v. Hünefeld-Mugova, E. & Wolkersdorfer, C. (2018): A Review of Mine Water Stratification. - In: Meier, G., et al. (eds): 18. Altbergbau-Kolloquium - Tagungsband. - p. 125-132, 2 Abb.; Nossen (Wagner).

A Review of Mine Water Stratification

Elke Mugova[1], Christian Wolkersdorfer[2,3]

[1]Technische Hochschule Georg Agricola, Forschungszentrum Nachbergbau, [2]South African Research Chair for Acid Mine Drainage Treatment, Tshwane University of Technology (TUT), [3]Lappeenranta University of Technology, Laboratory of Green Chemistry

1 Abstract

The flooding of underground mines is a process which has been known for many years and has been investigated since mines reached a certain depth. Stratification in a flooded mine is the formation of layered water bodies with different physicochemical properties and is a natural phenomenon described by several authors. Focusing on underground mines, this review paper summarizes all knowledge about stratification in this context. Investigation methods like shaft measurement with dippers or water sampling in a stratified system are explained. Furthermore, the application of numerical modelling, the use of small-scale testing facilities and tracer tests are overviewed. Research results from numerous publications are summarized and compared, bringing to understanding the location at which stratification appears in a flooded underground mine, the properties and stability of the layers, as well as buildup and breakdown scenarios. In addition, it explains the future use of stratification and further research ideas. One key finding of the review paper is that existing research about the topic draws conclusions which are largely site-specific. The development of a stratified system is strongly dependent on the setup of the mine. Therefore, a classification might be useful for predictions and the application of stratification for mine water treatment.

2 Keywords

stratification, underground mines, layering, mine water

3 Introduction

Stratification between different water bodies is mainly investigated in lakes and oceans (Blanc and Anschutz 1995, Voorhis and Dorson 1975) as well as in boreholes and groundwater measuring wells (Berthold and Börner 2008). Moreover it can be observed in pit lakes (Geller et al. 2013) and underground mines (ore, coal and salt), on which the review paper is focusing on. First observations about stratification in flooded underground mines were made by Stuart and Simpson (1961), later by Cairney and Frost (1975). Cutright (1979) mentioned also stratification, but without further explanations. Ladwig et al. (1984) was one of the first to publish more detailed results, describing the measuring method with a downhole probe and water sampling, as well as outlining that "[the] static or near-static water level conditions may be responsible for the observed development of water quality stratification." These were early ideas pointing out the advantage of mine water stratification. One paper that describes the topic in greater detail is from Nuttall and Younger (2004). Succeeding publications by other authors give no further explanations about the cause and mechanism of stratification in flooded underground mines but rather concentrate more on local measuring results, except those of the second author of this paper. It is to mention that the amount of publications is very limited and constrained to the European and Northern American regions. No research about stratification in underground mines is know from Africa or Asia, while research from Australia only focuses on pit lakes.

In cases where stratification is present in a mine, more precisely in a shaft, all authors describe the same scenario: water in the upper part of the mine has a better quality then water in the lower part of the mine (Ladwig et al. 1984, Nuttall and Younger 2004, Wolkersdorfer 2008), although the differences can vary considerably (Kories et al. 2004, Rüterkamp 2001). Various terms are used to describe the layers within a stratified system, such as freshwater, meteoric water (Henkel and Melchers 2017, Melchers et al. 2015, Rosner 2011, Rüterkamp 2001) or shaft water (Wolkersdorfer 1996) pertaining to the upper water body and saline water (Henkel and Melchers 2017) or sump water (Wolkersdorfer 1996) for the lower water body. In between exists an intermediate layer (Wolkersdorfer 2008), also known as transition layer (Wieber et al. 2016), boundary layer (Kories et al. 2004) or tranquillizing zone (Czolbe et al. 1992). A single water body with certain properties can be called homogeneous zone (Czolbe et al. 1992) or pond (Adams and Younger 2001). Even for the term stratification itself several phrases are common, namely mine water stratification (Rapantova et al. 2013a), mine pool stratification (Engineers 1975) or density stratification (Melchers et al. 2015).

