Mine Water Research with Analogue Modelling – The Agricola Model Mine

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Abstract

Investigations in flooded underground mines can be difficult to perform, expensive and, above all, time-consuming. An alternative to field work is the use of an analogue model such as the Agricola Model Mine (AMM). This is the world's unique 4 × 6 m analogue model of a flooded underground mine with four shafts, which are connected to each other on four levels. Based on three different experiments about density stratification, the first flush using fluorescent dye tracers, it could be shown that it is possible with the AMM to replicate different scenarios in a flooded mine.

Keywords: Analogue model, stratification, first flush, tracer test

Introduction

To investigate hydrodynamic processes in flooded mines, field experiments in the flooded mine itself are usually carried out. These may include depth profile measurements to investigate density stratification, or artificial tracer tests to investigate flow paths and velocities. In addition, water samples may be taken within the mine water pool or at the discharge point. If this is done over a longer period, the development of water quality can be evaluated. Analogue modelling can be used to gain further insight into the processes in the flooded mine if investigations in the real mine are not possible. Investigations can also be conducted using an analogue mine model. An analogue model allows different conditions and experiments in the flooded mine to be represented and evaluated. At the Tshwane University of Technology in Pretoria, South Africa, this is done using the *Agricola Model Mine* (AMM). The possibilities of analogue modelling will be demonstrated by means of various experiments, to indicate that analogue modelling of different scenarios in flooded mines helps to understand mine water related issues.

Methods

The AMM is a 4 × 6 m analogue model of a mine that can be flooded completely or only in certain sections. It consists of 4 shafts connected by 4 horizontal levels made of insulated PVC pipes. Different parts of the mine can be separated by valves and 36 sampling ports allow for water sampling and tracer injection. Electrical conductivity and temperature loggers are installed in various sections of the AMM. To simulate thermal gradient, heating foils are placed around the sumps. Flooding takes place via inlet hoses at each shaft, with continuous flow possible using peristaltic pumps (Figure 1).

To investigate different applications of the AMM such as density stratification or the first flush different fluorescent dye tracers were used. Therefore, in experiment 1, shafts #3 and #4 were separated and only shafts #1 and #2 were flooded. In shaft #2, a density stratification was created below level 145 by placing NaCl bags in this area. After flooding, a continuous flow from shaft #2 to shaft #1 in the upper part of the mine was achieved by using a peristaltic pump at the inflow (shaft

