Water Research 214 (2022) 118033

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Review

Density stratification and double-diffusive convection in mine pools of flooded underground mines – A review

Elke Mugova [a,*], Christian Wolkersdorfer [b]

[a] Technische Hochschule Georg Agricola (THGA), Forschungszentrum Nachbergbau, Herner Straße 45, 44787 Bochum, Germany, ORCID: 0000-0001-6019-9945

[b] South African Research Chair for Acid Mine Drainage Treatment, Tshwane University of Technology (TUT), Private Bag X680, Pretoria 0001, South Africa, ORCID: 0000-0003-2035-1863

ARTICLE INFO

Keywords:
Stratification
Layering
Mine water
Underground mine
Flooding
Pollution prevention

ABSTRACT

Layering of water bodies with different physico-chemical properties is called stratification. This physical effect is known from lakes or oceans but also occurs in flooded underground mines and has been studied in the past. This review gives a summary of their investigation methods, flow dynamics, stratification development and breakdown. Furthermore, the barrier effect of stratification is discussed, meaning that less mineralized water bodies (CF water bodies) on the top are separated from higher mineralized water bodies (WM water bodies) in the lower parts of the mine. This separation causes less mineralized water to discharge from the flooded mine and mine water treatment can be reduced or omitted. Various options to study mine water stratification will be discussed, thereunder tracer tests, camera-aided depth profile measurements and depth dependant mine water sampling. Studies about free convection and natural stratification as well as those about using artificial stratification to encapsulate the lower quality water in the deeper mine parts will be presented. No forecasting tool for the existence or development of stratification in flooded mines was found in the literature. References and a discussion about the long-term stability of the stratification and its potential implementation will be given. The conclusions show that precise predictions of mine water stratification are currently not possible in all detail, but wherever stratification occurs, it is mostly stable over a longer period of time as the density difference between the CF and WM layers prevents their mixing.

1. Introduction

1.1. Motivation and scope

Density stratification in flooded underground mines has been described for more than 60 years, and it is assumed that the separation of the mine water pool into layers with different water qualities might be used as an *in-situ* remediation method. This assumption comes from the observation that the deeper water bodies are usually higher mineralized than the shallower ones and discharging just the shallow water from a flooded underground mine could be a method for faster water quality improvement. Although numerous researchers have described density stratification in underground mines, there is a lack of systematic reviews of the literature on this effect, how it is measured, how it might develop and how to categorize mine water stratification. Due to the importance of density stratification for the discharged mine water quality and the current discussions in the Witwatersrand/South Africa and western German coal mining regions of how to use density stratification for improving mine water quality, this review paper aims in compiling the state of the current knowledge.

This paper's scope includes methods for conducting density stratification investigations, observations in various underground mines and their interpretation. No detailed descriptions of individual measurements of stratification will be given, but pattens and measurements common to all depth dependant physico-chemical measurements in flooded mine shafts are provided. It aims to give a comprehensive overview of the existing literature and the gaps in mine water density stratification research, especially for underground mines, and it suggests a uniform naming convention. This paper introduces the CF/WM-layer (cold fresh/warm mineralized) concept from oceanography and hopes that it will be used in future mine water stratification research. In addition, this review paper will draw first conclusions about the reasons for mine water stratification, where it occurs and how it can disappear when the conditions change. Finally, this paper will provide a means of

* Corresponding author.
E-mail addresses: elke.mugova@thga.de (E. Mugova), christian@wolkersdorfer.info (C. Wolkersdorfer).

https://doi.org/10.1016/j.watres.2021.118033
Received 17 June 2021; Received in revised form 25 November 2021; Accepted 30 December 2021
Available online 2 January 2022
0043-1354/

how density stratification can be used to improve the discharged mine water quality.

1.2. Stratification in natural water bodies

Discharges of polluted and unpolluted mine water are a worldwide problem, and in some cases mine water treatment is necessary before further discharge is possible (Wolkersdorfer, 2008; Younger et al., 2002). In certain cases, the occurrence of density stratification in the flooded mine workings results in a relatively better mine water quality close to the surface, hence alleviating or reducing the need for extensive mine water treatment, thus allowing passive mine water treatment (Wolkersdorfer et al., 2016). Stratification or layering in the context of this review paper is the compartmentation of water bodies with different physical or chemical properties.

Before focusing on stratification in flooded underground mines, a brief explanation of stratification in other natural water bodies shall be given. First detailed stratification studies in lakes were published by Findenegg (1933). Depending on the time of the year, lakes have no or up to three layers, named epilimnion (top layer), metalimnion or thermocline (middle layer) and hypolimnion (bottom layer) (Boehrer and Schultze, 2009). Most publications about lakes and flooded pit lakes cover thermal stratification (Boehrer and Schultze, 2008). A more fitting case, which better resembles the conditions in a flooded underground mine, is salt stratification found in inland lakes, caused predominantly by mining activities (for instance Boehrer et al., 1998, Kirkland et al., 1980). Salt stratification occurs, when the dissolved salt concentration exceeds 3 g/kg in lake water and in some cases concentrations as high as 300 g/kg were reported (for instance Williams, 1996, 1999). Pit lakes differ in their shape and size to natural lakes and much greater depths often cause a permanent stratification in these pit lakes (Boehrer et al., 1998; Denimal et al., 2005; Fisher and Lawrence, 2006; Gammons and Duaime, 2006; Geller et al., 2013; Miller et al., 1996; Stevens and Lawrence, 1998).

Another example for stratification in natural water bodies is stratification in oceans or adjacent seas like the Black Sea, Baltic Sea or Red Sea (Blanc and Anschutz, 1995; Boehrer and Schultze, 2008; Voorhis and Dorson, 1975), sometimes with the occurrence of internal waves (Gill, 1982; Pedlosky, 1990; Pond and Pickard, 1983). Thermohaline staircases, as a result of salt fingering and/or diffusive convection (Merryfield, 2000; Radko, 2013) appear in the ocean but can also be observed in flooded shafts (Bao and Liu, 2019b; Reichart, 2015; Rüterkamp and Meßer, 2000).

Stratification in boreholes, respectively groundwater monitoring wells, is described in detail by Berthold and Börner (2008). In addition to the field and laboratory experiments as well as numerical modelling of groundwater monitoring wells by Berthold (2009), a skimming well with saline groundwater in the lower parts and layered freshwater in the upper in the Indus River Basin in Pakistan is an example for stratification of groundwater (Asghar et al., 2002). Schelkes (1981) also describes the movement of groundwater in connection with stratification.

However, the reasons for stratification in flooded underground mines usually differ from those in boreholes, lakes and oceans. Since solar radiation has almost no influence on the warming of upper water bodies in boreholes, the density differences responsible for stratification are caused mainly by the mineralization of the water (Burghardt et al., 2017), an effect that can also be assumed for flooded underground mines. In both cases, various water bodies separate rather by chemical changes such as sulfate concentration or physical changes such as electrical conductivity or turbidity (Wolkersdorfer, 2008). If stratification occurs in flooded underground mines, water in the upper parts of the mine pool usually has a better quality, in other words is less mineralized than that in deeper parts of the mine (Ladwig et al., 1984; Nuttall and Younger, 2003; Wolkersdorfer, 2008). A strong dependence however, on the type of mine (ore, coal, salt) and its structure should be considered (Kories et al., 2004; Mugova and Wolkersdorfer, 2018; Rüterkamp, 2001), as the mining method, mine layout and depth seem to have a substantial influence on the occurrence of mine water stratification.

1.3. Research history and terminology

First known investigations of stratification in flooded underground mines were carried out in the U.S.A. by Stuart and Simpson (1961), describing "the presence of layering of the acid water." With bottles, they took water samples from three different depths, determining separated water bodies and measuring lower pH-values in greater depths in some of their mine pools. In the following years, Cairney and Frost (1975), Cutright (1979) as well as Sanders & Thomas Inc. (1975) continued with further stratification studies. However, experiments on stratification in flooded underground mines were already carried out in Germany at the beginning of the 1960s. There, temporal stratification of the mine pool could be achieved by injecting fresh water into the Maximilian shaft (Semmler, 1964). Unfortunately, no detailed description of the investigations has been published. This is the case for many flooded underground mines with density stratification. It would be helpful to bring the stratification into the context of the flooding history, but this information is not readily available. In most cases the pumps are simply switched off or removed and no follow-up monitoring is conducted.

To our knowledge, first precise temperature profiles were recorded by Uerpmann (1980), measured over a vertical distance of 300 m at one-metre intervals. He described single convection cells in various water bodies of flooded shafts and took additional measurements every 5 mm in the area between two water bodies. In addition, he conducted one of the first experiments on artificial stratification, using dyes to observe the mixing behaviour between water bodies and proposed estimated time frames required for stratification to develop. He noticed that the flow velocities in the boundary layers were always orders of magnitude lower than those in the convection zones. Uerpmann (1980) describes that "boundary layers with abrupt temperature and concentration changes represent a strong barrier to convective mass transfer." Ladwig et al. (1984) published an extensive report describing a measurement method using downhole probes, as well as how to take water samples in a flooded shaft. They concluded that the upper water body is less contaminated due to the occurrence of stratification and that "the static or near-static water level conditions may be responsible for the observed development of water quality stratification." Furthermore, they mention that "the stratification appears to be related to discharge elevations at the time of inundation, as well as present flow conditions. Relative positions of mined barrier pillars, out fall installations, and natural structural features combine to create an environment more favourable to flushing in the shallower parts of the mine system." Consequently, they concluded that higher mineralized or contaminated water usually collects in deeper mine workings (Ladwig et al., 1984).

One of the world's first detailed studies about mine flooding and stratification with numerous sensors and depth dependant measurements were conducted within the Hope Germany mine flooding project. This mine was actively flooded with saturated brine from a salt waste rock pile, and eventually a freshwater cap (CF layer) formed on top of the brine. Accurate depth profiles and flow measurements were taken by Herbert (1989) for the flooding process at this potash mine. He confirmed research results from previously published articles about stratification and studied turbulent flow conditions in the flooded shaft. In the 1990s and 2000s first papers on modelling stratification in flooded underground mines were published, with successful simulation of convection cells in flooded shafts (Czolbe et al., 1992; König and Blömer, 1999; Luckner and Morgenstern, 2006; Rüterkamp, 2001). In addition, a comparison of stratification in different mines was carried out by Coldewey et al. (1999), with the result that the occurrence of density stratification under certain boundary conditions is a natural effect. First tracer tests in flooded mines to study stratification were conducted by

Wolkersdorfer (1996), who identified effective velocities of up to 25 m/min with an average around 1 m/min (Wolkersdorfer et al., 1997).