The following text will summarize research about stratification in flooded underground mines. Investigation methods, and different scenarios will be explained such as during the flooding process, once the mine is flooded, and the mine under pumping conditions. The use of stratification as a prevention method against mine water pollution, as well as an outlook for further research is shared.

4 Methods

Water bodies that differ in their physicochemical properties are found by shaft measurements conducted with down-hole probes or dippers. By lowering the measuring device in the flooded shaft, parameters like temperature and electrical conductivity are recorded at certain distances. Smaller measuring intervals give results that are more precise. Parameter-depth-profiles reveal boundaries between different water bodies due to rapid change of temperature or electrical conductivity (Fig. 1). Together with temperature or electrical conductivity profiles, water samples can differentiate between water bodies with various chemical compositions, for instance different sulfate concentrations or isotopic composition (Czolbe et al. 1992, Henkel and Melchers 2017, Melchers et al. 2014, Nuttall and Younger 2004, Rüterkamp 2001, Snyder 2012, Wieber et al. 2016, Wolkersdorfer 1996, Zeman et al. 2008). Nowadays shaft cameras are also a handy tool to show intermediate layers via the changing colors and visibility of the water (Snyder 2012, Stemke et al. 2018). Usually, just single measurement campaigns are conducted, but repeated measurements over several years are described in the literature as well (Coldewey et al. 1999, Wieber et al. 2016).

Besides the shaft measurement, numerical modelling is an important method to understand flow patterns in mine voids and gain knowledge about stratification. Czolbe et al. (1992) used the finite difference method with a program named KASOMO, König and Blömer (1999) applied the program SPRING and Kories et al. (2004) proved that stratification can be stable over a long period of time by using the CFX program. Eckart et al. (2010) describes the application of CFD modelling in the context of stratification as well as the development and usage of a box model. These days CFD is used for modelling water flow in mine voids, whereby only the voids and not the surrounding fractured rock zones integrated in the model (Wolkersdorfer 2008).

Experiments about stratification between different water bodies in laboratory scale were conducted by Berthold and Börner (2008) for boreholes and monitoring wells, although these results are not directly translatable to a flooded underground mine. Coldewey et al. (1999) and Rüterkamp (2001) describe tests at a small-scale testing facility/technical center trail with two shafts and interconnected galleries, where they generated an artificial stratification and observed convection loops induced by external heating processes. Furthermore Eckart et al. (2010) explains the combination of their medium-scale testing facility and following modelling with CFD- and box model. Currently, the authors of this paper are setting up a medium-scale test facility (analogue model) of a flooded mine to understand stratification in greater detail. Results will be published as soon as they are available.

Flow measurement is another method to gain knowledge about processes in flooded mines and thereby the occurrence of stratified water bodies. Johnson and Younger (2002) used an impeller current meter for flow measurements in a shaft, Kories et al. (2004) an acoustic meter, Czolbe et al. (1992) a radioactive tracer and Wolkersdorfer (1996) used a flow meter, drift tracers as well as tracer substances. The usage of tracer tests in flooded underground mines is of worthy mention as it is possible to see flow pattern and calculate the velocity over a greater distance (Wolkersdorfer 2008). The tracer substance usually cannot break through an intermediate layer between two water bodies, through which stratification can be detected.