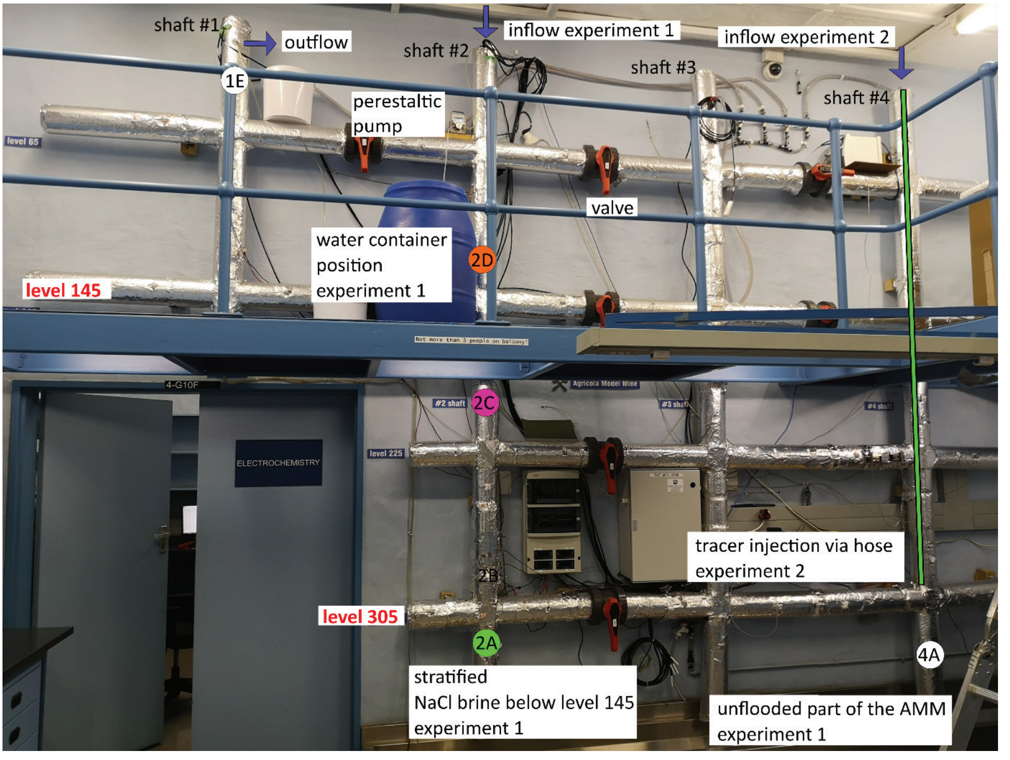

Figure 1 Agricola mine model (AMM) with water container and peristaltic pump position for experiment 1; in round circles selected injection and sampling ports; 2D (orange) injection EoY, 2C (pink) injection SRB, 2A (green) injection EoY; green hose in shaft #4 injection EoY above level 305

#2). After 69 days, the heating foil in the sump of shaft #2 was turned on to determine whether the geothermal gradient affected the stratification (heating the water to 20–21 °C). Fluorescent tracers were injected into shaft #2 at three different depths (eosinY, EoY, at section 2D, sodium rhodamine B, SRB, at section 2C and sodium fluorescein, NaFl, at section at 2A) to investigate the stability of the stratification and the first flush effect. To examine the stability of the stratification, a depth profile of the electrical conductivity was recorded in shaft #2 towards the end of experiment 1.

In the second experiment, the possibility of injecting the tracer into the mine water pool by using a hose and the behaviour of the tracer after the injection were investigated. For this purpose, the entire AMM was flooded and a low continuous inflow (20 mL/min) was established using a peristaltic pump at the inflow of shaft #4. As in experiment 1, the outlet was at the top of shaft #1. A hose was then lowered down in shaft #4 and tracer was pumped into the shaft via the hose. Just above level 305 the NaFl was injected into the flooded shaft.

In both experiments 1 and 2, samples were taken at regular intervals from the sampling ports along the flow paths and analysed using a spectrofluorometer (Cary Eclipse Fluorescence Spectrophotometer; Agilent) to observe the concentrations at the various sections and the development of the concentrations over time. In experiment 2, a continuous flow fluorimeter (P.-A. Schnegg, Neuchâtel) was installed behind the point of discharge to continuously measure the tracer concentration at a 1-min-interval (10 min towards the end of the experiment).

Results and Discussion

In both experiments 1 and 2, hydrodynamic processes were modelled in the AMM. In experiment 1, stratification remained stable over the entire experimental period (133 days), even after the heating foils in shaft #2 were switched on. Stability and barrier function of the stratification could be confirmed by the depth profile (Figure 2) as well as by the tracer concentrations. Almost no SRB and NaFl could be detected above level 145, both tracers remained in the lower water body. Some of the EoY injected in the upper part of shaft #2 sank into the sump due to its higher density compared to tap water. However, some remained around the injection port and was flushed out of the upper part of the AMM (above level 145). Based on the tracer concentrations at section 1E, a typical first flush curve of EoY could be identified (Figure 3). After about 10 days, the outflow as section 1 E showed very low EoY concentrations. A periodicity in the tracer concentrations was observed in shaft #2, below level 145 (Figure 3). This indicates the formation of convection cells (Kories *et al.* 2004; Taylor 1988). As experiment 1 was conducted analogue to the conditions and observations in the Finnish Metsämonttu mine, the observations of the analogue modelling can be used to interpret the real word scenario (Wolkersdorfer 2017). Stable stratification could be studied in the Finnish flooded mine as well as in the AMM. In addition, convection cells suspected in the real mine can be directly observed in the AMM.

