Investigating the Effects of Temperature on Density Stratification in a Flooded Analogue Model Mine

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Abstract

This paper outlines the effects of temperature as a controlling factor for density stratification in a flooded analogue model mine called the Agricola Model Mine (AMM). It is 4 × 6 m large and consists of four shafts and four levels. Mine water stratification results from density differences of the fluid controlled by physical properties including primarily temperature and total dissolved solids. It might be used as an *in-situ* remediation method. This study focuses on the effects of temperature on the stability of density stratification.

Keywords: Stratification, Abandoned Flooded Underground Mines, Mine Water, Mine Closure, Post Mining Remediation

Introduction

The purpose of this study is to determine controlling factors for water stratification in flooded underground mines in an analogue (physical) model mine. A laboratory based experiment was performed using the Agricola Model Mine (AMM). It is a physical representation of interconnected mine shafts and levels. Mine water flooding models vary therefore, helping to understand the release of potential contaminants from abandoned mines and they can be aided to model flows in flooded underground mines.

Mining plays a critical role in the degradation of the environment, especially on ground and surface water quality (Northey *et al*. 2019; Ochieng *et al*. 2017). It is therefore important to understand the environmental effects of mining activities, as this plays an essential role in developing mine water management as well as mine closure plans. It is essential to understand the water chemistry in abandoned mine workings prior to pumping to alleviate lower quality of water pumped from flooded mines. Such practices can be effectively incorporated in water treatment plans to reduce related financial costs (Wolkersdorfer *et al*. 2016). It is imperative to understand *in situ* ground water dynamics to implement remediation or treatment facilities

Hydrochemical stratification in flooded underground mines can result from flooding mine workings due to the cessation of pumping (Adams and Younger 2001; Denimal *et al*. 2005). Nuttall and Younger (2004), define stratification as layering of different water bodies with varying chemical composition and Wolkersdorfer (2008) defines stratification as a function of the water density. Parameters such as pH, temperature, Eh, electrical conductivity and chemical properties of the concerned mine body water aids in the comprehension of stratification. Wolkersdorfer (2008) states differences in temperature above 10K ($\Delta\rho > 2$ kg/m^3), differences in total dissolved solid, greater than 3 % ($\Delta\rho > 20$ kg/m^3) or greater turbidity differences ($\Delta\rho > 200$ kg/ m^3) can cause stable stratification; however the geothermal gradient can accelerate stratification breakdown.

Often, the geothermal gradient is important, as the mine water is heated in the lower sections of the mine, therefore rising to the upper parts of the mine, resulting in convective mixing, as a result of density differences of the two water bodies (Solodov *et al*. 2002). Therefore, heat induces free convection, resulting in buoyancy effects (Berthold and Börner 2008).