In the past few years, research has focused on the following two topics: geothermal applications and using mine water stratification for the prevention of large-scale mixing processes. Stratification might influence mine water geothermal applications and was studied by various authors (Bao and Liu, 2019a, 2019b, Burnside et al., 2016, Wieber et al., 2019), although this is not a new idea and was already investigated earlier by Cutright (1979). Taking advantage of stratification as a hydraulic or geochemical barrier to avoid the discharge of higher mineralized water, thus reducing or alleviating the need for extensive mine water treatment, is described in several research papers (Heidenreich et al., 1991; Kindermann, 1998; Melchers et al., 2019; Mugova and Wolkersdorfer, 2019a, 2019b, Wolkersdorfer et al., 2016).

Most of the research about stratification in flooded underground mines has been carried out in Europe, especially in Germany, Great Britain, France, the Czech Republic, Poland and North America (most notably in the Pennsylvanian Anthracite Mines). Research from Australia focuses mainly on pit lakes, and almost no research relating to mine water stratification seems to have been conducted in Asia or South America. Large differences in the use of the terminology were encountered in the literature. Many publications about stratification in flooded underground mines are written in German, and an exact translation of technical terms into English is not always possible. In the first publication on the subject, the term "layering of acid water" was used (Stuart and Simpson, 1961) but since 1975, the term "stratification" has become widely accepted (Cutright, 1979; Ladwig et al., 1984, Sanders and Thomas Inc. 1975). Some authors further specify the term stratification, such as hydrochemical stratification (Nuttall and Younger, 2003; Rapantova et al., 2013), density stratification (Coldewey et al., 1999) or thermohaline stratification (Bao and Liu, 2019b), meaning more or less the same effect.

In addition, different names for the individual mine water bodies and the area between them are used. Lower and upper, respectively bottom and top layer or zone is commonly used (Ladwig et al., 1984, Sanders and Thomas Inc. 1975). More precise would be terms linked to the chemical composition or perhaps the origin of the water, which is ultimately responsible for the differences in density. Highly mineralized water (Kories et al., 2004), heavy mineralized water or poorer quality water (Nuttall and Younger, 2003) is often used to describe the deeper water body. The term WM (warm mineralized) is used in oceanography, which can also describe the deeper water body in flooded mines (Ruddick and Gargett, 2003). In contrast, a near-surface water body is commonly referred to as fresh (ground)-water (Kories et al., 2004; Wolkersdorfer, 2008), clear water zone (Kindermann, 1998), shallow sourced water, less mineralized water (Nuttall and Younger, 2003), or meteoric water (Henkel and Melchers, 2017). Rosner (2011) uses the term freshwater cap or freshwater lens, and in oceanography the term CF (cool fresh) in contrast to WM (warm mineralised) is commonly used (Ruddick and Gargett, 2003). For a water body with similar characteristics, the expression homogeneous zone is used (Czolbe et al., 1992). A layer between homogeneous water bodies has been called transition between zones (Ladwig et al., 1984), separation zone (Heidenreich et al., 1991), boundary layer (Coldewey et al., 1999; Kories et al., 2004; Melchers et al., 2014), intermediate layer (Wolkersdorfer, 2008) as well as transition layer (Wieber et al., 2016). However, the use of the term boundary layer is incorrect because the term is already defined and describes a flowing fluid on a wall (Schlichting and Gersten, 2006). Studies by the authors of this paper show that the intermediate layer is not necessarily present, or it is only very thin.

2. Investigation methods to identify stratification

2.1. Depth dependant measurements – physico-chemical parameters

Depth dependant measurements with down-hole probes (Fig. 1) or dippers are the main investigation method to identify stratification in flooded shafts. Rapid changes of temperature or electrical conductivity indicate a change of the water's properties and thus stratification (Coldewey et al., 1999; Cutright, 1979; Czolbe et al., 1992; Ladwig et al., 1984; Melchers et al., 2019). If the vertical electrical conductivity profile shows a sudden increase in values, the down-hole probe's sensor has reached a higher mineralized water body, usually separated from the overlying water body by an intermediate layer (Fig. 2). It can be assumed that historic depth dependant measurements of physico-chemical parameters (± pre 1990s) are less precise, which makes it difficult to accurately localize the boundary between the water bodies. This contrasts with more recent measurements, where parameters are recorded at a high spatial resolution. Unpublished measurements by the authors show that parameters can change considerably within centimetres distance. When evaluating the measurement results, it needs to be verified that the probe acclimatised prior to the start of the measurement. In addition, the probe's downward velocity must be slow enough to allow an adjustment to the temperature changes in the shaft water body.

Fig. 1. Downhole probe for water sampling and on-site parameters (Barbara shaft, Urgeiriça, Portugal).

Water samples in flooded mines should be taken after recording a depth profile, as the intermediate layer's depth must be considered to avoid that unrepresentative samples are taken. Usually, various parameters are sampled and analysed, such as *in-situ* parameters and main as well as trace ions (Czolbe et al., 1992; Henkel and Melchers, 2017; Melchers et al., 2014; Nuttall and Younger, 2003; Rüterkamp, 2001; Snyder, 2012; Wieber et al., 2016; Wolkersdorfer, 1996; Zeman et al., 2008). One of the more recent approaches in studying stratified mine water bodies is using geochemical in conjunction with isotopic markers

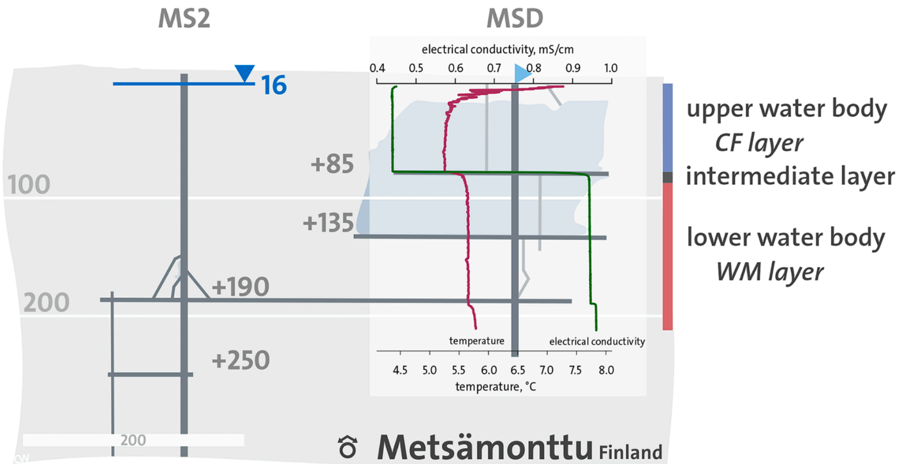

Fig. 2. Depth logging of temperature and electrical conductivity and naming of mine water bodies exemplified by shaft 1 ("MSD") of the Metsämonttu polymetallic mine, Finland.

to investigate the origin of the mine water (Melchers et al., 2019; Wolkersdorfer et al., 2020).

In most flooded mine shafts, only one single stratification measurement has been conducted, which does not allow a discussion of the temporal stratification development in these shafts. Only rarely, repeated measurements with widely varying results in the same shaft exist. In some cases, even when additional measurements were repeated after decades, the intermediate layer has not substantially changed its position. In other cases, yet, its position has changed considerably, or the stratification disappeared (Coldewey et al., 1999; Melchers et al., 2019; Reichart, 2015; Wieber et al., 2016; Wolkersdorfer, 1996; Wolkersdorfer et al., 2002). Another approach would be to perform continuous depth profile measurements at a shaft without changing the probe's position (Wolkersdorfer, 1996) or fibre-optic-distributed-temperature sensing (DTS), as in the German Eduard shaft (pers. Comm. Kurt Schetelig) or in the French Vouters shaft (Reichart, 2015; Reichart et al., 2011).

2.2. Depth dependant measurements – chemistry

Depth dependant mine water sampling for chemical analysis is done since 1961 (Stuart and Simpson, 1961). These authors initially lowered empty bottles into the desired depth and waited until the bottles were filled through a short open capillary pipe. Thereafter the bottles were hauled to the surface and the on-site parameters and chemical analysis conducted with the water in these bottles. Instruments used for chemical sampling so far were messenger-tripped bore hole or depth samplers (Cutright, 1979; Nuttall and Younger, 2003) and samplers with additional messenger weights to trigger a locking mechanism like conventional Bacon bomb samplers (Erickson et al., 1982), Kemmerer (stainless steel) point samplers (Bao, 2018; Snyder, 2012) or Van Dorn plastic point samplers with spring loaded endcaps (Snyder, 2012). Additionally, samplers with electronic opening and closing mechanisms (Coldewey et al., 1999; Erickson et al., 1982; Rüterkamp, 2001), ball-valve operated samplers (Coldewey et al., 1999; Gzyl and Banks, 2007; Snyder, 2012), Ruttner samplers (Chudy et al., 2020; Uerpmann, 1980; Wieber et al., 2016) or bailers, like point-source bailers (Toran, 1987), are used. Furthermore, water samples can be collected by pumping with submersible or peristaltic pumps (Elliot and Younger, 2007; Rapantova et al., 2013; Toran, 1987) or by water sampling below the water level during the course of flooding (Cutright, 1979; Wolkersdorfer, 1996). Passive grab or thief samplers such as the Discrete Interval Sampler™ (Nielsen, 2006), which can take water samples up to a depth of 1200 m, have successfully been used to collect depth dependant water samples in flooded, Spanish coal mines (pers. comm. Daniel González Suárez). Usually, the volume of the water samples ranges between 0.5 and 5 L (Fig. 3). Systems in which the closing mechanism is triggered by jerking movements are not suitable for flooded shafts. The closing mechanism can already be triggered by hitting shaft installations, as for example described by Coldewey et al. (1999). Older samplers with only mechanical locking mechanisms (messenger weights) are suitable to a certain extent, but they are not designed for larger depths (Erickson et al., 1982; Ladwig et al., 1984; Stuart and Simpson, 1961). Herbert and Sander (1989) developed and patented a sampling device for mine shafts that are flooded with brines. This device allows undisturbed sampling of the brine under ambient conditions and the measurement of on-site parameters such as pH, velocity of speed, temperature and conductivity. It was first tested and used during the Hope Germany mine flooding experiment. If only surface water chemistry is of interest, also telescopic samplers have been used to sample mine water in flooded mines.

2.3. Use of shaft cameras and underwater robots

With underwater cameras it is possible to observe the change from murky water to clear water (Fig. 4) and inflow from galleries and particle movement (Snyder, 2012; Stemke et al., 2017). Initially, normal borehole cameras were used (Wieber et al., 2019), however they are not ideal for flooded shafts. Only a few cameras are available that have been specifically developed for flooded underground mines, equipped with powerful lamps and up to 4k image resolution (Stemke et al., 2017). Another new development is the use of mine water robots like the

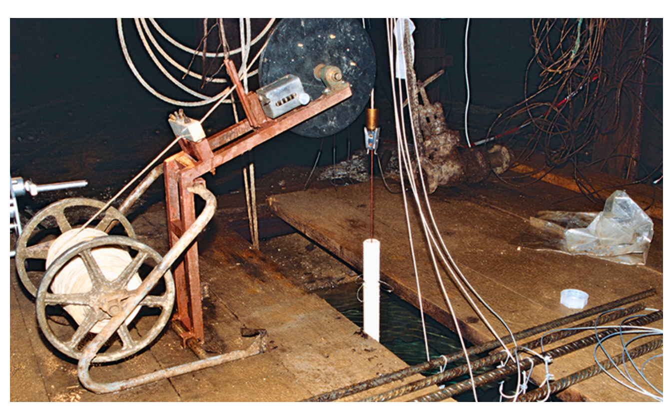

Fig. 3. 500-m-Winch, sample container, messenger weight and lock mechanism with depth counter for stratified water sampling (Georgi Unterbau, Austria, subvertical shaft).

