Tracer Tests as a Mean of Remediation Procedures in Mines

Christian Wolkersdorfer

TU Bergakademie Freiberg, Lehrstuhl für Hydrogeologie, Gustav-Zeuner-Str. 12, 09596 Freiberg/Sachsen, Germany, E-mail: c.wolke@tu-freiberg.de

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. Consequently, the knowledge about the hydraulic behaviour of the mine water within a 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, although 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 optimising 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 by the use of tracer tests.

Introduction

During the last decades hundreds of underground mines were closed and in most of the cases no preliminary investigations of the potential hydrodynamic regime within the flooded mine were conducted. Usually, the operator’s interest is to close down the mine as quick as possible and to flood the open underground space in the shortest possible time. Though this can be understood from an economic point of view, the ecologic consequences of such a procedure are seldom understood in detail.

Several tracer tests in flooded underground mines that were conducted since the early 1990ies, proved that two different types of mines must be distinguished from a hydrodynamic point of view. The first type, exemplified by the Niederschlema/Alberoda or Straßberg/Harz tracer tests have a complicated layout of shafts and galleries, whereas the second type, as the Brixlegg/Tyrol and the Rabenstein/Saxony tracer tests showed, have a simple mine layout.

A basic rule of the source-path-target methodology is to treat pollutants as close at the source as possible (Loxam 1988). Transferred to a flooded underground mine, the source would be the mine workings, the path could either be the drainage gallery or the shaft, whereas the target can be a receiving stream, an industrial plant, or a drinking water supply. For all three cases, solutions have been described in the literature, most of them focussing on either the path or the target.

All the tracer tests conducted by the TU Bergakademie Freiberg research team were multi-tracer tests with 2—6 injection points and up to three different types of tracers, thereunder *Lycopodium* spores, microspheres, Na-fluorescein, and rock salt brine. It could be shown that all those tracer types are suitable for acidic and circum-neutral mine waters and that the recovery rates are high enough to gain evaluable results (Wolkersdorfer 2002).

Investigations and Discussion

A total of nine mine water tracer tests were conducted by the Bergakademie Freiberg research team and nearly 30 different flow paths investigated. They have already been described in the literature (see table 1 and Wolkersdorfer 2002) and shall not be further discussed here. Instead, two interesting results from all those tests will be described and explained. At the end a final conclusion will be given.

Before a tracer test is conducted, several months of preliminary hydrogeological and hydrochemical investigations have to be spend. In all those investigations, conducted by Bergakademie Freiberg, flow measurements were a crucial point, as the flow determines the amount of tracer to be used and the possible duration of the tracer test. From that flow usually a simplified analytical piston flow model was applied for the calculation of the tracer amounts to be used and the expected test duration. Certainly, the flow in a conduit network is either laminar or turbulent and the velocity distribution in the conduits definitely does not meet a piston flow distribution, but simplified piston flow is commonly used to interpret tracer investigations (Maloszewski and Zuber 1996). Yet, in all – but one – cases it could be shown that the potential velocities were underestimated and the test's duration overestimated by a factor of 2 … 5. Unfortunately, no general rule for finding a reliable correction factor could be deduced from the current results. Therefore, it must be concluded that simplified piston flow models do not sufficiently enough describe the conduit flow in a flooded underground mine.

Due to the fact that the wall roughness in the adits and galleries is comparably high, a lower effective velocity compared to the velocity calculated by the piston flow model would have been expected. For the Brixlegg/Tyrol tracer test a numerical FEM model with ANSYS-FLOTRAN was set up to further investigate the results obtained (Unger 2002). Though it was possible to calibrate the model and understand some of the results, it became not clear what the reasons for the discrepancy between the two models were (Fig. 1). Similar experiences have been described by Ren et al. (1996) who investigated flow in soil cores and got 0.2 … 3 times higher effective velocities than those compared to a piston flow model.

