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Mine water tracer tests as a basis for remediation strategies

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Abstract

Mining usually causes severe anthropogenic changes by which the ground- or surface water might be significantly polluted. One of the main problems in the mining industry are acid mine drainage, the drainage of heavy metals, and the prediction of mine water rebound after mine closure. Therefore, the knowledge about the hydraulic behaviour of the mine water within the flooded mine might significantly reduce the costs of mine closure and remediation. In the literature, the difficulties in evaluating the hydrodynamics of flooded mines are well described, but only few tracer tests in flooded mines have been published so far. Most tracer tests linked to mine water problems were related to either pollution of the aquifer or radioactive waste disposal and not the mine water itself.

Applying the results of the test provides possibilities for optimizing the outcome of the source–path–target methodology and therefore diminishes the costs of remediation strategies. Consequently, prior to planning of remediation strategies or numerical simulations, relatively cheap and reliable results for decision making can be obtained via a well conducted tracer test.

Keywords: Mine water treatment; Stratification; Convection; First flush; Tracer tests; Microspheres; Reactive transport

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1. Introduction

Mine water emanates from working and abandoned surface and underground mines. Usually, it is ground water percolating through the host rocks or sediments, collected by the shafts, galleries, or open pits (Younger et al., 2002). In the case of open pits or mine waste piles, surface or precipitation water also comes into contact with the mine workings, worked host rocks, or sediments. Once the ground or surface water is extracted by a mine operator or has been in contact with mine workings, the water is called "mine water". According to the ERMITE definition, "mine water is water in mined ground including waste rock/tailing depositories and/or draining into an adjoining body of water including streams, lakes, aquifers, wetlands, and oceans" (ERMITE consortium, D4: European Policies and Mine Waters).

Although mine water is not necessarily contaminated, in many cases it contains elevated metal or acidity values which cause a severe threat to the receiving water courses and river catchments (Younger, 1997a, b; Furrer et al., 2002; Sivakumar et al., 1994; Tiwary and Dhar, 1994; Gray, 1998; Nordstrom et al., 2000). Non-contaminated mine water is used for several purposes, e.g. as cooling water for power plants, drinking water, mineral water, or for agricultural purposes (Banks et al., 1997; Stengel-Rutkowski, 2002; Stengel-Rutkowski, 1993).

However, there are heavily polluted mine waters which have to be treated by either active or passive treatment methods (Younger et al., 2002). Both methods have their advantages and disadvantages and therefore, the combination of such treatment options can often be an advantage for the responsible company or authority (Jakubick and Levins, 1997).

As active treatment is cost and labour intensive, mine operators usually aim to decrease the time during which the active treatment must be used. On the other hand, highly polluted mine waters or mine waters with a large pollution load cannot be properly treated by passive treatment methods, because the area of land that would be needed for treatment is either unavailable or would be too expensive (Brown et al., 2002).

Therefore, the knowledge of when to switch from active to passive treatment is essential for mine operators or authorities involved. To estimate the time scales during which mine water is highly polluted, an empirical formula is available (Younger, 1997a, b). As this formula also depends on the volume of the flooded mine workings and their hydraulic properties, knowing these parameters is essential for planning remediation strategies or calculating the reactive transport within the mine.

This paper will focus on tracer tests in flooded underground mines to evaluate their hydraulic characteristics. For this purpose, the results of several tracer experiments will be compared in the context of potential remediation strategies and the source–path–target methodology, which means that remediation action should be preferably taken at the source not the path or target (Loxam, 1988). An extensive overview of tracer tests in flooded mines and a detailed case study has been given elsewhere and shall not be repeated here (Wolkersdorfer, 2002).

2. Longevity of mine water pollution

It has long been known that mine water pollution, especially with acid mine drainage, could last for decades, even centuries (Leblanc et al., 2000). One characteristic feature of nearly all mine waters discharging from flooded underground mines is the "first flush" (Wood et al., 1999). Generally, after a mine has been flooded, the mine water contamination increases rapidly to a maximum from which the contamination gradually decreases to a more or less constant value. The time span from the peak concentration to the constant value is called "first flush" t_f. It mainly depends on the acidity removal by buffering or dissolution aci_{rem}, by the rate at which acid-containing minerals weather r_w, the volume of the inter-connected workings V, the hydraulic connection, and conductivities of the mine workings K, and the ground water recharge R_{GW}. This can be expressed by the following formula, whereas t_r is the duration of the mine water rebound (Younger et al., 2002):

$$t_f = f(aci_{rem}, r_w, V, K, R_{GW}) \approx (3.95 + 1.2)t_r. \quad (1)$$

From empirical studies it is known that the duration of the first flush t_f can be approximated by multiplying the mine water rebound time t_r by a factor of 4 as exemplified by the iron decrease of the Straßberg/Harz fluorspar mine of which the rebound time was 3 years (Fig. 1).