Fig. 4. Stratification in a flooded underground mine taken with a shaft camera. The camera is just slightly below the transition from a murky to clear water (courtesy: Thorsten Gökpinar; image optimized with colour and contrast enhancement, image width ≈ 1 m).

autonomous underwater explorer for flooded mines UX-1c from the UNEXMIN project (Fernandez et al., 2019; Žibret and Žebre, 2018). This robot is equipped with navigation instrumentation such as sonar, scanner and lasers as well as scientific instrumentation like temperature and pressure sensors.

2.4. Flow measurements in flooded mines

Flow measurements in flooded mines can be done in accessible galleries or in shafts. In the galleries, the flow measurement methods applied in surface water measurements can be used (Anklin et al., 2003, U. S. Department of the Interior – Bureau of Reclamation, 2001, Wolkersdorfer, 2008), while flow measurements in the shafts or in the whole flooded mine section need specific techniques. Rüterkamp et al. (2004) discuss selected methods suitable for flooded mines, such as acoustic meters (Kories et al., 2004; Rüterkamp et al., 2004), impeller current meters (Johnson and Younger, 2002), radioactive tracers (Czolbe et al., 1992), drift tracers like microspheres or dyed spores (Wolkersdorfer, 1996) or fluorescent dyes like Na-fluorescein (Wolkersdorfer, 2008). Flow measurements in analogue laboratory models such as laser Doppler anemometry or thermoanemometry are described in Martynenko and Khramtsov (2005). Knowledge about flow dynamics and flow velocities over longer distances can be gained via tracer tests. Furthermore, it is possible to inject different tracers at different depths into the flooded mine voids (Wolkersdorfer, 2008). Tracer tests, where tracers were injected below the intermediate layer have shown that the tracer cannot penetrate from the lower water body to the upper one (Neumann, 2007; Unger, 2002; Wackwitz, 2002). Laboratory investigations are another possibility to investigate stratification. Berthold (2009) as well as Berthold and Börner (2008) conducted detailed investigations for boreholes, which can only partly be transferred to flooded mine shafts. Another study was conducted by DMT GmbH & Co. KG using a small-scale testing facility, consisting of two shafts with three horizontal connections between the shafts. They generated an artificial stratification of freshwater on top of highly mineralised water and simulated the influence of the geothermal gradient by using a heating element. Their aim was to understand mine water stratification, convection flow in a shaft and convection loops in a mine (Coldewey et al., 1999; Rüterkamp, 2001). Based on this earlier experiment, the same research group conducted a larger and more detailed one on a scale of 1:500 for a 1000 m deep mine, allowing also inflow and outflow from and into the shaft. Frequent measurements of temperature and electrical conductivity allowed numerical CFD models and the DMT box model to be applied (Eckart et al., 2012; Eckart et al., 2010). The authors of this article are currently investigating mine water stratification on a 4 × 6 m analogue model, the Agricola Model Mine (AMM). Several shafts and galleries are connected with each other, and a geothermal gradient is simulated by heating elements. *In-situ* parameters of the water can be measured at various outlets at each model section. Main objectives of this experiment are to understand the flooding process of an underground mine, as well as to gain new insights into the occurrence and break down of stratification (Mugova and Wolkersdorfer, 2018).

A laboratory experiment, used as an explanation for convection loops between shafts and galleries by Wolkersdorfer (1996), was conducted by Bau and Torrance (Bau and Torrance, 1981a, 1981b, 1983). In their experiments, using open and closed convection loops heated at various locations, they noticed that "free convection loops provide a means for circulating fluid without the use of pumps" (Bau and Torrance, 1981a). Transferred to flooded mine shafts, the geothermal gradient can be considered the heating element and the free surface of the mine water in the shafts in conjunction with the mine air the cooling element. This explains the development of convection cells in the mine pools. Earlier experiments by Creveling et al. (1975) explain the temperature and velocity fluctuations that are measured when a probe is located for a while at the same location as has been observed by Wolkersdorfer (1996). These fluctuations result from the turbulent flow conditions as they develop in the flooded mine shafts.

2.5. Numerical stratification modelling

Numerical modelling of flooded underground mines tries to understand the hydrodynamics in the mine pool by using numerical codes of various complexity. A simple code, which simulates the flooding process but not the stratification, is for example the GRAM (Groundwater Rebound-in Abandoned Mineworkings) code (Adams and Younger, 1997), whilst more sophisticated models are using CFD (computational fluid dynamics) codes to understand the flow and stratification in the mine (Loredo et al., 2016; Wolkersdorfer, 2008).

Czolbe et al. (1992) developed the finite difference code Kasomo to investigate the flow in a flooded underground mine. They demonstrated the barrier function of the intermediate layer in the shaft. König and Blömer (1999) used the software code SPRING and Rüterkamp et al. (2004) compared differential computational fluid dynamic (CFD) programs for modelling stratification, finally using the code CFX. Rüterkamp et al. (2004) modelled a general approach of a flooded shaft and transferred these findings to a real mine in Germany. Based on the results of previous analogue modelling, Eckart et al. (2012) used CFD modelling, and their box model for data from a small-scale analogue model and applied it to real dimensions of a mine. They concluded, that modelling of the real-world scenario is not possible with the computer capacities that were available at that time. Reichart (2015) used the CFD code Comsol Multiphysics for investigating flow and convection in a mine shaft. He compared data from a 2D model with an existing mine shaft and used the results for a 3D model. Bao and Liu (2019b) worked with OpenFoam but focused on double-diffusive convection associated with stratification. They pointed out that stratification can only be successfully modelled with high resolution (dense grit), confirming conclusions by Rüterkamp et al. (2004), namely that layers will mix over long time, if a shaft has no in- or outflow. Numerical modelling based on mine water tracer tests were conducted by Unger (2002) and Hultsch (2006) using ANSYS/FLOTRAN. They were able to model the breakthrough of the tracer in the Austrian Georgi Unterbau and the German Felsendome Rabenstein mines.

With the advance of computation capacities, more sophisticated models can now be set up. Nonetheless, modelling a fully flooded mine is still a complex task. One example to identify the influence of a small-scale area would be the on-setting area at the shaft, at which intermediate layers are often located. Even if the modelling focuses only on this small area, the geometry is relatively complex, due to the existing pit under the tilting platform for example, which can strongly influence the flow velocity and flow direction. Likewise, in a flooded mine, there are usually no smooth shaft walls, resulting in turbulent flow. Shaft installations and reinforcing components also influence the flow, hence modelling in flooded mines must be viewed critically, as the mine layout and thus the flow regime differs from mine to mine.

3. Synthesis and discussion – processes

3.1. Classification of hydrodynamics in flooded underground mines

To understand stratification in flooded underground mines, knowledge about hydrodynamic principles is relevant. For example, the shaft lining's roughness and the shaft furniture, such as guide rails, together with the mine water's velocity determine whether there is turbulent or laminar flow in the shaft. Water can flow upwards or downwards in the shaft and can noticeably change its flow velocity (Wolkersdorfer, 2008). To develop an understanding of the system, the authors have developed a classification for flooded underground mines (Table 1), which can be used to set up conceptual models of flooded underground mines. The first category includes the source of the inflowing water, for example precipitation water that infiltrates via the overburden into the mine (a), ascending water from deep aquifers (b) or a combination of both. Moreover, the efflorescent salts in the mine workings could be washed out during the initial stage of the mine flooding, causing mine water with an elevated mineralisation collecting in the lower parts of the mine, and once the efflorescent salts are flushed away, the water quality slowly improves, building a layer with a better water quality on top of the higher mineralised mine water (d). Convective flow is another category with temperature or density differences of the water causing free or natural convection (A), whereas free convection is described with the Grashof number Gr (Kays and Crawford, 1993) in Eq. (1):

$$Gr = \frac{L^3 \cdot P^2 \cdot \beta \cdot \Delta T \cdot g}{\mu^2} \tag{1}$$

with

- L characteristic length, m
- p fluid density, kg m^{-3}
- β coefficient of thermal expansion, K^{-1}
- ΔT temperature difference, K
- g gravitational acceleration, m s^{-2}
- μ dynamic viscosity of fluid, Ns m^{-2}

In contrast, forced convection (B), for instance by operating pumps, or a combination of both (C) is possible. In shallow mines, the geothermal gradient has little or no influence (0), but the deeper a mine, the more its influence increases (1). In addition, it is relevant if a mine behaves as a single-shaft mine (SSM) or a multiple-shaft mine (MSM). Mines of the MSM type have a large number of interconnected shafts and working levels, while SSM types usually have one or a small number of shafts with restricted hydraulic connection (Wolkersdorfer, 2006). As the layout of a mine seems to have a decisive influence on flow velocities, which in turn have an influence on stratification, this classification group is relevant. At a flow rate above 1 m/min, mainly found in multiple-shaft mines (m), high effective velocities occur. Single-shaft mines (s) usually develop small flow rates below 1 m/min. These categories are helpful in classifying and consequently comparing flooded underground mines. Using the Metsämonttu mine in Finland, where stratification has been proven, the category for this mine would be aA1mxδ (water inflow from above, free convection, influence of geothermal gradient and multiple-shaft mine, diffusive convection).

Table 1
Proposed classification scheme for flooded underground mines.

Category	code	description
Type of inflow	a	water inflow from above (e.g. infiltration water from surface)
	b	water from below (e.g. deep aquifer)
	c	both (a and b combined)
	d	flushing
Dynamics	A	free convection
	B	forced convection
	C	free and forced convection
Temperature	0	geothermal gradient not relevant
	1	geothermal gradient relevant
Mine Type	s	single shaft mine
	m	multiple shaft mine
	x	mixed type
Double-Diffusion	δ	diffusive convection (DC): cool/fresh (CF) above warm/mineralized (WM)
	μ	mineralisation fingering (MF): warm/mineralized (WM) above cool/fresh (CF)
	–	not known

As much as the chemical quality of the ground water in the aquifers around a mine contributes to the pre-flooding water quality in the mines, there seems to be no direct relationship between the ground water quality and the stratified mine water quality during or post-flooding. Main reasons are, as described in Younger (1997), that the mine water quality is mainly controlled by 'vestigal' and 'juvenil' acidities and by efflorescent salts that are dissolved by the ground water flooding the mines. Only after the first flush, the discharged mine water quality from the CF-layer slowly reaches background ground water qualities.