Experiment 2a aimed in investigating dye tracer injection into a flooded underground mine and the flow through the AMM. One of the reasons for this test was to identify processes that caused the very low tracer recovery rates at the Georgi Unterbau

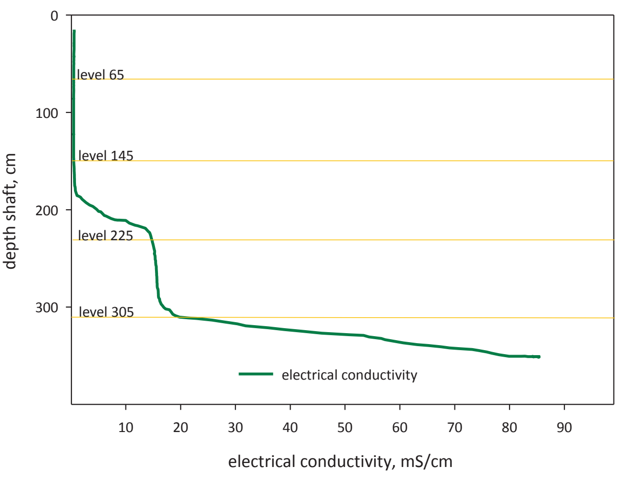

Figure 2 *Depth profile of electrical conductivity in shaft #2 (experiment 1)*

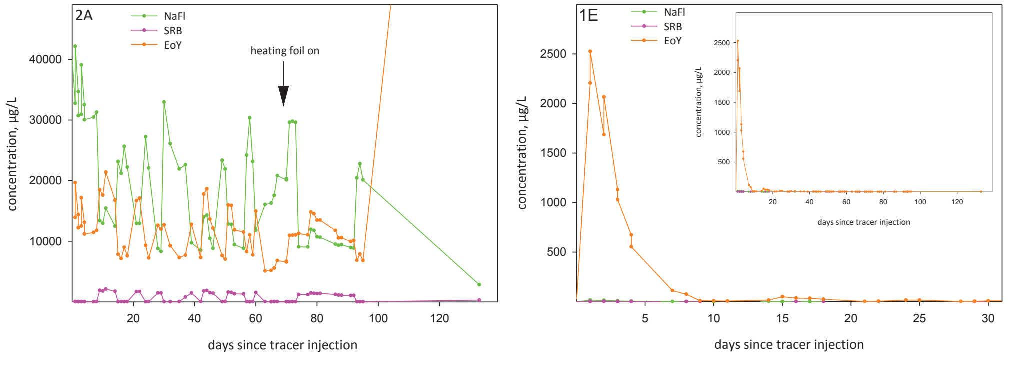

Figure 3 *left: NaFl, SRB and EoY concentrations at sampling port 2A (last measured values after a long sampling gap, presumably contamination during sampling); right: NaFl, SRB and EoY concentrations at sampling port 1E, before discharge (experiment 1)*

dye tracer test and the increase in tracer concentrations after the first breakthrough (Wolkersdorfer *et al*. 2002). In the first trial, the hose through which the tracer was injected was placed just below level 305. As a result, almost all the tracer sank down into the sump, and only a small amount of NaFl flowed through the AMM because the tracer accumulated in the sump. Due to the higher density most of the tracer was therefore "stuck" in the sump. Positioning a hose or pipe for tracer injection at the correct location is an important finding for tracer tests in real mines. From the analogue model it could be identified that an accurate knowledge of the injection depth is essential for a successful tracer test. For experiment 2b, the hose was positioned just above level 305. Through a window in the AMM insulation, the exact position and injection process could be visually observed. It was evident that a large amount of the tracer sank into the shaft sump, while some of this tracer was flowing with the overall flow into the connected level 305. Visual records from section 4A clearly show that a large fraction of the tracer accumulates in the sump (Figure 4). Samples along the flow path and fluorometer records indicate that the tracer passed through the AMM and reached the outflow after about 1 day. Several peaks can be seen at sampling section 1E (below the outlet) as well as at the other sections sampled along the flow path, indicating that tracer was released from the sump at shaft #4 at regular intervals. This very likely was caused by convection cells in the sump but will require further investigation.

