Stratification in flooded Underground Mines – State of Knowledge and further Research Ideas

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Abstract

Based on their physicochemical properties, water bodies can differentiate, resulting in stratification. Where stratification occurs, water with better quality is usually closer to the surface than higher mineralized water. The authors investigated if stratification in flooded underground mines can be used as a passive in-situ remediation method. After reviewing research results about stratification, it will be possible to give an overview about the state of knowledge, usage of terms as well as scenarios in which stratification occurs and breaks down. New approaches how to evaluate existing data as well as new research methods and further research ideas are described.

Keywords: stratification, underground mines, layering, mine water

Introduction

In mine water research, stratification is mainly considered in relation to pit lakes. Yet, this phenomenon also occurs in flooded underground ore, salt or coal mines (Geller et al. 2013; Wolkersdorfer 2008). Earliest observations of stratification in flooded underground mines have been described by Stuart and Simpson (1961). Ladwig et al. (1984) first described the topic in detail, for example the use of downhole probes and water sampling, and a recent review article was published by Mugova and Wolkersdorfer (2018). In all mines where stratification occurs, water with better quality is located in the upper part of the mine and due to higher mineralisation, the water closer to the sump is of worse quality (Ladwig et al. 1984; Nuttall and Younger 2004; Wolkersdorfer 2008). Although the same scenario is described, different terms are used in literature. For instance, stratification can be specified as mine water stratification (Rapantova et al. 2013), mine pool stratification (Engineers 1975) or density stratification (Melchers et al. 2015). Fresh water, meteoric water or shaft water (Melchers et al. 2015; Rosner 2011; Rüterkamp 2001; Wolkersdorfer 2008) are terms used for the upper water body, while saline water or sump water are terms used for the lower water body (Henkel and Melchers 2017; Wolkersdorfer 1996). The layer in-between has been described as intermediate layer (Wolkersdorfer 2008), transition layer (Wieber et al. 2016), boundary layer (Kories et al. 2004) or tranquillizing zone (Czolbe et al. 1992).

Methods

One of the most common methods to investigate stratification in flooded shafts is the application of down-hole probes and dippers, hence parameters such as temperature and electrical conductivity are measured. Rapid physico-chemical changes within a small distance indicate a boundary between two different water bodies. Additional, depth related water samples also help to identify a stratified system (Wolkersdorfer 2008). Shaft cameras are another tool used for investigating changes in visibility or the water's colour, indicating stratification (Snyder 2012; Stemke et al. 2018). Usually, layering in a shaft is detected only once on a single measuring campaign, however, in case of multiple campaigns, occurrence of stratification over a longer timespan or break down can be observed (Coldewey et al. 1999;

Wieber et al. 2016). Most research focuses on one single location. The authors of this paper compare worldwide existing depth logging data and create a database to find causal relationships between stratification and set up of mines. Different criteria like the geometry of the shafts and galleries, location of onset stations or distinction between single shaft and multiple shaft mines are considered. An additional measurement method in flooded mines is the application of tracers, for example fluorescent dyes. Tracer tests help to understand the velocities and flow pattern in the mine, which is important to explain the stratified system. Wolkersdorfer (2008) describes several worldwide tracer tests associated with stratification. Rüterkamp (2001) worked with a small-scale testing facility with two shafts and interconnected galleries to generate artificial stratification. Eckart et al. (2010) described the combination of experiments with small-scale testing facilities and numerical modelling. Tests about stratification are being carried out at an analogue mine water model in South Africa (Mugova and Wolkersdorfer 2018). The first numerical modelling about stratified systems in flooded underground mines was conducted in the early 1990´s by Czolbe et al. (1992). Later Eckart et al. (2010) used CFD modelling. Within the project describe here, onsetting stations will be numerically modelled with the program COMSOL Multiphysics (COMSOL 2018), as the onsetting stations seem to be the location for most of the observed stratifications.

Results and Discussion

Stratification in flooded underground mines has been described in more than 40 publications over the past 5 decades (Mugova and Wolkersdorfer 2018). After comparing existing publications, it can be concluded that stratification occurs in different states of the mine. During the mine water rebound, after flooding and during ongoing pumping activities (Johnson and Younger 2002; Melchers et al. 2015; Nuttall and Younger 2004; Rapantova et al. 2013; Wieber et al. 2016; Wolkersdorfer 1996). In general, an intermediate layer divides different water bodies due to chemical changes (e.g. sulphate concentration), physical changes (e.g. temperature) or turbidity, whereby the density difference is the decisive factor (Coldewey et al. 1999; König and Blömer 1999; Ladwig et al. 1984; Nuttall et al. 2002; Nuttall and Younger 2004; Rüterkamp 2001; Wolkersdorfer 1996; Wolkersdorfer 2008). According to Wolkersdorfer (2008) "[…] temperature differences above 10 K ($\Delta\rho$ > 2 kg/m³), total dissolved solid differences of more than 3% ($\Delta\rho$ > 20 kg/m³) or large differences in turbidity ($\Delta\rho$ > 200 kg/m³) can cause stable stratification". Moreover, the geothermal gradient is a driving force. Water is heated in the deeper sections of a shaft, rises along the shaft walls and stops at an anomaly, for instance a connected gallery. From there, the water flows down in the middle of the shaft towards the sump. Czolbe et al. (1992) and Kories et al. (2004) describe this movement as the occurrence of convection cells, though there are probably several cells named "bales". The intermediate layer is located at the boundaries of the convection cells, only minor exchange of heat and particles due to molecular diffusion is assumed in this area (Rüterkamp 2001). Occurrence of stratification in shafts is always in conjunction with inflow or outflow of water. The water may be of different origins (fig. 1). During the mine flooding, water can reach a connected gallery and therefore an anomaly at the shaft wall as described above (Nuttall and Younger 2004). Meteoric or infiltration water can enter the mine directly via the shaft or flow through the overburden (Coldewey et al. 1999). Wieber et al. (2016) use the term "surface water cap". Inflow from adjacent mine voids is another possible scenario how stratification can form, as well as the change of shaft properties such as shaft lining (Mugova and Wolkersdorfer 2018; Rüterkamp 2001). Whether a stratified system develops or not always depends on the mine set-up. A mine with multiple interconnected shafts can act as a thermosiphon, described by Bau and Torrance (1981), the concept first being adopted for flooded underground mines by Wolkersdorfer (1996). The prevention of convection loops allows stratification. If convection loops develop, an existing stratified system breaks down.