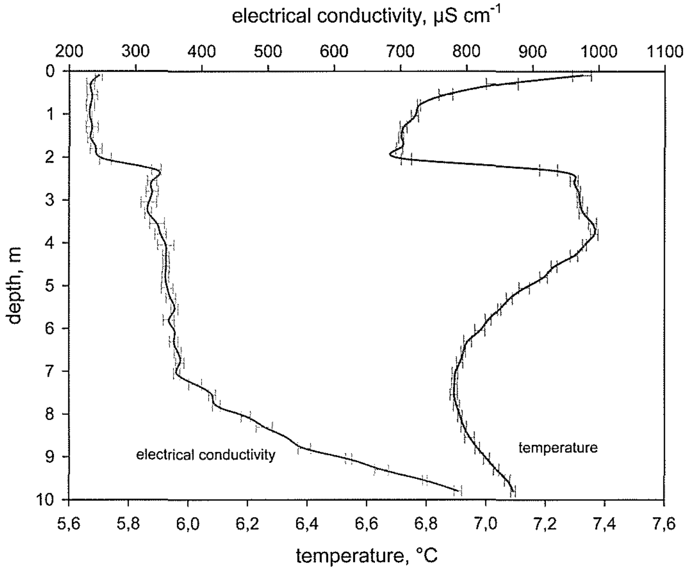

Fig. 1. Electrical conductivity and temperature–depth profile from a small-scale mine in Austria (from Wolkersdorfer 2008)

5 Results and Discussion

As per literature, stratification was observed in different states of the flooded underground mines during mine water rebound, after flooding, and whilst ongoing pumping activities (Johnson and Younger 2002, Melchers et al. 2015, Nuttall and Younger 2004, Rapantova et al. 2013b, Wieber et al. 2016, Wolkersdorfer 1996). Furthermore, it must be distinguished if surface water inflow, rising water from greater depth, or connected mine voids make the largest contribution to the flooding process. To have a closer look at natural stratification, and not to focus on forced stratification, which is influenced by manmade structures (Wolkersdorfer et al. 2016), different reasons for occurrence must be discussed (Fig. 2). Water bodies can be separated by chemical changes (e.g.

sulfate concentration), physical changes (e.g. temperature or electrical conductivity) or turbidity, primarily noticed at the area of onset (Coldewey et al. 1999, König and Blömer 1999, Ladwig et al. 1984, Nuttall et al. 2002, Nuttall and Younger 2004, Rüterkamp 2001, Wolkersdorfer 1996, 2008). Neither water inflow to the shaft, nor outflow from the shaft to roadways and galleries is the dominant process, however a distinction must be made between different origins of the water. Meteoric/infiltration water, either seeping into the shaft directly from the surface or through the shaft walls can build up a "surface water cap" (Wieber et al. 2016), or flow into the shaft via galleries (Coldewey et al. 1999). Futhermore, Nuttall and Younger (2004) describe the buildup of stratification by rising mine water. Additionally, Rüterkamp (2001) mentions that inflow from adjacent mine workings can cause layering. Depending on the setup of the mine workings, fluid or convection loops, more specifically thermosyphons between different shafts and galleries can be responsible for stratification, as described by Bau and Torrance (1981) and adopted for flooded underground mines by Wolkersdorfer (1996). In general, it is important to differentiate between stratification in a single-shaft mine without inflows from other mine voids and a mine system consisting of multiple shafts, galleries and adits where water flows and circulates on a much larger scale (Fig. 2). It is not clear though, if the surrounding rock type plays an important role. Melchers et al. (2014) describe stratification in shafts in the overburden and bedrock, while Rosner (2011) points out that inflow from the overburden after flooding was necessary to build up stratification. Also, the thickness of the water bodies varies between several meters to several hundred meters (Coldewey et al. 1999). Multiple water bodies in one shaft are possible (Zeman et al. 2008) and same (e.g. NaCl-type) or different (e.g. NaCl-type and CHO_3-type) water types can be found (Melchers et al. 2014). Descriptions about the thickness of the intermediate layer (boundary layer) vary as well between a few decimeters and some meters. Coldewey et al. (1999) describe a layer of 0.6 m, Kories et al. (2004) of 1.3 m, Wieber et al. (2016) measured 0.6 to 2.3 m and Wolkersdorfer (1996) 4 to 5 m. However, the thickness and position of the layer can change over time, it may get thicker towards the sump (Wolkersdorfer 1996) or thinner due to overlying surface water (Wieber et al. 2016). One continuous stable layer was observed over a period of 9 years by Kories et al. (2004), although even longer stability is to be assumed in some cases.

