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Post-Mining: Geomonitoring, process understanding, and utilisation of former mining areas

Dennis Quandt[1], Tobias Rudolph[2] & Christoph Hilgers[1]*

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Mining of and access to raw materials enable global prosperity and development. With the global increase in population, new technologies, and the energy transition, worldwide demands for raw materials will increase (Angerer et al. 2016; Acatech 2017; Kretschmann et al. 2017; Vidal et al. 2017; Hilgers & Becker 2020; Hilgers et al. 2021; Everingham et al. 2022). Since recycling alone cannot supply the growing demand, new mining areas have to be developed, while existing mining areas will be abandoned due to raw material depletion and/or (temporally) uneconomic production (Acatech 2017; Kretschmann et al. 2017). Abandoned mining operations consequently transition into the post-mining phase, which represents the last phase of the mine life cycle after exploration, appraisal, development, production, and expansion (Rudolph et al. 2020, 2021). Similar to the production phase, post-mining may be accompanied by ground movements and micro-seismicity, but also offers opportunities for re-use. These topics are of public interest and represent relevant research objects (Rudolph et al. 2020).

Modern published research on the topic of post-mining dates back to the 1970s and 1980s (Fig. 1). From the first mention of the term post-mining in a modern publication in 1976 until today, >1,400 scientific works comprising especially peer-reviewed papers but also conference contributions were published, featuring diverse aspects of post-mining (Clarivate Analytics Web of Science 2022). Since the early 2000s, the number of publications on post-mining and citations per year has increased rapidly. This trend temporally coincides with the successive closure of European (hard) coal mines transitioning into their post-mining phases. In the context of post-mining research, particular importance is therefore attached to hard coal mines, but also the lignite, oil and gas industry is considered (Rudolph et al. 2021). After all Dutch, Belgium and French coal mines were successively closed in 1974, 1993 and 2004, respectively (Baeten 1991; Swyngedouw 1996; De Jong 2004; Collon et al. 2015), further 58 hard coal mines were closed in the Czech Republic, Germany, Hungary, Italy, Poland, Romania, Slovakia, Slovenia, Spain and the United Kingdom within only four years between 2014 and 2018 (Alves Dias et al. 2018). This implies that out of 173 German hard coal mines at the peak of German hard coal mining in 1957, only two still existed in 2018 (Fig. 2; Statistik der Kohlenwirtschaft e. V. 2018; Steenblik & Mateo 2020). These last two German hard coal mines, Prosper Haniel and Zeche Ibbenbüren, were closed in 2018 (Statistik der Kohlenwirtschaft e. V. 2018).

The post-mining phase of each of these former mining areas is characterised by the necessity of the implementation of a mine water management, the application of a case-adjusted multidisciplinary geomonitoring, and land reclamation and re-use strategy in order to minimise risks and take advantage of the opportunity. Besides re-use potentials such as mine workings and infrastructure that may be used for mining museums and education, exhibitions and event venues (e.g. conferences), post-mining potentials may also encompass biomass production, geothermal energy applications and energy storage (e.g. Bungart & Hüttl 2001; Wirth et al. 2012; Menéndez et al. 2019). In the context of climate change, abandoned mines may contribute to the decarbonisation of the electricity supply using the heat of the pumped mine water.

Among the numerous research areas covered by the >1,400 publications shown in Fig. 1, five superordinate research areas emerge (Fig. 3; Clarivate Analytics Web of Science 2022):

- human and social sciences,
- ecology, biology and environmental sciences,
- geological sciences,
- and other natural sciences comprising chemistry, physics and mathematics.

*Addresses of the authors:
[1]Institute of Applied Geosciences, Structural Geology & Tectonics, Karlsruhe Institute of Technology (KIT), Campus Süd, Adenauerring 20a, 76131 Karlsruhe, Germany (dennis.quandt@kit.edu / christoph.hilgers@kit.edu)
[2]Forschungszentrum Nachbergbau, Technische Hochschule Georg Agricola, Herner Str. 45, 44787 Bochum, Germany (tobias.rudolph@thga.de)

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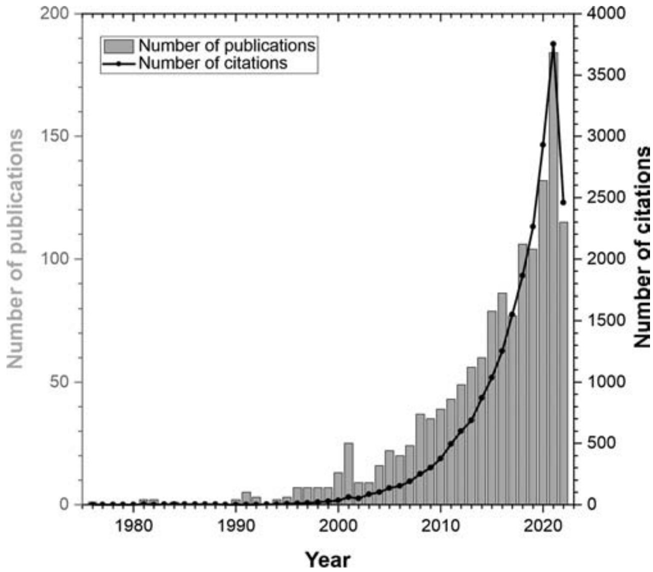

Fig. 1: Number of publications on post-mining and their citations per year since 1975 (data retrieved from Clarivate Analytics Web of Science on September 21, 2022). Only publications (i.e. peer-reviewed articles and review articles, meeting abstracts and proceedings papers, books and editorial material) containing the terms post-mining, postmining, and Nachbergbau (German for post-mining) in their title, abstract, and/or keywords were considered.