3.2. Occurrence and stability of stratification

Based on the categories above, it can be concluded that the conditions under which stratification occurs can vary greatly from mine to mine and that in most investigated cases, stratification can be observed (Wolkersdorfer et al., 2016). Stratification occurs at different states of mine water rebound: during the flooding process, after completed flooding and even during ongoing pumping activities (Johnson and Younger, 2002; Melchers et al., 2015; Nuttall and Younger, 2003; Rapantova et al., 2013; Wieber et al., 2016; Wolkersdorfer, 1996).

Stratification can appear in the steady state conditions of an already flooded mine shaft as well as in an instationary system while the mine is still in its flooding process (Coldewey et al., 1999). Detailed studies about these two conditions in flooded underground mines are still missing but experiments in the authors' analogue mine model (AMM) are currently under way. In most investigated mines, the geothermal gradient causes the mine water in the deeper sections of the mine to get warmer than in shallower sections which, when the temperature difference is high enough, results in free convection. A counterforce to the thermal convection can be the mineralisation of the mine water, which might even result in density inversions, such preventing free convection. Numerical and analogue models showed that the water heats from the shaft wall and rises upwards along the walls (Martynenko and Khramtsov, 2005). Once the ascending water reaches an anomaly, for example a gallery, or has already cooled down to such an extent that an ascent is no longer possible, it flows back through the middle of the shaft until it reaches the shaft's sump or another water body (Heidenreich et al., 1991). This results in density driven free convection cells, which have been shown in experiments using radioactive tracers (Czolbe et al., 1992). Modelling results suggest that it might not necessarily be one large convection cell but rather many small cells called "bales" (Kories et al., 2004), which is also discussed in the theoretical explanations by Aigner et al. (2015). König and Blömer (1999) assume that shafts with smaller diameters develop more convection cells and higher velocities. Eventually, convection cells and therefore homogeneous water bodies develop by the interruption of the liquid movement in the shaft. This interruption can be provoked by the geological conditions such as crevasses, inflows or different thermal rock conductivity but also by adjacent mine workings (Coldewey et al., 1999; Czolbe et al., 1992).

So far, no investigation observed that density stratification caused geological features to occur, such as fractures or karst features. In no case a direct relationship between the geological setting and the stratification could be identified – except that the geological setting is responsible for the mine layout, which in turn influences the stratification to a degree not known yet. Based on all measurements and publications reviewed, the mine layout seems to be the key controlling factor for the stratification, while inflows of ground water are not that relevant. As much as the mineralogical composition of the host rock and the raw material will control the final water quality, the stratification itself has no relation with the geological structures. This is an indication that the geological setting of the mine seems to be irrelevant for the stratification *per se*.

Stratification occurs at the boundary of convection cells, otherwise homogeneous water bodies, and can be considered stable if 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) occur (Kranawettreiser, 1989). Furthermore, Aigner et al. (2015) distinguishes between static stratification, which is caused by thermal or saline pressure differences and dynamic stratification, which is caused by turbidity-laden flow. At the intermediate layer between two water bodies, mainly molecular diffusion and minor exchange of heat and particles appears (Czolbe et al., 1992; Rüterkamp, 2001), as has been shown by the laboratory experiments of Uerpmann (1980). It has been shown by *in-situ* measurements of various research groups that homogeneous water bodies can reach a thickness of several meters to hundreds of meters, whereas the intermediate layer is comparably thin. In literature, the thickness of the intermediate layer is described as being between a few decimeters (0.6 m and 1.3 m) by Coldewey et al. (1999) or Kories et al. (2004) and some meters (2 to 5 m) by Wieber et al. (2016) or Wolkersdorfer (1996). Recent measurements by the authors indicate that the intermediate layer can even be thinner and that delay of the probe or smudging during the measurement could misrepresent the results. Wolkersdorfer (1996) mentions that the thickness could increase over time towards the sump. In contrast, Wieber et al. (2016) and Rüterkamp et al. (2004) describe a decrease in thickness due to inflowing surface water. As per Rüterkamp et al. (2004), the thickness of the transition zone is influenced by the amount of inflowing and outflowing water, and the location or depth of connected galleries. Depending on the flow velocity, there is no exchange between the water body above and the water body below, once the intermediate layer reaches a certain thickness (Aigner et al., 2015). This velocities difference dependant thickness of the intermediate's layer can be represented by Eq. (2):

$$\Delta x > \frac{(\Delta v)^2}{24 \cdot g \cdot \frac{\Delta p}{p}} \tag{2}$$

with

g gravitational acceleration, m s^{-2}
x depth, m
p fluid density, g m^{-3}
v velocity in each of the fluid's layers, m s^{-1}

In some cases, a staircase profile of the layers was observed, which can be attributed to double-diffusive convection (Fig. 5) or internal waves (Eckart et al., 2012; Radko, 2013; Wolkersdorfer, 2008), which appears because of the diffusivity differences in heat and salinity. In mine shafts, it has been observed that CF/WM (cold fresh/warm mineralised) scenarios are more common than WM/CF double-diffusion scenarios and that the first are more stable than the latter. Aigner et al. (2015) explain that with increasing velocity differences between the layers, waves appear at the boundary between them. Although not specifically pertaining to the intermediate layer, Bao and Liu (2019b) describe staircase profiles in flooded shafts, while Reichart (2015) discusses the Bénard/Lapwood convection cells in connection with staircase profiles.

With the current knowledge about mine water stratification, it is not conclusively possible to predict the long-term stability of stratification, as it can change over time (Table 2). In some mines under CF/WM conditions, a long-term stability seems to exist, whilst WM/CF conditions are less stable in the long term.

Stable stratification exists when the following conditions apply (3) (Gebhart et al., 1988):

$$\frac{d}{dx} p_\infty(T_\infty, p_\infty) \leq 0 \tag{3}$$

with

x depth, m
p fluid density, g m^{-3}
T temperature, K
p depth dependant pressure, Pa

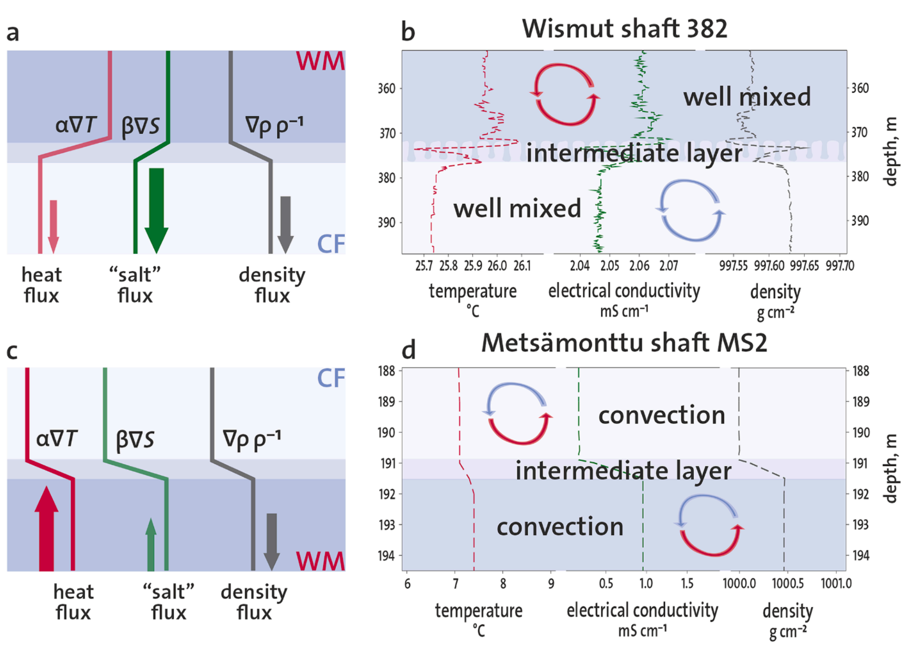

Fig. 5. Graphical representation of stratification in a double-diffusion scenario (modifed and extended from Kelley 2001, Ruddick and Gargett 2003) with real stratification measurements in flooded mine shafts. a, b: salt finger mode with warm/mineralised (WM) above cool/fresh (CF), Wismut, Germany: 2011-11-12 (credits Wismut GmbH); c, d: diffusive convection with cool/fresh (CF) above warm/mineralised (WM), Metsämonttu, Finland: 2017-09-23, density calculated with the UNESCO equation (Fofonoff and Millard, 1983).

Table 2
Overview of recurring stratification measurements in flooded mine shafts.

Shaft name, country	year of measurement	findings, reference
Hermann 1, Germany	1994, 1998, 2003, 2016	Position of the intermediate layer has not changed over a 22-year period (Melchers et al., 2019).
Hermann 2, Germany	1990, 1994, 1998	Position of the intermediate layer has not changed over a 8-year period (Coldewey et al., 1999).
Metsämonttu MSD shaft, Finland	2016, 2017, 2018	Position of the intermediate layers at two different depths has not changed over a 3-year period (results Ch. Wolkersdorfer).
Jindřich II, Czech Republic	2004 – 2007	Position of the intermediate layers at two different depths has not changed over a 4-year period (pers. comm. J. Zeman).
Aleška shaft, Czech Republic	2 × 2005	Position of the intermediate layer has not changed over a 6 month period (pers. comm. J. Zeman).
Sicilia shaft, Germany	1998, 2001, 2003	The measurements were taken during the course of the flooding. Stable intermediate layer for 2 years since 2001 (Coldewey et al., 1999; Kories et al., 2004).
Flour shaft, Germany	1992 – 2000 and 2003	Several intermediate layers stable at different depths over a 10-year period. Due to structural changes in the mine workings, stratification in the upper area collapsed, but the intermediate layer in the lower area of the shaft remained stable (Rüterkamp and Meßer 2000, results Ch. Wolkersdorfer).
Ü539 raise, Germany	1992 – 2000, and 2002, 2003	Position of the intermediate layer has not changed over a 5-year period. Due to structural changes the intermediate layer collapsed between 1997 and 1998 (Rüterkamp and Meßer 2000, results Ch. Wolkersdorfer).
Glückaufsegen 3, Germany	1989, 1997	In 1997 the intermediate layer was 2 – 20 m higher compared to 1989 (Coldewey et al., 1999).
Pozo El Entrego, Spain	2008, 2019	The comparison is difficult, because in 2008 the sampling points were far apart from each other. One of two intermediate layers probably still exists.
Vouters 2, France	2009, 2010, 2011, 2012, 2013	The results are very different. A rapid change of parameters in the upper part of the depth profile was visible in 2010 only and not thereafter. One deeper intermediate layer shifted downwards by 3 – 80 m, other intermediate layers have been at the same position over the years. Towards the sump, a staircase profile can be recognised, however its position varies from year to year (Reichart 2015).
Simon 5, France	2009, 2010, 2011	In 2009, a clear intermediate layer could be identified in both the temperature as well as the electrical conductivity profile. In the following years this jump in the profile was no longer present (Reichart 2015).
Reiche Zeche Shaft, Germany	1990, 2001	A comparison is difficult because the 1990 measurements are not very detailed. One jump can be identified approximately at the same depth, although in 1990 the temperature increased and in 2007 the temperature decreased (Neumann 2007; Wolkersdorfer 2008).
Grube Georg Shaft 2, Germany	2008, 2009	Within half a year, the intermediate layer changed its position by about 50 m upwards. In the following weeks, the position remained constant, however the parameters such as water temperature changed (Wieber et al., 2016).
Nikolaus-Bader-Shaft, Austria	2004 – Ongoing	The shaft is only 10 m deep. Three to four intermediate layers are developing and breaking down but stay approximately consistent in depth.
Georgi Unterbau, Austria	2001, 2002	Stable stratification for at least 2 years which broke down after a salt tracer was injected. Redeveloped after a while. Numerical modelling showed that the stratification results from a colder inflow (Unger 2002).