To have a closer look at the reasons why stratification builds up, density differences between water bodies must be considered. According to Wolkersdorfer (2008) "[...] temperature differences above 10 K ($\Delta\rho$ > 2 kg/m^3), total dissolved solid differences of more than 3% ($\Delta\rho$ > 20 kg/m^3) or large differences in turbidity ($\Delta\rho$ > 200 kg/m^3) can cause stable stratification". The geothermal gradient acts like a driving force: water in the deeper parts of the shaft heats up and rises up along the shaft wall, until reaching an anomaly, for example a connected roadway. The above-mentioned conditions take effect and an intermediate layer occurs; the water flows back downwards in the middle of the shaft towards the sump. A density driven free flow convection cell builds up, although to speak of one big steady state convection cell is probably wrong. Czolbe et al. (1992) and Kories et al. (2004) assume that several convection cells or "bales" within one water body exist. König and Blömer (1999) conclude from modelling results, that a reduced shaft diameter leads to more convection cells. At the boundary between two stable convection cells stratification occurs due to density differences. Molecular diffusion causes minor exchange of heat and particles (Czolbe et al. 1992, Rüterkamp 2001). In some cases, a staircase profile was observed at the intermediate layer to which Wolkersdorfer (2008) mentions double-diffusive flow or internal waves as possible causes.

The influence of turbidity to the stratified system is described differently by various authors. Water movement in a convection cell should be predominantly laminar flow due to upward moving at the warmer shaft walls and downward moving in the middle of the shaft. Nuttall and Younger (2004) also assume that laminar flow is the main flow pattern taking place in a stratified system because there is minimal mechanical mixing in the water column. Then again Frolik (2009), Wolkersdorfer (1996) and Coldewey et al. (1999) explain turbulent convective flow within the shaft as being more likely caused by shaft lining and roughness of the wall. Wolkersdorfer (2008) mentions several tracer tests in flooded mines with the finding that flow in flooded mine voids is almost always turbulent due to "[…] rock´s roughness, the mine support, broken roof and waste material left by the miners".

As with the buildup and occurrence of stratification in flooded underground mines, different factors also lead to its breakdown (Fig. 2). In general, the intermediate layer collapses due to external changes, however the setup of the mine plays the biggest role. The infiltration of surface water causes minor density differences between the 'heavier' mine water body in comparison to the 'lighter' surface water above resulting in the breakdown of the stratified system. This scenario applies to single-shaft mines without adits or outflows. Wieber et al. (2016) investigated several breakdowns at a shaft in Germany where mine water had almost no exchange with other waters except infiltrating surface water, hence stratification got destroyed over time. Another reason for breakdowns are external forces; manmade activities like pumping in the shaft, measurements or injections during tracer tests, as well as natural incidents such as earthquakes or storms. Additionally, the system can be disrupted by breakdown of dams in connected mine voids (Nuttall and Younger 2004, Wolkersdorfer 2008). In case the mine is still in its flooding process, stratification can also break down when the rising mine water reaches an outflow pathway or adit. The same principle can apply to connected galleries and the buildup of convection loops, described in detail by Wolkersdorfer (1996) and Nuttall and Younger (2004). The breakdown by jet like vertical or horizontal inflow into the shaft, mentioned by Wolkersdorfer (2008) has not yet been investigated.