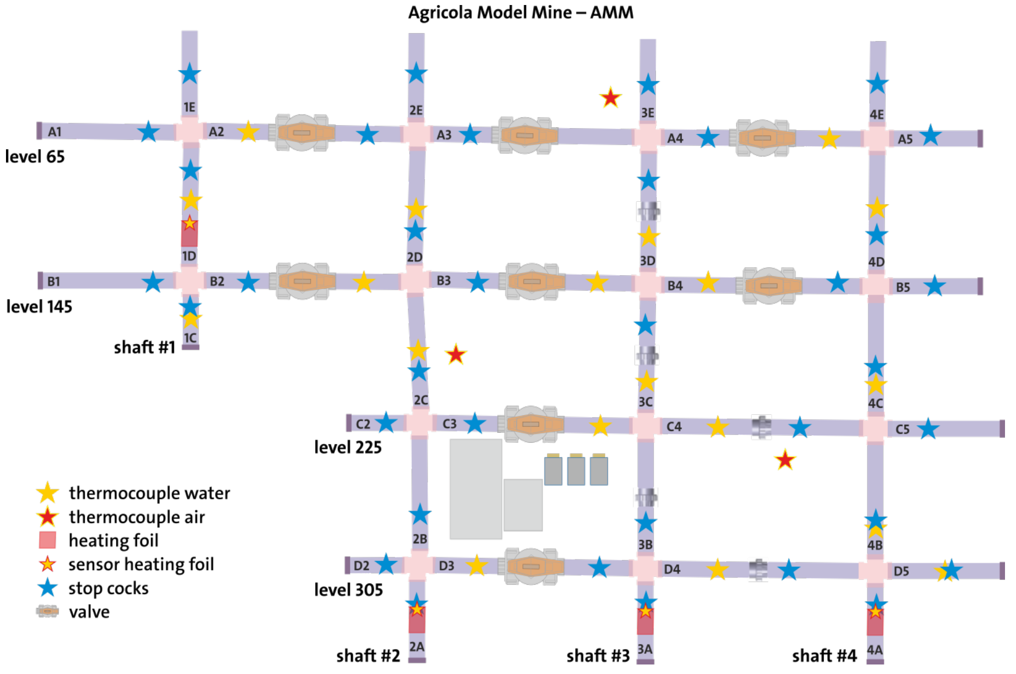

Figure 1 Schematic representation of the Agricola Mine Model (AMM) at the Tshwane University of Technology. Each section is numbered individually for identification purposes, and some can be separated from each other by valves (e.g. within sections A2 or A3).

The AMM

The AMM (Figure 1) was constructed at Tshwane University of Technology's Arcadia campus in the mine water laboratory. It is 4 × 6 m large and consists of four shafts (shaft #1 – #4) that can be isolated with valve systems, and four working levels, ranging from 65 cm to 305 cm depths, and it can hold a maximum of 153 L of water. These shafts and working levels were constructed with insulated PVC tubes mounted to the laboratory wall.

Eight temperature controlled 12 V, 137 × 320 mm large heating foils with a surface temperature of 60 °C are mounted outside the tubes at sections 1C, 2A, 3A, 4A to simulate a geothermal gradient. Thermocouples are inserted inside the tubes at each section to record the fluid's temperature while flowing through the AMM. Furthermore, three thermocouples are mounted outside the AMM to measure the air temperature. All temperature data was logged using Huato S220-T8 data loggers.

Additionally, the shafts can either be flooded individually by manipulating the valves or they can be flooded simultaneously. Sampling ports (consisting of a stop cock and a lure lock) are attached to the model on every section and used as a pathway to inject tracers or to take water samples.

Methods

Experiments ran for ±30 days by flooding the model and injecting tracers into the system. Samples were taken regularly (usually daily) to monitor parameters such as temperature, flow direction and flow patterns by injecting Sodium Fluorescein (uranine dye) and analysing it fluorometrically. Furthermore, electrical conductivity was measured to monitor stratification development at a) static conditions and b) stratification breakdown while increasing temperature using heating foils, representing the geothermal gradient.

Levels 225 and 305 cm were filled with 93 L of fresh water and samples were collected and analysed using a spectrophotometer. Shortly thereafter, 60 L of brine with a NaCl concentration of 70 g/L and sodium fluorescein dye (uranine) at a concentration of 800 µg/L was pumped into shafts 2, 3 and 4 simultaneously from the top. One CTD diver (Van Essen Instrument, Netherlands) was lowered daily into each shaft to measure the electrical conductivity. One baro-diver was used to measure the air pressure outside the shaft to calculate the water levels correctly. Initially, the experiment was conducted at steady state conditions to create an artificial density stratification, to observe the duration of the stabilisation, and later the heating foils were switched on and the temperature was increased constantly to break down the stratification.

Results and Discussion

Uranine distribution in the AMM

Two stratified water bodies were evident in the AMM at the commencement of the experiment. A 549 µg/L average concentration of uranine dye was measured in the highly mineralised layer (WM layer) and a 0 µg/L average concentration in the cold tap water layer (CF layer). Furthermore, a 402 µg/L average concentration was measured at the transitioning layers C2 – C5 and 0 µg/L (layer 2C – 4C). During the experiment, the average concentration remained the same in all the layers, implying that the stratification was still stable, regardless of the temperature increase by the heating foils (19–20 °C). However, the stratification finally disintegrated, when the temperature was increased to 43 °C. On termination of the experiment, an even uranine distribution with an average concentration of 200 µg/L was observed across all the sections of the AMM. The results can be seen in a video, showcasing the uranine distribution throughout the duration of the experiment (www.wolkersdorfer.info/Ur5video).