Another approach to evaluate the stability of stratification in flooded shafts is the Richardson number (Ri) or Richard's criterion, which determines if two layers in a fluid will mix, whereby stable conditions usually exist with Ri > 0.25 (Gebhart et al., 1988; Rieutord, 2015; Wolkersdorfer, 2008), which is called Miles' theorem.

Many factors are known to cause the buildup or breakdown of mine water stratification (Fig. 6). Meteoric or infiltration water can seep through the overburden or can flow directly into the mine via shafts. Near-surface inflows can result in a layer of water with lower density, sometimes called "fresh or surface water cap" (Rosner, 2011; Wieber et al., 2016), which equals a CF over WM situation. A good example for the formation of a CF layer are the Hermann shafts in Germany. Since its flooding began, there have been near-surface freshwater water influxes, and the CF layer became thicker over time (Coldewey et al., 1999). In the flooded Ermelo Colliery, South Africa, Johnstone et al. (2013) describe, that the higher mineralized mine water is "trapped" within the mine voids by a CF layer.

Not only surface water, but also rising mine water during the flooding process can result in stratification (Nuttall and Younger, 2003). This is probably closely related to an anomaly in the shaft wall during the flooding. Though this assumption might be possible, however, it is more likely that galleries or roadways connected to the shaft are of greater importance. The occurrence of an intermediate layer at on-setting stations was often observed. Flow into the shaft, for example from adjacent mine workings seems to be the main cause for the development of stratification (Coldewey et al., 1999; Eckart et al., 2012; Rüterkamp et al., 2004). On the other hand, Wolkersdorfer (1996) had already described convection loops or thermosiphons, derived from experiments carried out by Bau and Torrance (1981a, 1981b, 1983). These convection loops between interconnected shafts and galleries could cause higher flow velocities and could be responsible for a jet stream like inflow (Aigner et al., 2015). Examples such as the Hermann shafts and the Sicilia shaft in Germany, laboratory experiments (Coldewey et al., 1999; Melchers et al., 2019) and obervations during camera drives support this assumption.

4. Synthesis and discussion – scientific relevance

4.1. Processes that cause build up or breakdown of mine water stratification

Barriers are believed to prevent convection loops, since these can break down the stratification (Wolkersdorfer, 1996). Ultimately, it depends on the spatial position of the convection loops whether they result in stabilizing or destructing the stratification. The same applies to infiltrating meteoric or groundwater. Though it favours the development of a CF layer, it can also cause lower density differences between water bodies, which means that the necessary density difference for a stable stratification cannot be maintained (Wieber et al., 2016). Although being more likely for single-mine shafts with no direct in- or outflow, rain events could cause a rapid, sometimes temporary collapse of the stratification. External forces affecting the existing stratification can also result in its collapse. These include human activities like pumping, shaft measurements, injections during tracer tests (Elliot and Younger, 2014; Frolik, 2009; Wolkersdorfer, 2008), or a modification of the flow path, for example by installing a drainage adit. In addition, natural events like storm events or earthquakes can affect the mine water pool and cause a stratification breakdown (Wolkersdorfer, 2008).

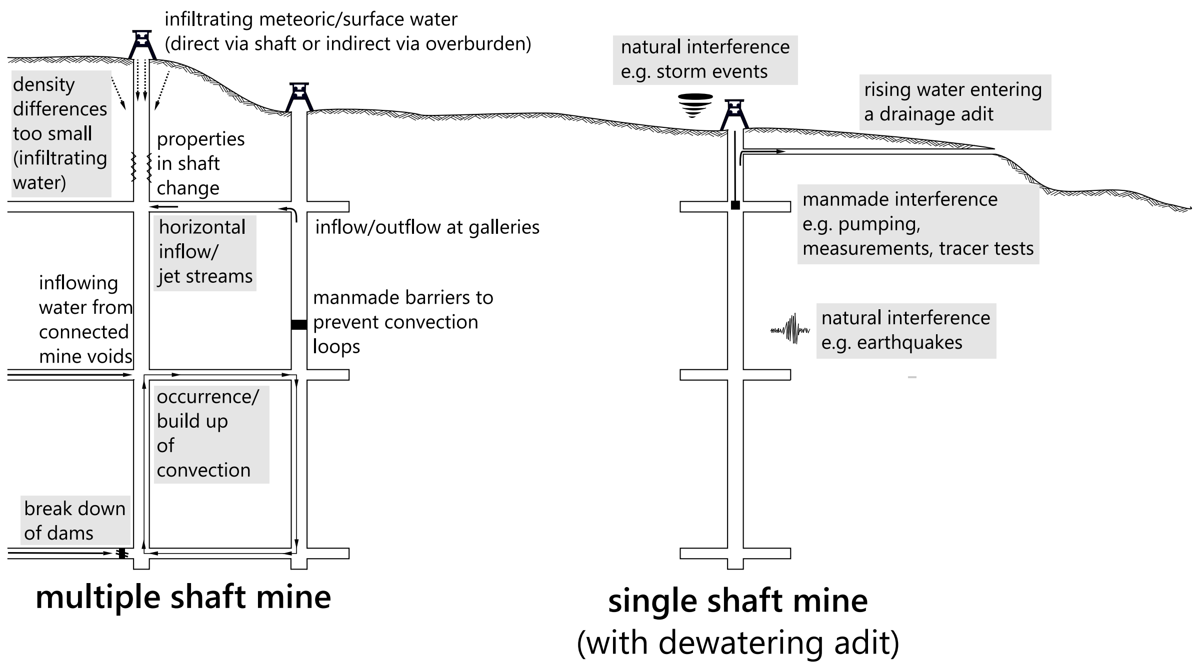

Fig. 6. Occurrence (no frame) and breakdown (grey boxes) scenarios of stratification in a flooded underground mine, responsible for occurrence or breakdown (framed), modified after Wolkersdorfer (1996).

Breaking of dams can change the overall flow regime but also result in the formation of new convection loops (Nuttall and Younger, 2003; Wolkersdorfer, 2008).

The same results can occur as soon as the rising mine water table drains off via a gallery or adit as observed during the flooding of the German Niederschlema/Alberoda uranium mine (Wolkersdorfer, 1996). Jet streams can also influence the stratification in a negative way, especially when they are vertical. Even small differences in density between the jet and the surrounding water are sufficient for effective mixing (Stefan and Gu, 1992) and can thus break down or prevent stratification within a flooded mine. Bao and Liu (2019b) used numerical modelling of a mine shaft to show that without further inflows to the shaft, the number of layers reduces over time, which they call a “merging event”. This might explain the occurrence and breakdown of stratification in a short period of time. Moreover, Reichart (2015) assumes from the results of his numerical modelling that a small reversal of the temperature gradient is enough to disrupt the convection cells and thus the stratification.

4.2. Stratification as an in-situ-mitigation of mine water – natural and artificial stratification

In the literature, several considerations have been discussed and proposed to take advantage of the barrier effect caused by mine water stratification, thereunder for radioactive waste disposal in flooded salt mines (Heidenreich et al., 1991; Kindermann, 1998; Uerpmann, 1980). In all cases, the aim is to separate the mostly higher mineralised WM water body in a mine from the usually less mineralised CF water body. This separation can mitigate or alleviate the need for extensive mine water treatment (Wolkersdorfer et al., 2016). So far, it is known that stratification and thus a barrier effect occurs under certain conditions but cannot be predicted reliably – which does neither mean it will not occur or that stratification can’t be used to help avoiding environmental impacts. Therefore, approaches to artificially create stratification in flooded underground mines exist. An example of artificial stratification in pit lakes is described by Fisher and Lawrence (2006), who generated a CF layer above a WM layer in a 350 m deep pit lake. In the 1960s/1970s artificially creating stratification was tested by means of an infiltration test well at the Maximilian shaft (Germany). There, the injected freshwater pushed the higher mineralized mine water to greater depths, a CF layer formed and was stable at least between 1960 and 1972, demonstrating that artificial stratification might be a possibility (Rüterkamp et al., 2004; Semmler, 1964). The idea of an artificial CF layer was reconsidered and briefly described by Kories et al. (2004), Luckner and Morgenstern (2006) as well as Eckart et al. (2010), but without showing any particular proposals for implementation. None of the authors developed a method of how artificial stratification could be carried out in practice, where the water supply could come from or if it must be supplied continuously (Mugova and Wolkersdorfer, 2019a). Numerical modelling by Rüterkamp et al. (2004), Bao and Liu (2019a) and Bao and Liu (2019b) indicated that the CF and WM layers could combine, should freshwater not be continuously supplied.

Another possibility to create artificial stratification is to modify the mine water flow paths through horizontal or vertical barriers (Wolkersdorfer, 1996). This 1996 publication is based on a 3-year-study of stratification in a flooded underground mine supported by the results of a tracer test and focuses specifically on man-made barriers (dams or bulkheads) to prevent convection loops. However, these barriers should be installed during the closure phase. So far, an *in-situ* application has not yet been constructed, but it is obvious from the authors’ investigations and the analogue mine model results that any interruption of convection loops (e.g. closing dams, constructing barriers) helps to support artificial stratification.

5. Conclusions and outlook

Although research about stratification in flooded underground mines has been conducted for many decades, the number of publications on this topic is limited. While the existing publications focus on the description of the subject, many details, especially regarding hydrodynamics, are still unsolved. Several possibilities of how stratification can occur are described, but the detailed mechanisms of stratification development in flooded underground mines is not yet solved. Based on the published depth profiles, the transition between two water bodies occurs mainly at the on-setting stations, where shafts and adits connect with each other, indicating a relationship between stratification and these connections. However, detailed studies of the flow pattern in this area have not yet been conducted. In addition, the current knowledge does not allow predictions at which depth, or at which on-setting stations the intermediate layer develops. Stratification also occurs between two individual connections to the shaft, without a perceivable connection to adjacent mine workings. This stratification may have a different evolution history.