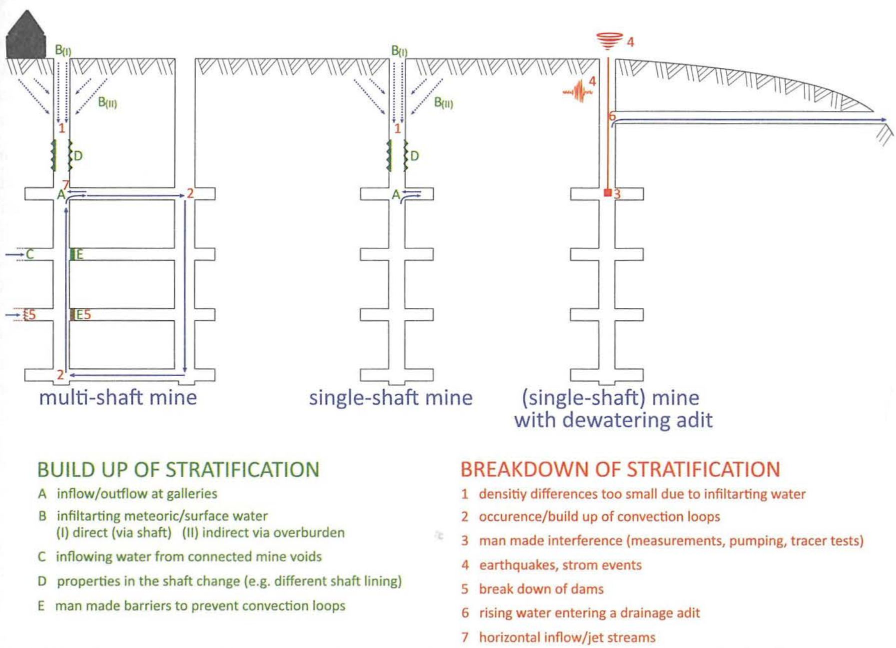

Fig. 2 Build up and breakdown scenarios of stratification in a single- and multi-shaft mine

Stratification in flooded underground mines has been researched for more than 40 years. Nevertheless, a clear prediction when a stratified system develops or breaks down is not yet possible. To apply stratification as a treatment method, it must be seen from different perspectives: the flooding process, the flooded mine itself as well as possible pumping activities must be monitored and sometimes regulated. If stratification occurs in a mine, attention must be drawn on the measurement results. Depth logging and water samples can deliver completely different results within a few meters, hence to assume that only one water body would exist throughout the shaft might be wrong. This knowledge is very important when it comes to characterizing mine water treatment plants, because the water quality in the upper part is not necessarily the same as the water quality deeper within the mine (Nuttall and Younger 2004). An application for mine water stratification is to use the barrier property of the intermediate layer to prevent pollution of outflowing water from the shaft (Wolkersdorfer et al. 2016). By 1980, Uerpmann (1980) had already published first ideas for radioactive water disposal in a mine. Wolkersdorfer (1996) also developed the concept that a stable stratified system with better quality water close to the surface would minimize the need for treatment facilities. His concept promotes manmade barriers, for example by dams to prevent the effect of thermosiphons, whereby water cannot circulate between shafts and galleries. In addition, Kories et al. (2004) suggest that "[...] the layering effect can be enhanced by natural and artificial fresh water recharge." Until now the authors are not aware of any deliberate use or even generation of stratification in flooded underground mines. Numerical modelling and further detailed field measurements are necessary to gain more findings about the topic. Coldewey et al. (1999), for example, points out that more sensitive data about velocities in single convection cells, the spatial expansion of convection cells and convection loops as well as qualitative and quantitative investigation of inflows are required. Field measurement in different mine types by depth logging, water samples and tracer tests together with small scale testing facilities should be continued.

6 Conclusions

After reviewing more than 30 publications from 1961 to 2018, it can be concluded that stratification in flooded underground mines is well observed in salt, coal and ore mines. However, a detailed understanding about the process of buildup and breakdown is not yet present. Even though several published and unpublished measurement results about separation of different water bodies in flooded shafts exists, it is not yet definable at which point in time a stratified system develops. The main difficulty being, that most mines have a different setup and flooding process. Single and multi-shaft mines differ in their flow pattern. In a single-shaft mine usually only convective cells within the shaft occur, in a multi-shaft mine convections loops or thermosiphons are also possible, which may influence the stratified system in a complete different way. Therefore, it might be useful to classify a flooded underground mine into several categories to understand why stratification exists under certain conditions. Perhaps it is possible to find crosslinks between the underground structure and i) after what time stratification develops, ii) how long it is stable iii) when it breaks down and iv) conditions and times for redevelopment. Finally, the question must be answered if stratification will develop eventually in all flooded underground mines under the right conditions, which are yet to be defined. Overall, further research should focus on prediction of stratification. In the long-term it is important to work towards the application of stratification to prevent pollution by emerging mine water and use stratification to reduce or avoid mine water treatment facilities. Given these points a general concept must be developed to determine whether stratification in future flooded mines is to be left to occur naturally or if manmade intervention can enhance the process.