Flow measurement in the AMM

Flow measurements were taken with a flow meter located vertically at leg 2B. An average flow of 0.017 m/s was measured, with a maximum flow of 0.025 m/s and minimum of flow of 0.006 m/s (Figure 2). On the commencement of the experiment, the temperature on the heating foils was steadily increased from 19 °C to 39 °C daily for the first 300 hours, hence the sharp increase in flow from an average of 0.013 m/s to 0.020 m/s. The flow stabilised for a while, from 300 to 1360 hours, averaging 0.020 m/s flow rate and a maximum temperature of 45 °C was set on the heating foils. The flow then decreased after 1360 hours to 0.015 m/s average flow.

Laminar flow conditions prevailed very likely throughout the experiment as shown by the Reynold's numbers at different temperature measurements. A Reynold's number of Re = 120 was calculated for 20 °C, Re = 134 for 25 °C and Re = 150 for 30 °C. Regardless of laminar flow in the AMM based on the Reynold's numbers, presence of turbulent flow must not be disregarded, as obstacles in the shafts, such as tubes, cables and other point of connections, inside the AMM might interfere with the flow (Renz *et al.* 2009; Wolkersdorfer 2008). An indication for turbulent flow are the fluctuations of the measured parameters, as they are characteristic indications for turbulent flow conditions.

An additional flow measuring device was installed horizontally at C4 four days post the commencement of the experiment. The flow measurements varied greatly from the previous measurements (Figure 3). A 0.008 m/s average flow rate was recorded from the beginning to 205 hours, at temperatures ranging from 21 to 45 °C on the heating foils.

Between 200 and 1300 hours, the temperature increased, and the flow rate remained constant at 0.015 m/s average flow, with the highest temperature (45 °C) set on the heating foils, for this experiment. Consequently, the flow rate decreased 130 hours later, averaging 0.010 m/s and remained constant through to the end of the experiment. The Reynold's numbers were Re = 72 (20 °C), Re = 86 (25 °C) and Re = 89 (30°C), thus indicative of laminar flow in the AMM. However, as discussed before, this doesn't rule out the presents of turbulent flow in the AMM, resulting from obstacles present in the shafts and galleries.

The vertical flow rate measured in the shafts of the AMM seems to be higher, as compared to the horizontal flow rate in the galleries of the AMM. Temperature increase and difference in density, induces free convection resulting from buoyancy, thus resulting in heat and mass diffusion and possibly further accelerating the flow rate (Berthold and Börner 2008). Therefore, the addition of the geothermal gradient, aided in increasing the average flow rate from 0.013 m/s in previous experiments at steady state conditions to 0.017 m/s in the vertical sections of the AMM. An additional flow meter to measure the horizontal flow rate was installed late in the experiment, thus there was no data to compare with at steady state conditions.

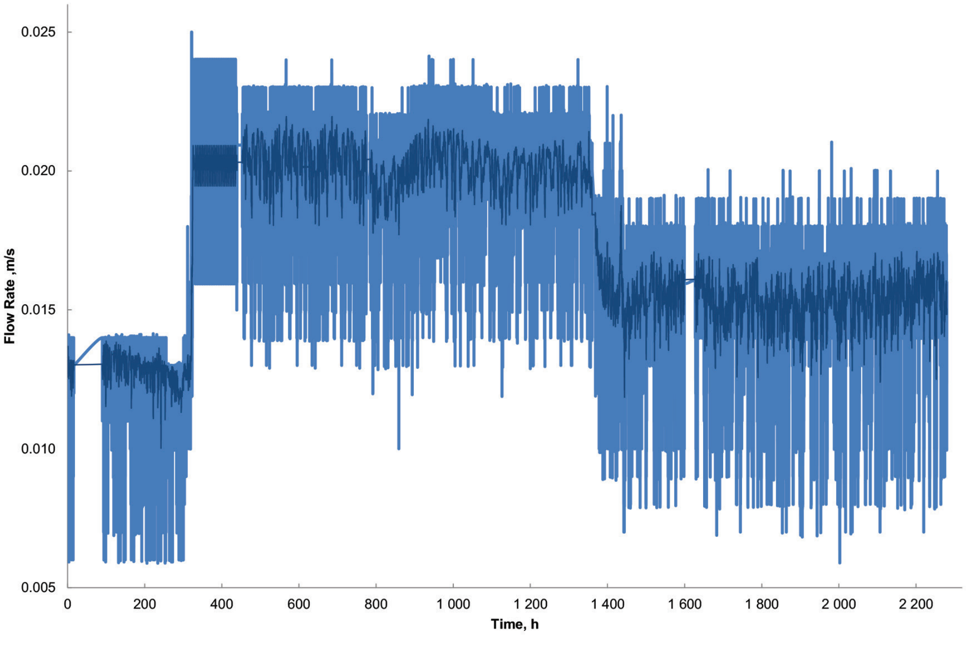

Figure 2 *Flow rate in the AMM plotted against time, sensor located vertically at section 2B*