Further research is needed to show whether different types of stratification, based either upon formation or location for example, can be classified. For this matter, more depth dependant physico-chemical and temporal measurements should be conducted in flooded underground mines and compared with existing measurements. These measurements should be backed up with laboratory investigations and numerical models using e.g. CFD (computational fluid dynamics). Finally, not much is known about the temporal development of mine water stratification. Consequently, it is currently not possible to predict precisely whether stratification will develop in a flooded underground mine or not, though nearly all investigated mines are stratified to a certain degree. To develop forecasting tools and to be able to use the barrier effects of stratification, a more detailed understanding of the hydrodynamics in flooded mines is necessary. As has been shown, tracer tests have proven to be a suitable test method, while investigations using shaft cameras provide valuable new insights in the individual flow scenarios.

The details of the various vertical pyhsico-chemical profiles differ from each other but allow conclusions about flow patterns. Furthermore, stratification seems to be related to the mine set-up and comparisons of different mines could be important for further predictions. To be able to use stratification for isolating higher mineralized mine water from discharge to receiving water courses, it is important to ensure its long-term stability. Causes for stratification breakdown must be excluded as far as possible, to obtain a permanent near surface CF layer above a WM layer. Once the positive effects of stratification have developed, be they intentionally or unintentionally, caution must be taken to keep the stratification in place. Possible scenarios that might interfere with a stable stratification might be geothermal pumps in the mine, pumping water from deeper parts of a flooded mine or the construction of dewatering adits.

Already during mine planning, the closure and potential flooding scenarios should be considered in the view of the cradle-to-grave concept. By implementing an appropriate design, the development of a stable CF/WM stratification can be favoured in a flooded underground mine and, thus, can be used as a tool for *in-situ* mitigation of flooded underground mines and to minimize environmental pollution by mining influenced water.

CRediT authorship contribution statement

Elke Mugova: Investigation, Writing – original draft. **Christian Wolkersdorfer:** Funding acquisition, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank our colleagues Thorsten Gökpinar, Michael Paul, Guillaume Reichart, Georg Wieber and Josef Zeman for providing us with information and sharing their data. Wismut GmbH is thanked for allowing us to use data from their shaft measurements. Two anonymous reviewers are thanked for helping to improve this paper with their comments and questions.

Funding

We thank our research institutions for providing support in conducting this research. Funding has been provided by the German foundation “Forum Bergbau und Wasser” and by the South African SARChI Chair program (NRF Grant UID 86948).

References

Adams, R., Younger, P.L., 1997. Simulation of Groundwater Rebound in Abandoned Mines Using a Physically based Modelling Approach. In: Veselič, M. (Ed.), Proceedings, 6th International Mine Water Association Congress, 2. IMWA, Bled, Slovenia, pp. 353–362.

Aigner, D., Carstensen, D., Glazik, G., Kraatz, W., Kranawettreiser, J., Martin, H., Wagner, H, Aigner, D., Carstensen, D., 2015. Dichteströmungen [Density flow] Aigner, D., Carstensen, D. (Eds.), In: Technische Hydromechanik [Technical hydromechanics], 2. Beuth, Berlin, pp. 221–251.

Anklin, M., Apple, C., Arant, J.B., Baan, T.J., Boyes, W.H., Boyes Jr., W.H., Crabtree, G. M., Dinapoli, L.D., Drahm, W., Eren, H., Foundos, A.P., Gibson, I.H., Hashemian, H. M., Houghen, J., Howe, W.H., Kayser, D.S., Kopp, J.G., Kozák, J., Lipták, B.G., Lomas, D.J., Mair, D.C., Pawlowski, A.V., Plach, K.O., Ptácnák, M., Rudbäch, S., Sanders, G.G., Siev, R., Stoddard, J.B., Szonntagh, E.L., Yoder, J., Yoder, J., 2003. Flow Measurement. In: Lipták, B.G. (Ed.), Instrument Engineers' Handbook – Process Measurement and Analysis. CRC, Boca Raton, pp. 151–400.

Asghar, M.N., Prathapar, S.A., Shafique, M., 2002. Extracting relatively-fresh groundwater from aquifers underlain by salty groundwater. Agric. Water Manag. 52 (2), 119–137. https://doi.org/10.1016/S0378-3774(01)00130-5.

Bao, T., 2018. Understanding Large-Scale Natural Mine Water-Geologic Formation Systems For Geothermal Applications. PhD thesis. Michigan Technological University, Michigan.

Bao, T., Liu, Z., 2019a. Geothermal energy from flooded mines: Modeling of transient energy recovery with thermohaline stratification. Energy Convers. Manag. 199, 111956 https://doi.org/10.1016/j.enconman.2019.111956.

Bao, T., Liu, Z., 2019b. Thermohaline stratification modeling in mine water via double-diffusive convection for geothermal energy recovery from flooded mines. Appl. Energy 237, 566–580. https://doi.org/10.1016/j.apenergy.2019.01.049.

Bau, H.H., Torrance, K.E., 1981a. On the stability and flow reversal of an asymmetrically heated open convection loop. J. Fluid Mech. 109, 417–433. https://doi.org/10.1017/S0022112081001146.

Bau, H.H., Torrance, K.E., 1981b. Transient and Steady behavior of an open, symmetrically-heated, free convection loop. Int. J. Heat Mass Transf. 24 (4), 597–609. https://doi.org/10.1016/0017-9310(81)90004-1.

Bau, H.H., Torrance, K.E., 1983. On the effects of viscous dissipation and pressure work in free convection loops. Int. J. Heat Mass Transf. 26 (5), 727–734. https://doi.org/10.1016/0017-9310(83)90023-6.

Berthold, S., 2009. Geophysikalischer Nachweis freier Konvektion in Grundwassermessstellen und Bohrungen [Geophysical determination of free convection in groundwater monitoring wells and boreholes]. Proc. Dresdner Grundwasserforschungszentrums e.V. 2009 39, 1–230.

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

Blanc, G., Anschutz, P., 1995. New stratification in the hydrothermal brine system of the Atlantis II deep, Red Sea. Geology 23 (6), 543–546 https://doi.org/10/bqwbbj.

Boehrer, B., Heidenreich, H., Schimmele, M., Schultze, M., 1998. Numerical prognosis for salinity profiles of future lakes in the opencast mine Merseburg-Ost. Int. J. Salt Lake Res. 7 (3), 235–260. https://doi.org/10.1007/BF02441877.

Boehrer, B., Schultze, M., 2008. Stratification of lakes. Rev. Geophys. 46 (2) https://doi.org/10.1029/2006rg000210.

Boehrer, B., Schultze, M., 2009. Density Stratification and Stability. In: Likens, E. (Ed.), Encyclopedia of Inland Waters. Elsevier, Oxford, pp. 583–593.

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 Bergmänische Wasserwirtschaft [Glossary mine water management]. Fachsektion Hydrogeologie in der DGGV, Neustadt/Wstr.

Burnside, N.M., Banks, D., Boyce, A.J., Athresh, A.P., 2016. Hydrochemistry and stable isotopes as tools for understanding the sustainability of minewater geothermal energy production from a 'standing column' heat pump system; Markham Colliery, Bolsover, Derbyshire, UK. Int. J. Coal Geol. 165, 223–230. https://doi.org/10.1016/j.coal.2016.08.021.

Cairney, T., Frost, R.C., 1975. A Case study of mine water-quality deterioration, Mainsforth Colliery, County Durham. J. Hydrol. 25 (3–4), 275–293. https://doi.org/10.1016/0022-1694(75)90026-8.

Chudy, K., Worsa-Kozak, M., Wójcik, A., 2020. Groundwater Chemistry and Stratification in the Flooded Hard-Coal Mine Shaft “Nowy I” (Nowa Ruda Region, SW Poland). Water 12 (11), 3257. https://doi.org/10.3390/w12113257.

Coldewey, W.G., Hewig, R., Richter, R., Rüterkamp, P., Wedewart, M., 1999. Mittelfristige Entwicklung des Chemismus und der Dichteschichtungen von Grubenwässern in Bergwerken und ihre Auswirkungen auf nutzbares Grund- und Oberflächenwasser [Medium-term development of the chemism and density stratification of mine water and their impact on usable groundwater and surface water]. Deutsche Montan Technologie GmbH, Essen, p. 83.