Obviously, if the duration of the first flush could be reduced by any interaction with the to be flooded underground mine, the duration of active treatment could be

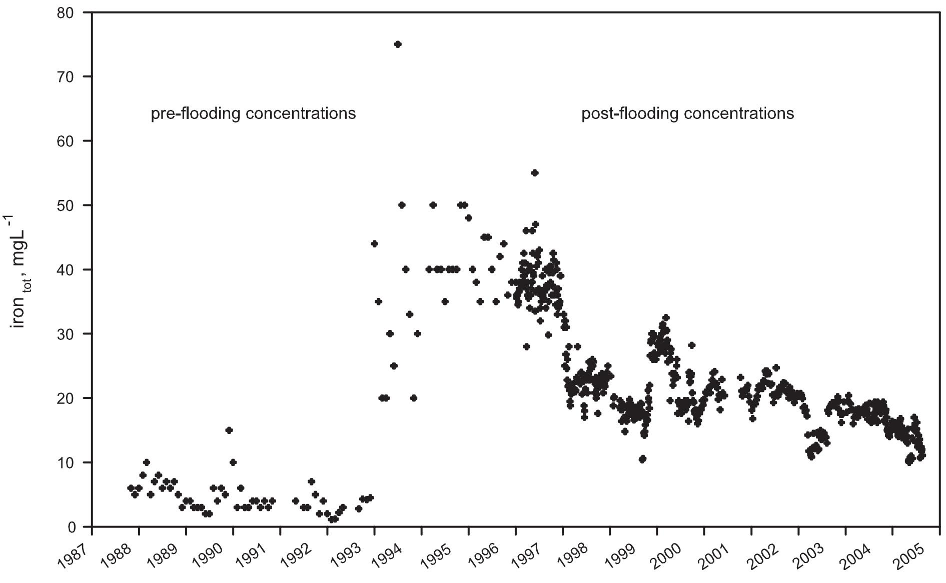

Fig. 1. Pre- and post-flooding iron concentrations in the Fluor-shaft of the Straßberg/Harz fluorspar mine between 1987 and 2005. Unfiltered Fe_{tot}. Courtesy GVV – Gesellschaft zur Verwahrung und Verwertung von stillgelegten Bergwerksbetrieben mbH.

reduced as well. Furthermore, if the peak pollutant concentration could be reduced, the application of passive treatment methods could start earlier than without interaction.

From the five factors controlling the duration of the first flush (Eq. (1)), only three can be influenced: the acidity removal or reduction rate, the ground or mine water recharge, and the hydraulic conductivity. Acidity removal, e.g. by adding alkaline substances into the flooded mine, would result in a lower peak and a shorter duration of the first flush. An increase or decrease of the mine water recharge which could be reached by covering the mine's catchment area or through an active flooding by pumping water into the mine would only influence the duration of the first flush. These two possibilities will not be further discussed here as both measures would result in enormous investigations which cannot be covered by the mine operator. Instead, this paper will focus on how to evaluate the hydraulic behaviour of flooded underground mines and how the duration of the first flush can be influenced by other means.

3. Convection and stratification

During our investigations of flooded underground mines (Wolkersdorfer and Hasche, 2004) both homogeneous mixing of mine water as well as stratification could be observed (Fig. 2, Wolkersdorfer, 2002). These features were not new and are known since the 1960s, yet have never been studied in more detail. Yet, from the investigations of Bau and Torrance (1983) it could be deduced that flooded mines are open thermosyphons and forced or free convection are likely to occur, with the result that large parts of the mine will be homogenously mixed. Based on about 115 physicochemical measurements in the flooded Niederschlema/Alberoda uranium mine during a time span of 3 years, an extensive tracer test and a numerical Computational Fluid Dynamics (CFD) simulation were conducted to investigate the causes for these features in more detail (Fig. 3).