Conclusion and Outlook

With the different experiments and scenarios described here, it has been shown that the real conditions in a flooded underground mine can be simulated with an analogue model mine (AMM) and that the AMM is an important tool for the investigation of flooded mines. In real mines, stable stratification was observed over months, years and decades. This stable stratification could also be confirmed in the AMM, with a shortened experimental period. Furthermore, the first flush can be simulated in the analogue model and thus examined

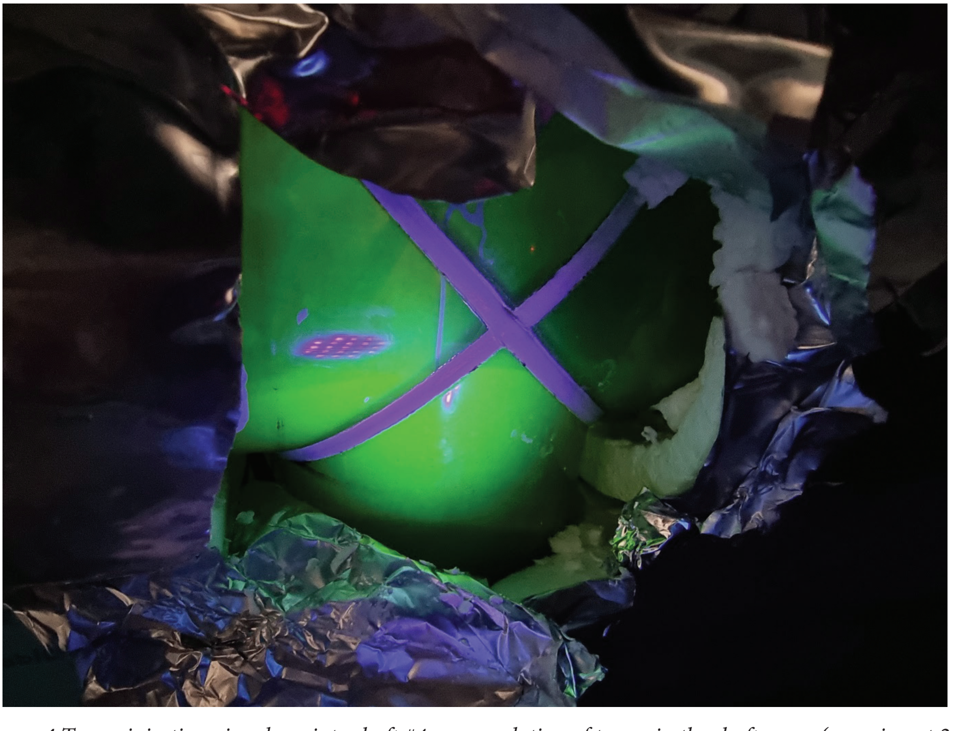

Figure 4 *Tracer injection via a hose into shaft #4, accumulation of tracer in the shaft sump (experiment 2*

both at the discharge and in the mine pool itself. It is beneficial that the boundary conditions of the AMM are well defined and known, there are fewer unknown influences. In the laboratory, changes in the mine water can be measured or sampled at various points in the analogue mine. In a real mine, this is difficult or impossible. Experiments in the AMM can be repeated under slightly different conditions, which is not feasible in most field experiments. This makes it possible to find an ideal setup for field experiments, especially for tracer tests. In the AMM experiment, for example, it was shown that there are sources of error, such as the wrong injection level for tracers, which strongly influence the results of the experiment and may lead to incorrect assumptions. A further advantage of the AMM is that the much shorter duration of experiments in the AMM saves resources. AMM experiments are cheaper than field experiments. Despite these advantages, it is important to note that the AMM is only a simplified version of a flooded mine. For example, it is currently not possible to simulate the interaction between the shaft and the surrounding rock. Combining analogue and numerical modelling bridges this gap. CFD software such as COMSOL Multiphysics® can be used to numerically model the experiments in the AMM, allowing comparison of the analogue and numerical results, as well as more advanced approaches that are not viable with the AMM. Analogue models in mine water research can explain observations in real mines that could not previously be demonstrated with sufficient data.

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