8