Creveling, H.F., de Paz, J.F., Baladi, J.Y., Schoenhals, R.J., 1975. Stability characteristics of a single-phase free convection loop. J. Fluid Mech. 67 (1), 65–84. https://doi.org/10.1017/S0022112075000171.
Cutright, B.L., 1979. Water use possibilities in abandoned iron mines. Misc. Pap. Geol. Nat. Hist. Surv., 79-3, 13.
Czolbe, P., Kretzschmar, H.-J., Klafki, M., Heidenreich, H., 1992. Strömungszellen im gefluteten Salzschacht [Flow cells in the flooded shaft of a salt mine]. N. Bergbautech. 22 (6), 213–218.
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.
Eckart, M., Kories, H., Rüterkamp, P., 2012. Abschlussbericht: Anwendungsorientierte Prognoseverfahren zur Einstellung und Erhaltung von Dichteschichtungen in gefluteten Grubenräumen Final report: Application-oriented prediction methods for the built up and protection of denisty stratification in flooded mine voids, DMT GmbH & Co. KG, Essen, p. 230.
Eckart, M., Rüterkamp, P., Klinger, C., Kories, H., Gzyl, G., 2010. Qualitätsentwicklung der Grubenwässer bei der Flutung von Steinkohlen- und Erzbergwerken [Quality development of mine water during the flooding of hard coal and ore mines]. In: Merkel, B., Schipek, M- (Eds.), Grubenwässer – Herausforderungen und Lösungen: Proceedingband zu dem Fachkolloquium im Rahmen des 61. Berg- und Hüttenmännischen Tages der TU Bergakademie Freiberg am 10. und 11. Juni 2010. TU Bergakademie Freiberg, Freiberg, pp. 123–132.
Elliot, T., Younger, P.L., 2007. Hydrochemical and isotopic tracing of mixing dynamics and water quality evolution under pumping conditions in the mine shaft of the abandoned Frances Colliery, Scotland. Appl. Geochem. 22 (12), 2834–2860. https://doi.org/10.1016/j.apgeochem.2007.07.007.
Elliot, T., Younger, P.L., 2014. Detection of mixing dynamics during pumping of a flooded coal mine. Ground Water 52 (2), 251–263. https://doi.org/10.1111/gwat.12057.
Erickson, P.M., Kleinmann, R.L.P., Posluszny, E.T., Leonard-Mayer, P.J., 1982. Hydrogeochemistry of a large mine pool. In: Kesserû, Z. (Ed.), Proceedings 1st International Mine Water Congress, A. IMWA, pp. 27–42.
Fernandez, R.A.S., Grande, D., Martins, A., Bascetta, L., Dominguez, S., Rossi, C., 2019. Modeling and control of underwater mine explorer robot UX-1. IEEE Access 7, 39432–39447. https://doi.org/10.1109/ACCESS.2019.2907193.
Findenegg, I., 1933. Alpenseen ohne Vollzirkulation [Alpine lakes without complete circulation]. Rev. Gesamten Hydrobiol. 28 (3–4), 295–311. https://doi.org/10.1002/iroh.19330280309.
Fisher, T.S.R., Lawrence, G.A., 2006. Treatment of Acid Rock Drainage in a meromictic mine pit lake. J. Environ. Eng. 132, 515–526. https://doi.org/10.1061/(ASCE)0733-9372(2006)132:4(515).
Fofonoff, N.P., Millard, R.C., 1983. Algorithms for computation of fundamental properties of seawater. UNESCO Tech. Pap. Mar. Sci. 44, 53.
Frolik, A., 2009. Stratyfikacja hydrogeochemiczna wód w zatopionych podziemnych wyrobiskach górniczych [Hydrogeochemical stratification of waters in flooded underground mine workings]. Przegl. Gorn. 65 (7–8), 84–90.
Gammons, C.H., Duaime, T.E., 2006. Long Term Changes in the Limnology and Geochemistry of the Berkeley Pit Lake, Butte, Montana. Mine Water Environ. 25 (2), 76–85. https://doi.org/10.1007/s10230-006-0114-6.
Gebhart, B., Jaluria, Y., Mahajan, R.L., Sammakia, B., 1988. Buoyancy-Induced Flows and Transport. Springer, Berlin.
Geller, W., Schultze, M., Kleinmann, R., Wolkersdorfer, C., 2013. Acidic Pit Lakes – The Legacy of Coal and Metal Surface Mines. Springer, Heidelberg. https://doi.org/10.1007/978-3-642-29384-9.
Gill, A.E., 1982. Atmosphere-Ocean Dynamics. Academic Press, New York.
Gzyl, G., Banks, D, 2007. Verification of the “first flush” phenomenon in mine water from coal mines in the upper Silesian Coal Basin, Poland. J. Contam. Hydrol. 92 (1–2), 66–86. https://doi.org/10.1016/j.jconhyd.2006.12.001.
Heidenreich, H., Klafki, M., Kretzschmar, H.-J., Ziegert, H.R., 1991. Strömungsmechanisch-mathematische Simulation eines gefluteten Endlagers [Fluid mechanical-mathematical simulation of a flooded nuclear waste repository mine]. Kernenerg. 34 (6), 270–275.
Henkel, L., Melchers, C., 2017. Hydrochemical and isotopegeochemical evaluation of density stratification in mine water bodies of the Ruhr coalfield. In: Wolkersdorfer, C., Sartz, L., Sillanpää, M., Häkkinen, A. (Eds.), IMWA 2017 – Mine Water & Circular Economy. Lappeenranta University of Technology, Lappeenranta, pp. 430–436.
Herbert, H.-J., 1989. Geochemische Vorgänge bei der Flutung des Kalisalzbergwerks Hope. Abschlußbericht des Teilvorhabens Geochemie [Geochemical processes during the flooding of the hope potash salt mine. Final report of the sub-project geochemistry]. gsf-Bericht 5/98, 62.
Herbert, H.-J., Sander, W., 1989. Verfahren zur verfälschungsfreien Messung und Probennahme von hochkonzentrierten Salzlösungen im Untertagebereich [Method for the error-free measurement and sampling of highly concentrated brines in underground mines]. Kali Steinsalz 10 (4/5), 137–141.
Hultsch, J., 2006. Tracerversuch im gefluteten Kalksteinbergwerk Felsendome Rabenstein – Hydrochemische Untersuchungen und Hydrodynamische Modellierung mit ANSYS/FLOTRAN [Tracer Test in the Flooded Felsendome Rabenstein Limestone Mine – Hydrochemical investigations and Hydrodynamic Modelling with ANSYS/FLOTRAN]. Unpubl. Dipl. thesis. TU Freiberg, Freiberg.
Johnson, K.L., Younger, P.L., 2002. Hydrogeological and geochemical consequences of the abandonment of Frazer’s Grove carbonate hosted Pb/Zn fluorspar mine, North Pennines, UK. In: Spec. Publ. Geol. Soc. Lond, 198. UK. Spec. Publ. – Geol. Soc., London, pp. 347–363. https://doi.org/10.1144/GSL.SP.2002.198.01.24.
Johnstone, A.C., Dennis, I., McGeorge, N., 2013. Groundwater Stratification and Impact on Coal Mine Closure, In: Brown, A., Figueroa, L., Wolkersdorfer, C. (Eds.), Reliable Mine Water Technology. International Mine Water Association, Golden, pp. 1003–1008.
Kays, W.M., Crawford, M.E., 1993. Convective heat and mass transfer, 3rd ed. McGraw-Hill New York.
Kelley, D.E., 2001. Six questions about double-diffusive convection, From Stirring to Mixing in a Stratified Ocean – Hawaiian Winter Workshop. From Stirring to Mixing in a Stratified Ocean – Hawaiian Winter Workshop. University of Hawaii at Manoa, Manoa, pp. 191–198.
Kindermann, L., 1998. Kontrolle geochemischer Parameter beim Wiedereinbau von Reststoffen in ein stillgelegtes Bergwerk [Control of geochemical parameters during the redeposit of residual materials in a decommissioned mine]. Wiss. Mitt. Inst. Geol. 7, 196–201.
Kirkland, D.W., Bradbury, J.P., Dean, W.E., 1980. The heliothermic lake: a direct method of collecting and storing solar energy. Open File Rep. 80-807, 80–807. https://doi.org/10.3133/ofr80807.
König, C., Blömer, C., 1999. Berechnung von temperatur- und dichteabhängiger Strömung in gefluteten Schächten [Calculation of temperature- and density-dependent flow in flooded shafts]. GKW-Ingenieurgesellschaft mbH, Bochum, p. 37.
Kories, H., Rüterkamp, P., Sippel, M., 2004. Field and numerical studies of water stratification in flooded shafts. In: Jarvis, A.P., Dudgeon, B.A., Younger, P.L. (Eds.), International Mine Water Association Symposium 2004. University of Newcastle, Newcastle upon Tyne, pp. 149–159.
Kranawettreiser, J., 1989, 1st ed.. Dichteströmungen [Density flows]. VEB Verlag für Bauwesen, Berlin.
Ladwig, K.J., Erickson, P.M., Kleinmann, R.L.P., Posluszny, E.T., 1984. Stratification in Water Quality in Inundated Anthracite Mines, Eastern Pennsylvania. Bur. Mines Rep. Invest. 8837, 1–35.
Loredo, C., Roqueñí, N., Ordóñez, A., 2016. Modelling flow and heat transfer in flooded mines for geothermal energy use: A review. Int. J. Coal Geol. 164, 115–122. https://doi.org/10.1016/j.coal.2016.04.013.
Luckner, L., Morgenstern, A., 2006. Grundlagen von Schichtungsprozessen in gefluteten Untertagebergwerken [Fundamentals of stratification processes in flooded underground mines]. World Min. Surf. Undergr. 58 (5), 311–315.
Martynenko, O.G., Khramtsov, P.P., 2005. Free-Convective Heat Transfer – With Many Photographs of Flows and Heat Exchange. Springer, Heidelberg.
Melchers, C., Coldewey, W.G., Goerke-Mallet, P., Wesche, D., Henkel, L., 2015. Dichteschichtungen in Flutungswasserkörpern als Beitrag zur Optimierung der langzeitigen Wasserhaltung [Density stratification in mine water bodies as a contribution to the optimisation of long-term water management], In: Paul, M. (Ed.) Sanierte Bergbaustandorte im Spannungsfeld zwischen Nachsorge und Nachnutzung WISSYM 2015. Wismut GmbH, Chemnitz, pp. 99–106.
Melchers, C., Henkel, L., Jasnowski-Peters, H., Wiegelmann, H., 2019. Ermittlung der Kinematik der Dichteschichtungen im Grubenwasser des Ruhrgebietes – Abschlussbericht [Investigation of the Kinematics of Density Stratification in the Mine Water of the Ruhr Area – Final Report]. Technische Hochschule Georg Agricola, Forschungszentrum Nachbergbau, Bochum, p. 83.
Melchers, C., Wesche, D., Coldewey, W.G., 2014. Ausbildung von Dichteschichtungen in Schächten des Steinkohlenbergbaus im Ruhrrevier [Development of density stratification in hard coal mining shafts in the Ruhr area]. 14. Altbergbau-Kolloquium, Gelsenkirchen, pp. 156–162.
Merryfield, W.J., 2000. Origin of thermohaline staircases. J. Phys. Oceanogr. 30 (5), 1046–1068 https://doi.org/10/bdr7h4.
Miller, G., Lyons, W., Davis, A., 1996. Understanding pit water quality. Environ. Sci. Technol. 30 (3), 118A–123A. https://doi.org/10.1021/es9621354.
Mugova, E., Wolkersdorfer, C., 2018. A Review of Mine Water Stratification. In: Meier, G., Benndorf, J., Löbel, K.-H., Butscher, C., Tondera, D., Busch, W., Dziurzynski, W., Sroka, A. (Eds.), 18. Altbergbau-Kolloquium – Tagungsband. Wagner, Nossen, pp. 125–132.
Mugova, E., Wolkersdorfer, C., 2019a. Dichteschichtung als potentielle In-situ-Behandlung von Grubenwasser in gefluteten Untertagebergwerken [Density stratification as a potential in-situ measurement of mine water in flooded underground mines], Bergbau, Energie und Rohstoffe 2019. Technische Hochschule Georg Agricola, Deutscher Markscheider-Verein e.V., Bochum, pp. 155–159.
Mugova, E., Wolkersdorfer, C., 2019b. Stratification in Flooded Underground Mines – State of Knowledge and Further Research Ideas. In: Khayrulina, E., Wolkersdorfer, C., Polyakova, S., Bogush, A. (Eds.), Mine Water – Technological and Ecological Challenges (IMWA 2019). Perm State University, Perm, Russia, pp. 40–44.
Neumann, C., 2007. Ermittlung der Hydrodynamik mit Hilfe von Tracertests im Richtschacht Reiche Zeche/Freiberg (Sachsen) [Investigation of hydrodynamics with tracer tests in the Reiche Zeche/Freiberg Directional Shaft (Saxony)]. Technische Universität Bergakademie Freiberg, Freiberg, p. 62. Student research project.
Nielsen, D.M., 2006. Practical Handbook of Environmental Site Characterization and Ground-Water Monitoring, 2nd ed. CRC Press, Boca Raton.
Nuttall, C.A., Younger, P.L., 2003. Hydrochemical stratification in flooded underground mines: an overlooked pitfall. J. Contam. Hydrol. 69 (1–2), 101–114. https://doi.org/10.1016/S0169-7722(03)00152-9.
Pedlosky, J., 1990. Geophysical fluid dynamics, 2nd. Springer, New York.
Pond, S., Pickard, G.L., 1983. Introductory Dynamical Oceanography, 2nd ed. Pergamon Press, Oxford.
Radko, T., 2013. Double-Diffusive Convection. Cambridge University Press, Cambridge.