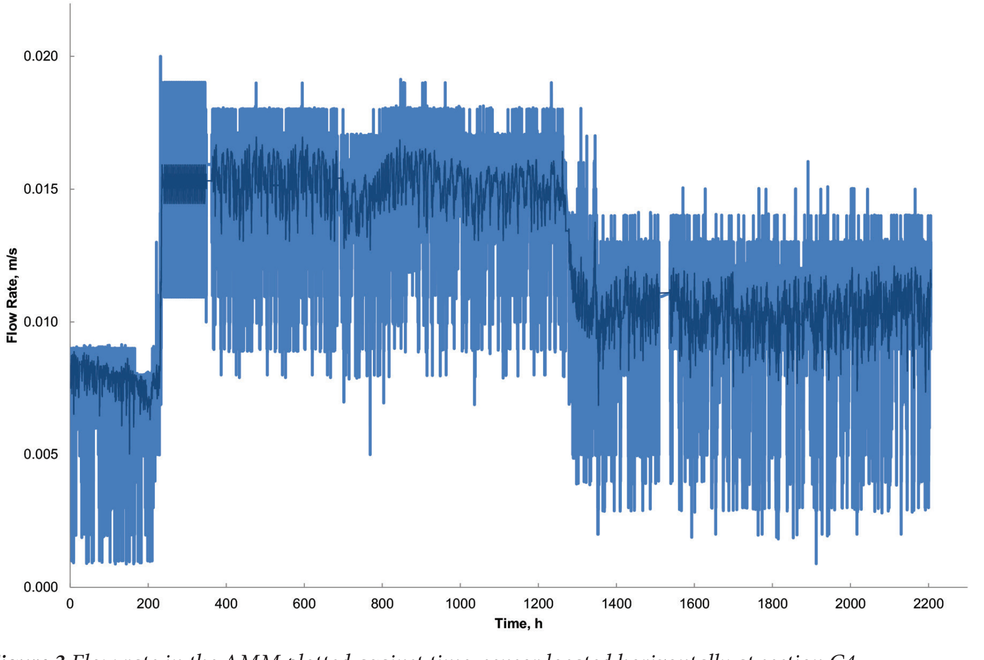

Figure 3 *Flow rate in the AMM plotted against time; sensor located horizontally at section C4*

Temperature measurements

Three room air temperature thermocouples recorded minimum temperatures ranging between 14.4 and 14.8 °C and maximum temperatures between 28.2 and 29.0 °C (figure to be found at www.wolkersdorfer.info/Ex5Temp). Air temperature increased gradually from the day the experiment commenced, and 800 hours later the temperature decreased abruptly for a short while. It remained stable and just days before the ceasing of the experiment, the measurement showed a gradual decrease in temperature.

A similar temperature trend was observed in the *in situ* water readings, regardless of the maximum temperature readings, ranging between 35.7 and 45.0 °C and minimum temperature readings, ranging between 2.7 and 14.7 °C. The temperature in all the legs, started low and increased constantly due to the addition of energy by the heating foils. In the two lower levels (305 and 225) filled with warm mineralised water, temperature had a similar trend. This means that the temperature increased constantly and then decreased abruptly. A sharp drop in temperature was observed first in section 4B in shaft #4, 800 hours post the commencement of the experiment, then followed by section 2B, in shaft #2, 1358 hours later. This corresponds to the uranine diffusion times observed at the respective legs.

Thereafter, the temperature increased for a short while, then remained constant until the last day of the experiment. The temperature trend in level 225, 145 and 65, differs from one another. In level 145, the temperature was increasing and remained constant for a longer time, at sections 2C, B3, 3C, B4 and 4C, then a sharp increase was suddenly observed for a short while. The temperature at 2C was low due to the warm water from B1 and B2, thus the colder water from section 2C was very likely too heavy to move upwards.