7 Acknowledgements

The authors thank their respective research institutions for providing support in doing their research. Forum Bergbau und Wasser made travel funds available.

References

Adams, R. and Younger, P.L. (2001) A Strategy For Modeling Ground Water Rebound in Abandoned Deep Mine Systems. Ground Water 39, 249-261.

Bau, H.H. and Torrance, K.E. (1981) On the stability and flow reversal of an asymmetrically heated open convection loop. Journal of Fluid Mechanics 109, 417-433.

Berthold, S. and Börner, F. (2008) Detection of free vertical convection and double-diffusion in groundwater monitoring wells with geophysical borehole measurements. Environ. Geol. 54, 1547-1566.

Blanc, G. and Anschutz, P. (1995) New stratification in the hydrothermal brine system of the Atlantis II Deep, Red Sea. Geology 23(6), 543-546.

Cairney, T. and Frost, R.C. (1975) A Case study of mine water-quality deterioration, Mainsforth Colliery, County Durham. J. Hydrol. 25(3-4), 275-293.

Coldewey, W.G., Hewig, R., Richter, R., Rüterkamp, P. and Wedewart, M. (1999) Mittelfristige Entwicklung des Chemismus und der Dichte-Schichtungen von Grubenwässern in Bergwerken und ihre Auswirkungen auf nutzbares Grund- und Oberflächenwasser, Deutsche Montan Technologie GmbH, Essen.

Cutright, B.L. (1979) Water use possibilities in abandoned iron mines. Miscellaneous Paper - Wisconsin Geological and Natural History Survey 79-3, 13.

Czolbe, P., Kretzschmar, H.-J., Klafki, M. and Heidenreich, H. (1992) Strömungszellen im gefluteten Salzschacht. Neue Bergbautech. 22(6), 213-218.

Eckart, M., Rüterkamp, P., Klinger, C., Kories, H. and Gzyl, G. (2010) Qualitätsentwicklung der Grubenwässer bei der Flutung von Steinkohlen- und Erzbergwerken. Wiss. Mitt. 42, 123-132.

Engineers, S.a.T.I.C. (1975) Mahanoy Creek Mine Drainage Pollution Abatment Project, Project SL 197. Operation Scarlift Commonwealth of Pennsylvania Milton J. Shapp, G.D.o.E.R. (ed), Pottstown, Pennsylvania

Frolik, A. (2009) Stratyfikacja hydrogeochemiczna wód w zatopionych podziemnych wyrobiskach górniczych. Przegl. Gorn. 65(7-8), 84-90.

Geller, W., Schultze, M., Kleinmann, R. and Wolkersdorfer, C. (2013) Acidic Pit Lakes – The Legacy of Coal and Metal Surface Mines, Springer, Heidelberg.

Henkel, L. and Melchers, C. (2017) Hydrochemical and isotopegeochemical evaluation of density stratification in mine water bodies of the Ruhr coalfield, Lappeenranta, Finland.

Johnson, K.L. and Younger, P.L. (2002) Hydrogeological and geochemical consequences of the abandonment of Frazer's Grove carbonate hosted Pb/Zn fluorspar mine, North Pennines, UK. Spec. Publ. – Geol. Soc. London 198, 347-363.

König, C. and Blömer, C. (1999) Berechnung von temperatur- und dichteabhängiger Strömung in gefluteten Schächten, p. 37, GKW-Ingenieurgesellschaft mbH, Bochum.

Kories, H., Rüterkamp, P. and Sippel, M. (2004) Field and numerical studies of water stratification in flooded shafts. Jarvis, A.P., Dudgeon, B.A. and Younger, P.L. (eds), University of Newcastle, Newcastle upon Tyne.

Ladwig, K.J., Erickson, P.M., Kleinmann, R.L.P. and Posluszny, E.T. (1984) Stratification in water quality in inundated anthracite mines, eastern Pennsylvania, pp. ii, 35 p., U.S. Dept. of the Interior, Bureau of Mines, Avondale, MD.