Rapantova, N., Licbinska, M., Babka, O., Grmela, A., Pospisil, P., 2013. Impact of uranium mines closure and abandonment on groundwater quality. Environ. Sci. Pollut. Res. Int. 20 (11), 7590–7602. https://doi.org/10.1007/s11356-012-1340z.
Reichart, G., 2015. Modélisation thermo-hydrodynamique d'un réservoir minier profond ennoyé – Le cas du Bassin Houiller Lorrain [Thermo-hydrodynamic modelling of a deep flooded mining reservoir – The case of the Lorraine coalfield]. PhD (Docteur de l'Université de Lorraine) thesis. Université De Lorraine, p. 265.
Reichart, G., Vaute, L., Collon-Drouaillet, P., Buès, M.A., 2011. Modelling heat and salinity related convective processes in deep mining flooded wells. In: Rüde, T.R., Freund, A., Wolkersdorfer, C. (Eds.), Mine Water – Managing the Challenges –11th International Mine Water Association Congress. RWTH Aachen University, Aachen, pp. 183–188.
Rieutord, M., 2015. Fluid Dynamics – An Introduction. Springer, Cham.
Rosner, P., 2011. Der Grubenwasseranstieg im Aachener und Südlimburger Steinkohlenrevier – Eine hydrogeologisch-bergbauliche Analyse der Wirkungszusammenhänge [Mine water rebound in the Aachen and South Limburg coalfields – a hydrogeological-mining analysis of the causal relationships]. PhD thesis. Rheinisch-Westfälische Technische Hochschule Aachen, Aachen.
Ruddick, B., Gargett, A.E., 2003. Oceanic double-diffusion – introduction. Prog. Oceanogr. 56 (3), 381–393. https://doi.org/10.1016/S0079-6611(03)00024-7.
Rüterkamp, P., 2001. Bildung von Dichteschichtungen in Grubenwässern [Development of density stratification in mine water]. Glückauf Forschungsh. 62 (2), 40–44.
Rüterkamp, P., Kories, H., Rübel, H.-J., Sippel, M., 2004. Abschlussbericht zum Untersuchungs- und Entwicklungsvorhaben Erstellung numerischer Modelle zur Berechnung von Dichte-Schichtungen bei einem Grubenwasseranstieg [Final report on the investigation and development project development of numerical models for the calculation of density stratification during mine water rebound]. Deutsche Montan Technologie GmbH, Essen, p. 173.
Rüterkamp, P., Meßer, J., 2000. Untersuchungen zur hydraulischen und hydrochemischen situation in den drei Teilrevieren der gefluteten Flussspatgrube Straßberg [Investigations on the hydraulic and hydrochemical situation in the three sections of the flooded straßberg fluorspar mine]. Deutsche Montan Technologie GmbH, Essen, p. 46.
Sanders & Thomas Inc. (1975) Mahanoy Creek Mine Drainage Pollution Abatement Project – Operation Scarlift. Commonwealth of Pennsylvania Report Number: SL 197, Pottstown, Pennsylvania.
Schelkes, K., 1981. Bewegung des Grundwassers [Groundwater movement]. Entsorgung 1, 344–357.
Schlichting, H., Gersten, K., 2006. Grenzschicht-Theorie [Boundary layer theory], 10th ed. Springer, Berlin.
Semmler, W., 1964. Hydrogeologie in Bergbaugebieten [Hydrogeology in mining areas]. Z. dt. Geol. Ges. 116 (1), 38–54.
Snyder, D., 2012. Vertical gradients in geochemistry of flooded mine shafts in Butte, Montana. MSc thesis. Montana Tech of The University of Montana, Ann Arbor, p. 125.
Stefan, H.G., Gu, R., 1992. Efficiency of Jet Mixing of Temperature-Stratified Water. J. Environ. Eng. 118 (3), 363–379. https://doi.org/10.1061/(ASCE)0733-9372(1992)118:3(363).
Stemke, M., Gökpinar, T., Wohnlich, S., 2017. Erkundung stillgelegter Erzbergwerksschächte mittels Unterwasserkamera [Investigation of abandoned ore mine shafts using an underwater camera]. Bergbau (11), 511–513.
Stevens, C., Lawrence, G., 1998. Stability and meromixis in a water-filled mine pit. Limnol. Oceanogr. 43 (5), 946–954. https://doi.org/10.4319/lo.1998.43.5.0946.
Stuart, W.T., Simpson, T.A., 1961. Variations of pH with depth in anthracite mine-water pools in Pennsylvania; Article 37. U. S. Geol. Surv. Prof. Pap. 0424-B, B82-B84.
Toran, L., 1987. Sulfate contamination in groundwater from a carbonate-hosted mine. J. Contam. Hydrol. 2 (1), 1–29. https://doi.org/10.1016/0169-7722(87)90002-7.
U. S. Department of the Interior – Bureau of Reclamation, 2001. Water Measurement Manual, 3rd revised ed. U.S. Government Print. Office, Washington.
Uerpmann, E.-.P., 1980. Hydrogeologische Fragen bei der Endlagerung radioaktiver Abfälle [Hydrogeological aspects of the final disposal of radioactive waste]. Unpubl. PhD thesis. TU Clausthal, Clausthal-Zellerfeld.
Unger, K., 2002. Hydrodynamische Verhältnisse im gefluteten Unterbau des Bergwerks Großkogel/Tirol – Numerische Modellierung mit ANSYS-FLOTRAN [Hydrodynamic Conditions in the Flooded Substructure of the Großkogel mine/Tyrol – Numerical modelling With ANSYS-FLOTRAN]. Unpubl. Dipl. thesis. TU Bergakademie Freiberg, Freiberg.
Voorhis, A.D., Dorson, D.L., 1975. Thermal convection in the Atlantis II hot brine pool. Deep-Sea Res. 22 (3), 167–175. https://doi.org/10.1016/0011-7471(75)90056-X.
Wackwitz, T., 2002. Multitracerversuch im gefluteten Blindschacht des Bergwerks Großkogel/Tirol: Vorbereitung, Durchführung und GIS unterstützte Auswertung [Multitracer test in the flooded subvertical shaft of the Großkogel mine/Tyrol: preparation, implementation and GIS-supported evaluation]. Unpubl. Dipl. thesis. TU Bergakademie Freiberg, Freiberg.
Wieber, G., Enzmann, F., Kersten, M., 2016. Entwicklung und Veränderung der Dichteschichtung in Schächten gefluteter Erzbergwerke [Development and variation of the density stratification in shafts of flooded ore mines]. Mainzer Geowiss. Mitteilungen 44, 205–226.
Wieber, G., Stemke, M., Wonik, T., Enzmann, F., Kersten, M., 2019. Stratification Dynamics and Geothermal Potential of a Deep Shaft in the Flooded Wolf Mine, Siegerland/Germany. Mine Water Environ 38 (2), 325–334. https://doi.org/10.1007/s10230-019-00602-8.
Williams, W., 1996. The largest, highest and lowest lakes of the world: Saline lakes. Verh. Int. Ver. Theor. Angew. Limnol. 26 (1), 61–79. https://doi.org/10.1080/03680770.1995.11900693.
Williams, W.D., 1999. Salinisation: A major threat to water resources in the arid and semi-arid regions of the world. Lakes Reserv. Res. Manag. 4 (3–4), 85–91. https://doi.org/10.1046/j.1440-1770.1999.00089.x.
Wolkersdorfer, C., 1996. Hydrogeochemische Verhältnisse im Flutungswasser eines Uranbergwerks – Die Lagerstätte Niederschlema/Alberoda [Hydrogeochemical conditions in the mine water of an uranium mine – The Niederschlema/Alberoda deposit]. Clausthaler Geowiss. Diss. 50, 1–216.
Wolkersdorfer, C., 2006. Acid Mine Drainage Tracer Tests. In: ICARD 2006. Proceedings 7th International Conference on Acid Rock Drainage (ICARD), St. Louis.
Wolkersdorfer, C., 2008. Water Management at Abandoned Flooded Underground Mines – Fundamentals, Tracer Tests, Modelling, Water Treatment. Springer, Heidelberg. https://doi.org/10.1007/978-3-540-77331-3.
Wolkersdorfer, C., Hasche, A., Unger, K., Wackwitz, T., 2002. Tracer Techniken im Bergbau – Georgi-Unterbau bei Brixlegg/Tirol [Tracer techniques in mining – Georgi Unterbau mine near Brixlegg/Tyrol]. Wiss. Mitt. Inst. Geol. 19, 37–43.
Wolkersdorfer, C., Nordstrom, D.K., Beckie, R., Cicerone, D.S., Elliot, T., Edraki, M., Valente, T.M., França, S.C.A., Kumar, P., Oyarzún Lucero, R.A., Soler, A.I.G., 2020. Guidance for the Integrated Use of Hydrological, Geochemical, and Isotopic Tools in Mining Operations. Mine Water Environ. 39 (2), 204–228. https://doi.org/10.1007/s10230-020-00666-x.
Wolkersdorfer, C., Shongwe, L., Schmidt, C., 2016. Can natural Stratification prevent Pollution by Acid Mine Drainage? In: Drebenstedt, C., Paul, M. (Eds.), IMWA 2016 – Mining Meets Water – Conflicts and Solutions TU Bergakademie Freiberg. Leipzig, German, pp. 115–121.
Wolkersdorfer, C., Trebušak, I., Feldtner, N., 1997. Development of a Tracer Test in a flooded Uranium Mine using *Lycopodium clavatum*. In: Kranjc, A. (Ed.), Proceedings of the Tracer Hydrology 97 – International Symposium of Underground Water Tracing. Balkema, Rotterdam, 7, Balkema, Rotterdam, pp. 377–385.
Younger, P.L., 1997. The longevity of minewater pollution – a basis for decision-making. Sci. Total Environ. 194–195, 457–466. https://doi.org/10.1016/S0048-9697(96)05383-1.
Younger, P.L., Banwart, S.A., Hedin, R.S., 2002. Mine Water – Hydrology, Pollution, Remediation. Kluwer, Dordrecht.
Zeman, J., Šupíková, I., Cerník, M. 2008. Mine Water Stratification at Abandoned Mines and its Geochemical Model, Proceedings, 10th International Mine Water Association Congress. pp. 183–186.
Žibret, G., Žebre, M., 2018. Use of Robotics and Automation for Mineral Prospecting and Extraction. In: Joint Conference of UNEXMIN, ¡VAMOS! and RTM Projects. Geological Survey of Slovenia, Bled, p. 57. https://doi.org/10.5474/9789616498579.