The drop was followed by an increase in temperature and then remained constant through to the end of the experiment. Sections 1C and B2 in level 145 behaved differently from the other legs in the same level, as the temperature increased constantly in section 1C for most part of the experiment. 1600 hours later, the temperature increased abruptly, which might be due to the fact that the water in section 1C gradually warmed up and eventually was able to mix with the water in section 1D, where the heating foils were located. Section B2 was also an exception as the temperature increased constantly and then dropped gradually at around 800 hours, whereafter it started to gradually increase at 1400 hours and finally dropped again gradually. This was due to the mixing of the water from sections 1C, A2 and 2C, with varying temperature.

Electrical Conductivity and Temperature Measurements

To monitor the stability and breakdown of the artificial density stratification, electrical conductivity and temperature were measured in each shaft using CTD divers. On the day the experiment commenced (Figure 4a), 100 mS/cm electrical conductivity was measured in all the shafts at 200 cm depth. Exception was shaft #1, where the measurement in the two upper levels containing tap water was at 0 mS/cm and the temperature measurements were ranging between 17 and 19.5 °C. Consequently, the temperature was decreasing from the sump of the shaft and was the lowest at the transition layer (between the CF and WM layers) but increasing towards the collars of the shafts. The high temperature at the bottom of the shafts were due to the heating foils, running at 19 and 20 °C, and two water bodies were visible in the AMM.

Initially, the stratification remained stable at 100 mS/cm electrical conductivity at 200 cm depth. A similar temperature trend was observed: the temperature was higher in the sumps (Figure 4b). This was due to the geothermal gradient running at 20 and 21 °C and decreased towards the transitional layer. However, it remained stable for a short time in all the shafts and thereafter increased steadily in shaft #4, to 21 °C. However, at this instance three water bodies were evident, in shaft 2, 3 and 4 at the transition layer. Heat convection cells were forming, hence the mixing of the water in the CF and WM layers, due to heat and mass transfer. This phenomenon was explained by Berthold and Börner (2008), Mugova and Wolkersdorfer

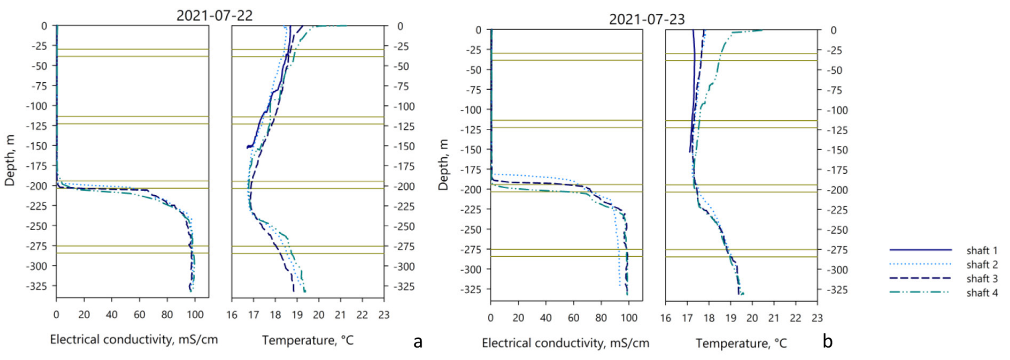

***Figure 4** Electrical conductivity and temperature measurements, for shaft 1, 2, 3 and 4 depicting a stable stratification in all shafts, except shaft1 (a. 2 stratified water bodies, b. 3 stratified water bodies)*

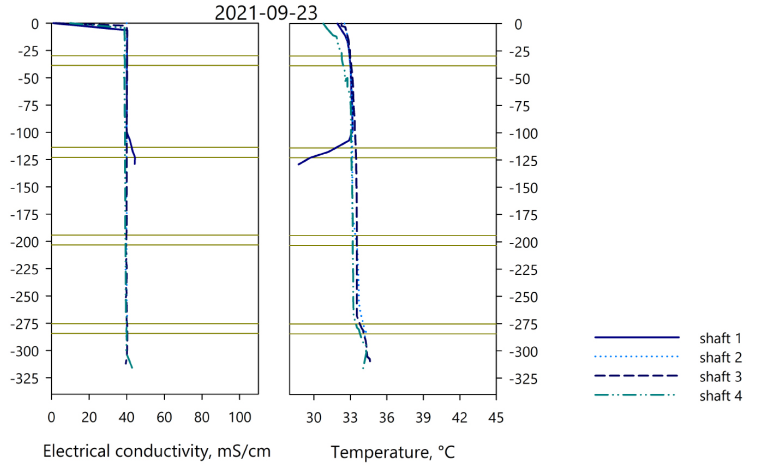

***Figure 5** Electrical conductivity and temperature measurements for shafts #1, #2, #3 and #4 depicting stratification breakdown in all the shafts*

(2022) and Uerpmann (1980) referring to the transitional layer as a boundary layer, where fluctuations in concentration and temperature are indicative of heat and mass transfer due to free convection, also known as bales (Kories *et al.* 2004).