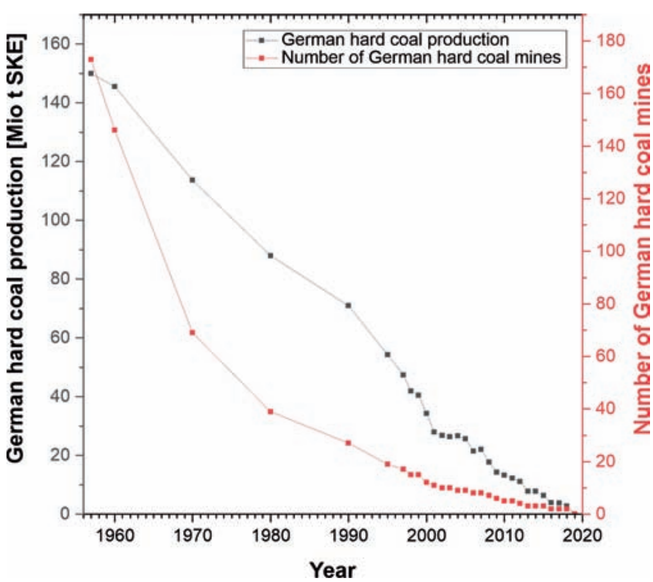

Fig. 2: German hard coal production in mineral coal units (SKE) and number of German hard coal mines over time (Statistik der Kohlenwirtschaft e. V. 2018). Besides mine closure, the amalgamation of mines reduces the total number of hard coal mines. Note that data before 1997 are incomplete and have been interpolated.

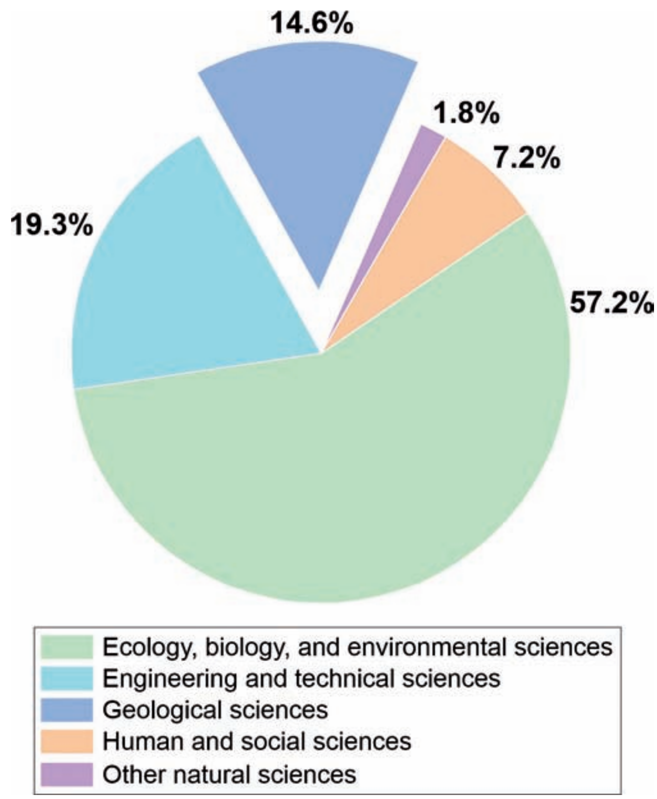

Fig. 3: Summarised research areas of publications on post-mining shown in Fig. 1 (data retrieved from Clarivate Analytics Web of Science on September 21, 2022). Geological sciences include structural geology, sedimentology, geochemistry, geophysics, mineralogy, remote sensing, meteorology, atmospheric sciences and palaeontology in order of decreasing counts.

Out of these five research areas, 57% of previous publications with reference to post-mining are represented by ecology, biology and environmental studies and only 15% of published post-mining related studies were conducted from a geological point of view (i.e. structural geology, sedimentology, geochemistry, geophysics, mineralogy, remote sensing, meteorology, atmospheric sciences and palaeontology in order of decreasing counts). This shows that in the last decades, post-mining studies focused on the consequences for flora and fauna, while studies on the geological subsurface and its interaction with surface processes are less represented in scientific literature. However, the integration of different disciplines has the potential to shed light on the magnitude of environmental changes in post-mining areas and, equally important, may contribute to a better process understanding, which may be transferred to future post-mining regions. Moreover, with an improved process understanding how mine water rebound, mine layout, geological structures, and petrophysical properties are interrelated with induced microseismicity and ground movements, the planning of future mining areas may be enhanced. This innovative approach requires the consideration of post-mining as an integral component of the mine life cycle.