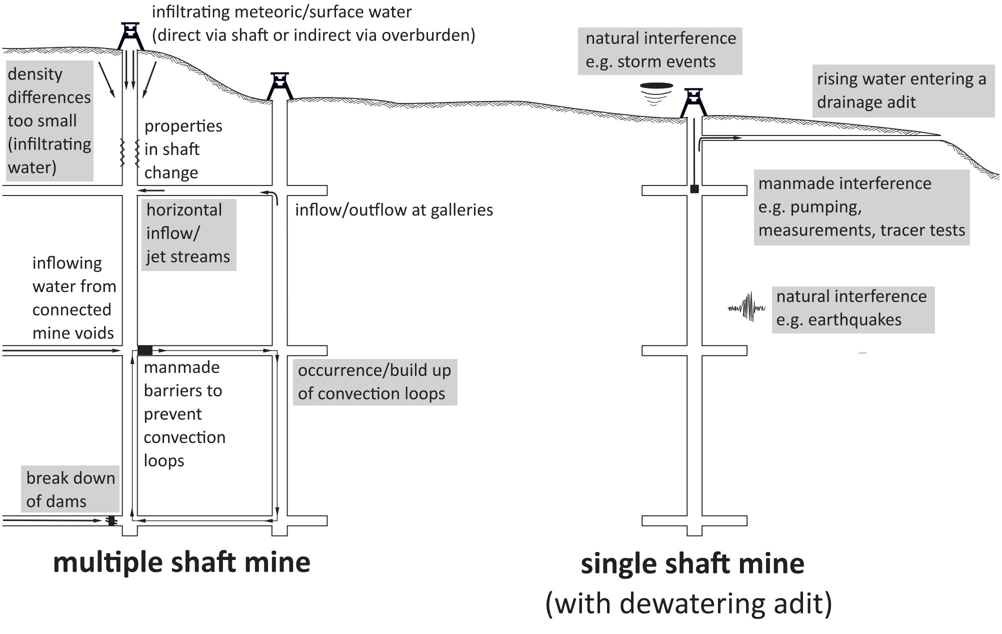

Figure 1 *Occurrence and break down (grey boxes) scenarios in a flooded underground mine (modified after Wolkersdorfer 1996)*

If the infiltrating surface water minimizes the density differences between the layers too much, stratification also breaks down (Wieber et al. 2016). Manmade interference like shaft measurements, pumping or tracer tests as well as natural interference like earthquakes or storm events can result in a stratification break down (Nuttall and Younger 2004; Wolkersdorfer 2008). Wolkersdorfer (2008) mentions horizontal jet stream-like inflow as another reason for a stratification break-down. There are no clear statements in the literature about the time spans, stratified systems remain stable. Kories et al. (2004) repeated measurements nine years after a first measurement, only to find still a stable stratified system. Based on the current knowledge, it can be assumed that under certain conditions the intermediate layer might be stable for decades.

There is currently no known publication regarding the intentional use of stratification in flooded underground mines as an in-situ remediation measure. Wolkersdorfer (1996) describes the potential prevention of convection loops given the optimal flooding levels and relevant manmade barriers; however, the concept was never applied in a mine. For the planning stage of treatment plants, stratification plays an important role. If a stratified system develops or exists, the discharge water quality is better, hence less effort for treatment is necessary. On the other hand, if stratification breaks down, but the treatment facility is only designed for better quality water, the treatment will result in the desired results. Consequently, a tool is necessary to predict occurrence, stability and break down of stratification in flooded underground mines. Causal relationships between stratification and the set-up of the mines will help to define criteria for prediction. If a mine fulfils certain criteria, predictions could be made about the potential for stratification to occur, where the intermediate layer will arise and which flooding level will facilitate the process. Furthermore, manmade barriers like dams could prevent convection loops and favour stratification. More depth logging data, repeated measurements and tracer tests are necessary to extend the database, as well as numerical modelling to support the findings. The predication of stratification might perhaps only work for small mines with just a few shafts and galleries. For a system of interconnected mines with many shafts and galleries there might be too many factors that have to be considered.

Conclusion

Although stratification in flooded underground mines has been well observed over the last decades, most research focuses on local measurements. Development and break down scenarios are known, but a detailed understanding is not yet present. Furthermore, it is not yet possible to predict mine water stratification. A database might help to find causal relationships between the underground structure and stratified systems. With such knowledge, predictions could help to apply stratification as a passive in-situ remediation method, plan suitable mine water treatment facilities and, finally, reduce costs.

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