One of the questions that arose was whether convective mixing or stratification might be used as a potential remediation method. Although a case is known where controlled pumping of the overlaying clear water zone is used to prevent the discharge of highly polluted mine water (Coulton et al., 2004) stratification usually cannot be used as a remediation method. The reasons for this were shown by an earlier work of the author (Wolkersdorfer, 1996). In an unpublished prestudy, more than 10 numerical simulations, all within the boundary conditions that were measured by physical or chemical methods in the Niederschlema/Alberoda mine were conducted. The results clearly showed that the overall flow in a mine with two shafts and three levels can rapidly change if the boundary conditions are only slightly changed. This behaviour is due to the fact that such systems behave chaotically and their prediction is usually difficult (Barry and Chorley, 2003). Nonetheless, the numerical simulations explained several of the variations that were observed within the measurement period of several years (Fig. 3). Meanwhile, such an observation-based CFD model has also been conducted by another research team (Kories et al., 2004).

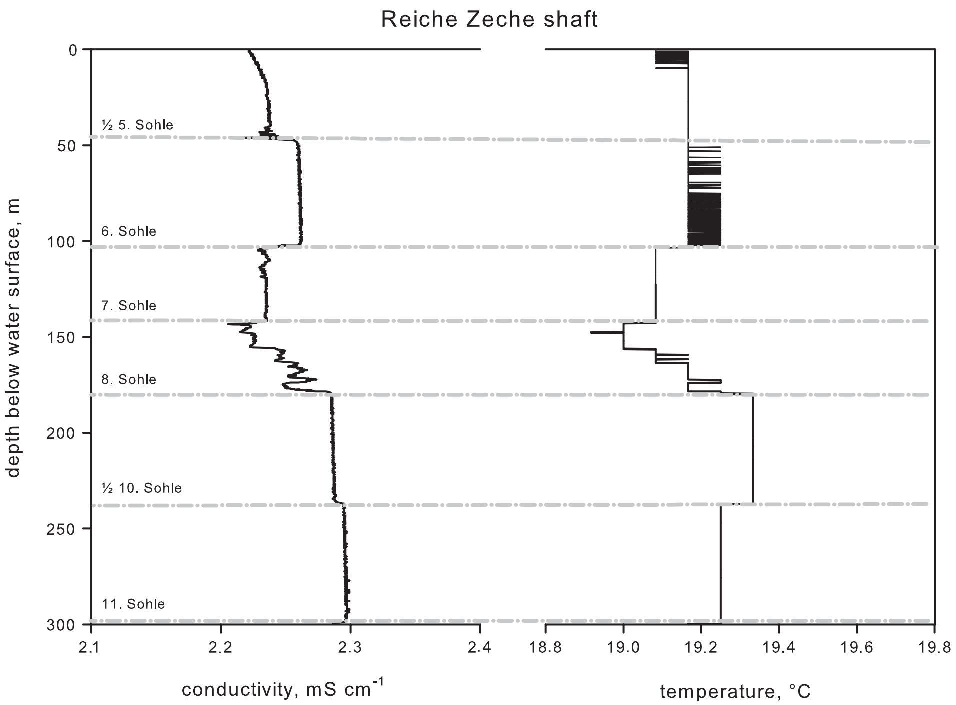

Fig. 2. Temperature and conductivity profiles within the 500 m deep Freiberg Reiche Zeche shaft. Stratified parts between different levels can be recognized. Measurements had to be stopped at a depth of 300 m due to the on-site situation in the mine.

However, the findings of the physicochemical measurements and the results of the numerical simulations in the Niederschlema/Alberoda mine had to be verified and explained by tracer tests in other flooded underground mines. At the time the first tracer test was planned no means were available to conduct a mine water tracer test aiming to explore the hydraulic properties of such a huge water body and depths of up to more than 1000 m.

4. Results of tracer tests

Tracer tests in underground mines are often related to potential radioactive waste disposal sites (e.g. Lee, 1984). Others were conducted to investigate mine water inrushes (Skowronek and Zmij, 1977), to optimize the mining strategy (Miller and Schmuck, 1995), or to investigate remediation strategies (Wolkersdorfer, 1996). Forty tracer tests in abandoned and flooded underground mines have been published so far or were conducted by our research team (Table 1). Interestingly enough, the