This special volume entitled "Post-Mining: Geomonitoring, process understanding, and utilisation of former mining areas" takes place within a time of change and is more topical than ever. Several coal mines have recently transitioned into the post-mining stage and the consequences of mine flooding and the ongoing land reclamation are subject of modern geo-environmental monitoring. Additionally, a deep understanding of the underlying processes and the interactions of subsurface and surface have only partially been provided in literature so far (e.g. Wolkersdorfer & Bowell 2004, 2005a, b, and references therein; Fourie & Tibbett 2019 and references therein; Fourie et al. 2021 and references therein). This special volume is thus the first of its kind integrating different disciplines and also aims to encourage further research on post-mining.

The papers published in this special volume deal with geological, geophysical and geodetic aspects of post-mining research. Several former European hard coal and lignite mining areas in Germany, France, Poland and Czech Republic are addressed, taking advantage of extensive data bases available for the respective former mining areas and applying state-of-the-art multidisciplinary methods. The papers therein cover the reservoir scale up to the microscale and range from surface to subsurface, thus defining the structure of this special volume, i.e. from large to small and from general to detailed.

Accordingly, the first paper by **Rudolph et al.** gives an extended general definition of the geo- and environmental monitoring in post-mining. Three case studies on hard coal mining areas are reviewed and the combination of different geo- and environmental monitoring techniques are discussed. A special focus is on the utilisation of satellite and airborne remote sensing techniques.

Primo Doncel et al. present an overview of induced micro-seismicity in different European hard coal mining areas. They correlate micro-seismic events detected in French, German, Polish and Czech coal regions with the respective mine flooding processes. Based on the results from the different study areas, they highlight the relationship between flooding rate and the occurrence of micro-seismicity.

Rische et al. deliver an extensive dataset of induced micro-seismic events in the Ruhr area. They demonstrate in detail how micro-seismicity and mine water rebound are correlated considering the spatial relationship between micro-seismic events, former subsurface mine layout, and mine water rebound levels. Their results underline the importance of the site-specific geotechnical conditions for micro-seismicity.

Blachowski et al. present a monitoring study of surface erosion in an abandoned, partly reclaimed lignite mining area in the German-Polish border area over an observation period of 18 months. Based on unmanned aerial vehicle photogrammetry, they created a digital elevation model of difference and observed elevation changes of up to 0.90 m. Their approach represents an affordable and time-efficient method that delivered accurate results. They emphasise the importance of comprehensive land rehabilitation in post-mining areas with regard to the natural processes shaping post-mining landscapes.

Bernsdorf & Khaing Zin Phyu pursue the question in how far low-cost soil moisture sensors can be used for large-scale geomonitoring of a polder region in Germany. They conclude that the low-coast sensors tested in their study are able to show annual patterns of soil moisture.

Allgaier et al. combine outcrop and well data for a fracture network characterisation. Together with a geomechanical approach to deduce potentially conductive fracture trends controlled by the present-day stress field, this combination provides an overall assessment of the fracture network. The results help to improve the understanding of the reservoir qualities of the overall tight Upper Carboniferous sandstones for future geothermal exploration in the Ruhr area.

Niederhuber et al. present a comprehensive stress dataset for the Ruhr area. The results of their reassessment show a homogeneous stress distribution with only limited variation. These data are essential for fault reactivation in the context of mine flooding and risk assessment.

Ukelis et al. demonstrate how geological, hydrogeological, pedological and geomechanical data can be combined in order to identify suitable locations for soil gas surveys. Their short-term gas measurements across a modelled fault outcrop in the Ruhr area show CO_2, ^{222}Rn and O_2 anomalies, which together with the geomechanical analysis are a strong indicator for a structurally controlled gas migration and thus give evidence of an exposed fault. These results are of importance for long-term monitoring of potential mine water-induced degassing in the area.

Quandt et al. present petrographical and petrophysical data of siliciclastic rocks from the former Ibbenbüren coal mine. The authors highlight the heterogeneity of the subsurface in terms of petrographical and petrophysical properties in the study area and point out the importance of considering this heterogeneity in potential attempts to model ground movements as a result of mine flooding.

Greve et al. gather petrophysical data on siliciclastic rocks sampled from drill cores from the Ruhr area in order to better understand how sedimentary facies and petrophysical properties affect thermal conductivity of the rocks studied. They conclude that the mine water rebound is focused along permeable faults and mine workings, which determine the applicability of geothermal re-use approaches.

Dogan et al. regard the topic of post-mining from an educational point of view. They represent two projects that deal with the motivation of pupils to take up studies that are related to science, technology, engineering and/or mathematics and distance learning between universities.

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