On day 63 post the commencement of the experiment, the mineralised water and tap water layers were completely mixed, implying that the stratification broke (Figure 5). The overall electrical conductivity for the *in situ* water in the AMM was 40 mS/cm, and the temperature increased to over 35 °C, in all sections except for section 1C.

Conclusions

Temperature addition to the AMM, had a paramount effect on the stratification stabilisation and breakdown. Stratification might be used as an *in situ* remediation method; however temperature control is of paramount importance in regulating optimal conditions for stratification development, stabilisation and breakdown. Furthermore, temperature differences also accelerated the flow in the AMM due to the development of convection cells from buoyancy, regardless of the presence of laminar flow in the AMM. Even though, turbulent flow in the AMM cannot be disregarded due to presence of obstacles in the AMM. The AMM, therefore, acts as a thermosiphon system, hence the development of the three water bodies, a day after increasing the temperature.

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References

Adams R, Younger P (2001) A strategy for modeling ground water rebound in abandoned deep mine systems. Groundwater 39(2):249-261. https://doi.org/10.1111/j.1745-6584.2001.tb02306.x

Berthold S, Börner F (2008) Detection of free vertical convection and double-diffusion in groundwater monitoring wells with geophysical borehole measurements. Environ Geol 54(7):1547-1566. https://doi.org/10.1007/s00254-007-0936-y

Denimal S, Bertrand C, Mudry J, Paquette Y, Hochart M, Steinmann M (2005) Evolution of the aqueous geochemistry of mine pit lakes–Blanzy–Montceau-les-Mines coal basin (Massif Central, France): origin of sulfate contents; effects of stratification on water quality. Appl Geochem 20(5):825-839. https://doi.org/10.1016/j.apgeochem.2004.11.015

Kories H, Rüterkamp P, Sippel M Field and numerical studies of water stratification in flooded shafts. In: International Mine Water Association Symposium, 2004. 149-159 p

Mugova E, Wolkersdorfer C (2022) Density Stratification and Double-Diffusive Convection in Mine Pools of Flooded Underground Mines–A Review. Water Res 118033. https://doi.org/10.1016/j.watres.2021.118033

Northey S, Mudd G, Werner T, Haque N, Yellishetty M (2019) Sustainable water management and improved corporate reporting in mining. Water Resour Ind 21:1 - 20. https://doi.org/10.1016/j.wri.2018.100104

Nuttall CA, Younger PL (2004) Hydrochemical stratification in flooded underground mines: an overlooked pitfall. J Contam Hydrol 69(1). https://doi.org/10.1016/S0169-7722(03)00152-9

Ochieng GM, Seanego ES, Nkwonta OI (2017) Impacts of mining on water resources in South Africa: A review. Sci Res Essays 5:3351 - 3357

Renz A, Rühaak W, Schätzl P, Diersch H-J (2009) Numerical modeling of geothermal use of mine water: challenges and examples. Mine Water Environ 28(1):2-14. https://doi.org/10.1007/s10230-008-0063-3

Solodov I, Malkovsky V, Pek A, Benson S (2002) New evidence for the combined influence of vapor condensation and thermal convection on groundwater monitoring wells. Environ Geol 42(2):145-150. https://doi.org/10.1007/s00254-001-0484-9

Uerpmann E-P (1980) Hydrogeologische Fragen bei der Endlagerung radioaktiver Abfälle. Ges. für Strahlen-u. Umweltforschung

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

Wolkersdorfer C, Shongwe L, Schmidt C Can natural Stratification prevent Pollution by Acid Mine Drainage? In: Drebenstedt C, Paul M (eds) International Mine Water Association 2016 – Mining Meets Water – Conflicts and Solutions, Leipzig/Germany, 2016. TU Bergakademie Freiberg, Freiberg, 115-121 p