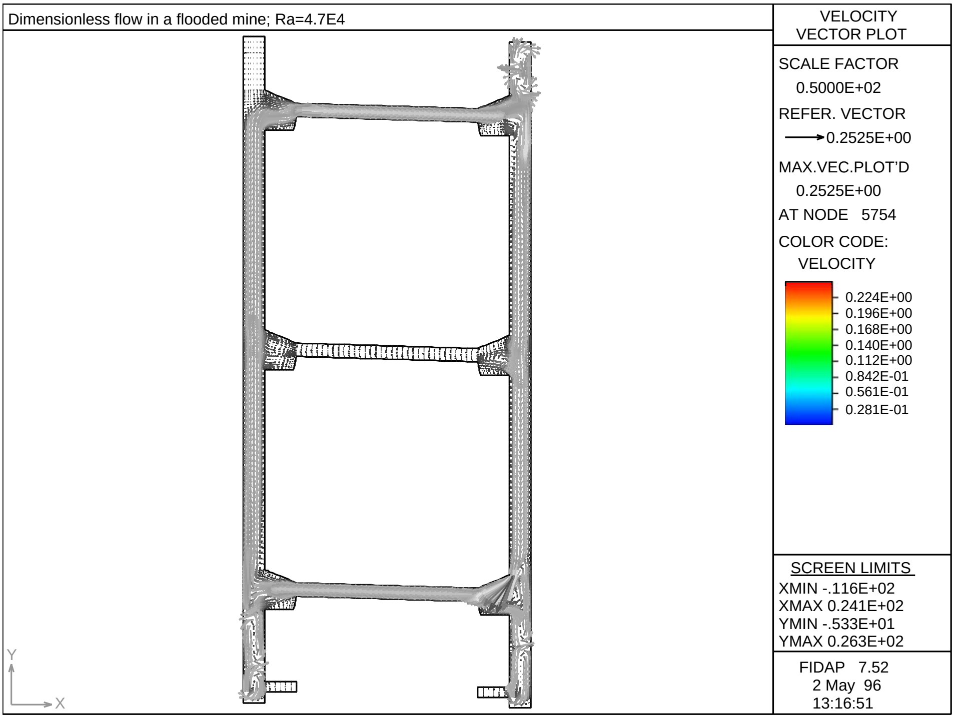

Fig. 3. Results of a CDF simulation of a flooded mine with two shafts and three adits. Different convection cells can clearly be identified.

mean velocities evaluated by these tracer tests vary within a small range from 0.3 to $1.7\,\mathrm{m\,min^{-1}}$ (95% confidence interval of 40 tracer tests) and the absolute values between 0.01 and $1.8\,\mathrm{m\,min^{-1}}$ (10% and 90% percentile of 40 tracer tests). The maximal and minimal effective velocities evaluated so far were 1×10^{-4} and $1 \times 10^{1}\,\mathrm{m\,min^{-1}}$. Furthermore, the effective velocities show small dependencies on the distance between the injection and sampling point whereas the maximum velocity increases with the distance. Although the reasons for this behaviour are not fully understood yet, the results of the Niederschlema/Alberoda and Straßberg/Harz tracer tests indicated that independent of the driving forces (free convective flow or forced flow), the velocities in mines with more than two shafts well interconnected by at least three levels result in a quick mixing in the flooded water body. On the other hand, mine parts with a lesser interconnection tend to form stratification with a slower release of pollutants.

To verify these results two tracer tests in "simple" mines were conducted: the Brixlegg/Tyrol and the Felsendome Rabenstein/Saxony underground mines. In the Brixlegg mine a slight stratification could be observed in December 2000, May 2001, August 2001, and February 2002. From this is was concluded that the mine water above the mixing layer at a depth of 40–45 m would be part of the overall upward

Table 1. Distances and mean velocities of worldwide tracer tests in underground mines