Melchers, C., Coldewey, W.G., Goerke-Mallet, P., Wesche, D. and Henkel, L. (2015) Sanierte Bergbaustandorte im Spannungsfeld zwischen Nachsorge und Nachnutzung – WISSYM 2015. Paul, M. (ed), pp. 99-106, Wismut GmbH, Chemnitz.

Melchers, C., Wesche, D. and Coldewey, W.G. (2014) Ausbildung von Dichteschichtungen in Schächten des Steinkohlenbergbaus im Ruhrrevier, Gelsenkirchen.

Nuttall, C.A., Adams, R. and Younger, P.L. (2002) Integrated hydraulic-hydrogeochemical assessment of flooded deep mine voids by test pumping at the Deerplay (Lancashire) and Frances (Fife) Colliery. Spec. Publ. – Geol. Soc. London 198, 315-326.

Nuttall, C.A. and Younger, P.L. (2004) Hydrochemical stratification in flooded underground mines: an overlooked pitfall. J. Contam. Hydrol. 69(1-2), 101-114.

Rapantova, N., Licbinska, M., Babka, O., Grmela, A. and Pospisil, P. (2013a) Impact of uranium mines closure and abandonment on groundwater quality. Environ Sci Pollut Res Int 20(11), 7590-7602.

Rapantova, N., Licbinska, M., Babka, O., Grmela, A. and Pospisil, P. (2013b) Impact of uranium mines closure and abandonment on groundwater quality. Environmental Science and Pollution Research 20(11), 7590-7602.

Rosner, P. (2011) Der Grubenwasseranstieg im Aachener und Südlimburger Steinkohlenrevier – eine hydrogeologisch-bergbauliche Analyse der Wirkungszusammenhänge. Dissertation, Rheinisch-Westfälischen Technischen Hochschule Aachen, Aachen.

Rüterkamp, P. (2001) Bildung von Dichteschichtungen in Grubenwässern. Glückauf-Forschungshefte 62(2), 40-44.

Snyder, D. (2012) Vertical gradients in geochemistry of flooded mine shafts in Butte, Montana. M.S., Montana Tech of The University of Montana, Ann Arbor.

Stemke, M., Gökpinar, T., Wieber, G. and Wohnlich, S. (2018) Erfassung und Bildung von Schichtungen im Wasser gefluteter Bergwerksschächte Ruhr Universität Bochum, Johannes Gutenberg Universität Mainz, Bochum.

Stuart, W.T. and Simpson, T.A. (1961) Variations of pH with depth in anthracite mine-water pools in Pennsylvania; Article 37. U. S. Geological Survey Professional Paper, B82-B84.

Uerpmann, E.-P. (1980) Hydrogeologische Fragen bei der Endlagerung radioaktiver Abfälle, Unveröff. Diss. TU Clausthal, Clausthal.

Voorhis, A.D. and Dorson, D.L. (1975) Thermal convection in the Atlantis II hot brine pool. Deep-Sea Research 22, 167-175.

Wieber, G., Enzmann, F. and Kersten, M. (2016) Entwicklung und Veränderung der Dichteschichtung in Schächten gefluteter Erzbergwerke. Mainzer Geowissenschaftliche Mitteilungen.

Wolkersdorfer, C. (1996) Hydrogeochemische Verhältnisse im Flutungswasser eines Uranbergwerks – Die Lagerstätte Niederschlema/Alberoda. Clausthaler Geowissenschaftliche Dissertationen, 50:1-216, 131 Abb., 61 Tab.

Wolkersdorfer, C. (2008) Water Management at Abandoned Flooded Underground Mines – Fundamentals, Tracer Tests, Modelling, Water Treatment, Springer, Heidelberg.

Wolkersdorfer, C., Shongwe, L. and Schmidt, C. (2016) Can natural Stratification prevent Pollution by Acid Mine Drainage? Paper presented at the IMWA 2016 – Mining Meets Water – Conflicts and Solutions, Leipzig/Germany. - p. 115-121, Freiberg (TU Bergakademie Freiberg).

Zeman, J., Šupíková, I. and Cerník, M. (2008) Mine Water Stratification at Abandoned Mines and its Geochemical Model. Proceedings, 10th International Mine Water Association Congress, 183-186.