Another result is more obvious and refers to the ratio of horizontal to vertical lengths of the mine workings. The longer the water flows through horizontal mine workings, the bigger is the effective velocity, because horizontal mine workings, compared to vertical workings (especially shafts) commonly have smaller diameters. This fact was first described in Wolkersdorfer et al. (1997) and since than has been observed in other mines as well. From a practical point of view this behaviour can be used to control the duration of the first flush or the maximum concentration of the pollutants after the mine has been flooded. If the vertical mine workings are dammed and a preferential flow at the horizontal mine workings is obtained, the maximum pollutant concentrations might be expected earlier than

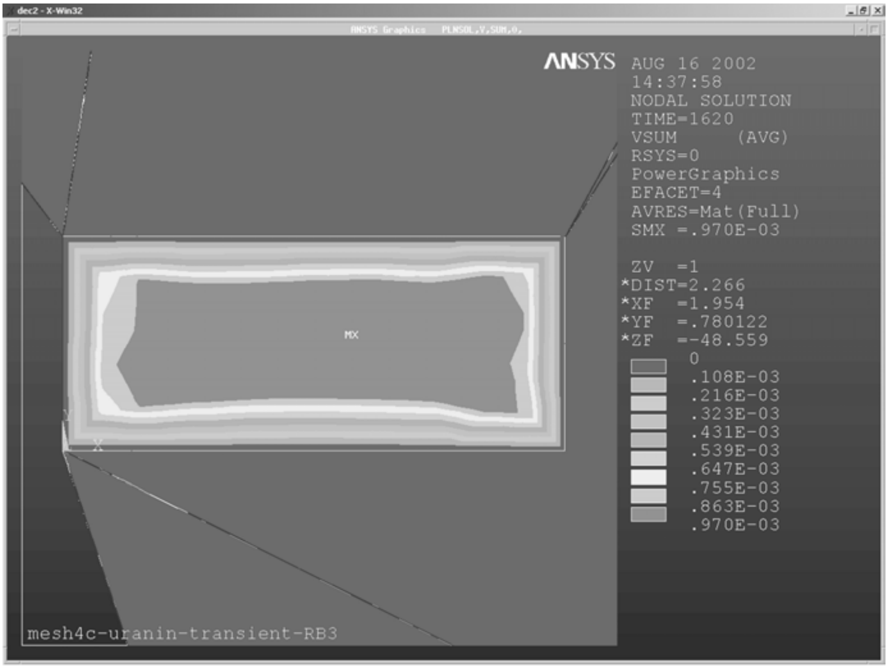

Fig. 1. Results of the numerical simulation in the Brixlegg Georgi-Unterbau mine. The velocity distribution indicates that the flow in the shaft, though very low, seems to be turbulent (from Unger 2002).

without any technical installations. On the other hand, dams on the horizontal mine workings would minimize the annual pollutant load (indeed not the total load).

One of the main results of the tracer test has been indicated in one of the first paragraphs of this paper. It is connected to the mine geometry and, simplified, means that complicated mine geometries with many shafts and levels have higher effective velocities than mines with a simple geometry. When Uerpmann (1980) investigated potential scenarios for radioactive waste disposal, he assumed that a mine with only one shaft would be optimal to reduce the radio nuclide transport from the source to the anthroposphere. An extreme situation occurred in the Rabenstein/Saxony underground limestone mine, where the tracer needed nearly 2 years to come back to background values (first two rows in tab. 1). This flooded mine has only two shafts and 2 levels and therefore is an extreme simplified type of mine. The other extreme is the Niederschlema/Alberoda mine with extreme quick response times and distances of nearly 3 km (tab. 1, Wolkersdorfer et al. 1997).

In the view of the mentioned source-path-target methodology (Loxam 1988) and the results obtained form the tracer tests it is recommended to install technical installations to separate mine parts with height contamination or acid producing potentials from the other parts of the mine. As fast ground water transport is usually restricted to the upper parts of the mine the dams should be constructed in such a way that the upper parts are separated from the lower parts, where – based on the investigations of the Bergakademie Freiberg – higher pollutant concentrations are usually expected. Using the means of technical installations can reduce both the annual pollutant load and the maximum concentration of the first flush. Yet, the total load over the lifetime of the mine water discharge can not be affected by such means.