Distance (km)	v_{eff} (m min^{-1})	v_{eff} (m d^{-1})	Reference
0.015	0.0001	0.1	Wolkersdorfer (unpublished)
0.17	0.0003	0.4	Wolkersdorfer (unpublished)
0.2	0.001[a]	1.4	Aljoe and Hawkins (1993)
0.044	0.004	5.8	Aljoe and Hawkins (1993)
0.093	0.004	5.8	Wolkersdorfer (unpublished)
0.093	0.006	8.6	Wolkersdorfer and Hasche (2004)
0.13	0.01	14.4	Aljoe and Hawkins (1994)
0.077	0.01	14.4	Canty and Everett (1998)
0.78	0.01	14.4	Wolkersdorfer (1996)
0.238	0.014	20.2	Wolkersdorfer (unpublished)
0.048	0.02	28.8	Wolkersdorfer et al. (2002)
0.01	0.03	43.2	Wolkersdorfer et al. (2002)
1.182	0.07	101	Wolkersdorfer (unpublished)
0.35	0.1	144	Mather et al. (1969)
1.181	0.1	144	Wolkersdorfer (unpublished)
3.539	0.1	144	Wolkersdorfer (unpublished)
0.077	0.12	173	Canty and Everett (1998)
0.077	0.14	202	Canty and Everett (1998)
0.283	0.15	216	Wolkersdorfer and Hasche (2004)
1.773	0.15	216	Wolkersdorfer and Hasche (2004)
0.171	0.17	245	Canty and Everett (1998)
6.564	0.17	245	Wolkersdorfer (unpublished)
1.7	0.2	288	Parsons and Hunter (1972)
0.229	0.23	331	Canty and Everett (1998)
3.6	0.3	432	Aldous and Smart (1987)
4.798	0.3	432	Wolkersdorfer and Hasche (2004)
0.15	0.4	576	Mather et al. (1969)
0.172	0.4	576	Wolkersdorfer et al. (1997)
0.216	0.5	720	Wolkersdorfer et al. (1997)
0.22	0.5	720	Wolkersdorfer et al. (1997)
0.2	0.6	864	Mather et al. (1969)
3.18	0.7	1008	Wolkersdorfer and Hasche (2004)
0.5	1.3	1872	Aldous and Smart (1987)
2.25	1.5	2160	Wolkersdorfer and Hasche (2004)
0.776	1.6	2304	Wolkersdorfer et al. (1997)
0.736	1.8	2592	Wolkersdorfer et al. (1997)
0.78	2	2880	Wolkersdorfer et al. (1997)
2.159	5.7	8208	Wolkersdorfer et al. (1997)
2.723	7.9	11376	Wolkersdorfer et al. (1997)
0.5	11.1	15984	Aldous and Smart (1987)

Table is given for comparisons only, details concerning geological setting and hydraulic parameters are given in the literature cited. Mean of all 40 tracer tests: 0.3–1.7 m min^{-1} (95% confidence interval of 40 tracer tests).

[a]Result probably wrong.

directed mine water flow whereas the water body below that level might be excluded from that flow. Therefore, a multi-tracer test with tracer injections in four different levels was conducted. It could be shown that the uppermost water body takes part in the overall flow whilst the deeper levels seem to be governed by diffusive flow. Although the effective velocities (0.02–0.03 m min^{-1}) in the upper water body do not fall in the 95% confidence interval, they fit well into the 10–90% percentile of all surveyed tracer tests in underground mines.

In the Felsendome Rabenstein, preliminary investigations in 2002 and 2003 showed that there is only a minor stratification of 0.1 K which might not be strong enough to prevent the flow from the lowest mine level to the shaft's drainage point. Furthermore, the mine has only two shafts which are connected by two levels. Consequently, it was assumed that there is a slow effective velocity between the two shafts and within the control shaft as well. A tracer was injected into the two shafts, and based on the flow measurements in summer 2002 a duration of 1–2 months was calculated for the concentration of the tracer to return to background. Yet, the tracer concentrations did not decrease to the background values even after 19 months into the test period. From the tracer's maximum at about 3 months after the tracer test's beginning it can be calculated that the effective velocities between the injection and sampling points are about 0.1–0.4 m d^{-1}.

5. Discussion and conclusions

As has been shown, mean effective velocities in flooded underground mines generally vary within a relatively small interval from 0.3 to 1.7 m min^{-1}, although the absolute values can range over 5 orders of magnitude. Furthermore, complex mine geometries with many galleries and shafts favour convective flow as in the case of the Niederschlema/Alberoda, the Straßberg/Harz and the upper level of the Brixlegg/Tyrol mines.

On the other hand, simple mine geometries and a lack of interconnected workings as in the case of the lower levels of the Brixlegg/Tyrol mine and the Felsendome Rabenstein prevent or delay the outflow of the mine water.

In conclusion, it must be stated that the mine geometry significantly controls the hydrodynamics within a flooded mine. Because, seen in the context of the source–path–target concept, the mine is the pollutant's source, a manipulation of the mine geometry prior to flooding will control the duration of the first flush as well as its maximum peak. Technical barriers that inhibit the evolution of fast convective cells will result in a smaller maximum and a longer duration of the first flush. Because in such cases, lower loads will be obtained, passive treatment options within the pathway or at the target can be installed at an earlier time compared to a situation without technical barriers.

Otherwise, if the loads are already that high, that active treatment plants are to be used, the quick flushing of the mine, possibly supported by active flooding procedures, will be advantageous.

Thus, mine water tracer tests foster the necessity for more effective remediation strategies. In the case of already flooded mines they can help to understand the hydrodynamics within the mine and whether grouting techniques could be used to control the flow regime.

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