By controlling the pollutant source of a flooded underground mine and reducing the pollutants' concentrations, passive treatment technologies can substitute active techniques at an earlier time than without such control measures.

Acknowledgements

The investigations described here are the results of 10 years of tracer studies in flooded underground mines. I would like to thank all my colleagues and all the mine operators who helped in conducting the tests. The DFG and the European Union financed several of the used data in this publication and in table 1.

Table 1. Distances and mean velocities of worldwide tracer tests in underground mines. 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); $^{\times}$ result propably wrong.

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$^{\times}$	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)

References

Aldous P J, Smart P L (1987) Tracing Ground-Water Movement in Abandoned Coal Mined Aquifers Using Fluorescent Dyes. Ground Water 26(2):172–178.

Aljoe W W, Hawkins J W (1993) Neutralization of Acidic Discharges from Abandoned Underground Coal Mines by Alkaline Injection. Report of Investigations – US Bureau of Mines 9468:1–37.

Aljoe W W, Hawkins J W (1994) Application of aquifer testing in surface and underground coal mines. Proceedings, 5th International Mine Water Congress, Nottingham, UK 1:3–21.

Canty G A, Everett J W (1998) Using tracers to understand the hydrology of an abandoned underground coal mine, vol. 15. Princeton: Proceedings, 15th Annual National Meeting – American Society for Surface Mining and Reclamation: 62–72.

Loxam M (1988) The predictive assessment of the migration of leachate in the subsoils surrounding mine tailings and dredged spill sites. In: Salomons W, Förstner U. Environmental management of solid waste – Dredged materials and mine tailings. Berlin u.a.: Springer: 3–23.

Maloszewski P, Zuber A (1996) Lumped Parameter Model for the Interpretation of Environmental Tracer Data. IAEA-TECDOC – Manual on mathematical models in isotope hydrogeology 910:1–58.

Mather J D, Gray D A, Jenkins D G (1969) The use of tracers to investigate the relationship between mining subsidence and groundwater occurrence at Aberfan, South Wales. J Hydrol 9(2):136–154.

Parsons A S, Hunter M D (1972) Investigation into the movement of groundwater from Bryn Pit above Ebbw Vale, Monmouthshire. Water Pollut Control 71:568–572.

Ren G-L, Izadi B, King B, Dowding E (1996) Preferential Transport of Bromide in undisturbed Cores under different Irrigation Methods. Soil Sci 161(4):214–225.

Uerpmann E-P (1980) Hydrogeologische Fragen bei der Endlagerung radioaktiver Abfälle. Clausthal: Unveröff. Diss. TU Clausthal: 128.

Unger K (2002) Hydrodynamische Verhältnisse im gefluteten Unterbau des Bergkwerks Großkogel/Tirol – Numerische Modellierung mit ANSYS-FLOTRAN. Freiberg: Unveröff. Dipl.-Arb. TU Bergakademie Freiberg: 117.

Wolkersdorfer C (1996) Hydrogeochemische Verhältnisse im Flutungswasser eines Uranbergwerks – Die Lagerstätte Niederschlema/Alberoda. Clausthaler Geowissenschaftliche Dissertationen 50:1–216.

Wolkersdorfer C (2002) Mine water tracing. Geological Society Special Publication 198:47–61.

Wolkersdorfer C, Hasche A (2004) Tracer Investigations in flooded mines – The Straßberg/Harz Multitracer Test. Conference Papers, vol. 35. Wien: Umweltbundesamt: 45–56.

Wolkersdorfer C, Trebušak I, Feldtner N (1997) Development of a Tracer Test in a flooded Uranium Mine using Lycopodium clavatum. In: Kranjc A. Tracer Hydrology 97, vol. 7. Rotterdam: Balkema: 377–385.

Wolkersdorfer C, Hasche A, Unger K, Wackwitz T (2002) Tracer Techniken im Bergbau – Georgi-Unterbau bei Brixlegg/Tirol. Wissenschaftliche Mitteilungen 19:37–43.