ACID MINE DRAINAGE TRACER TESTS[1]

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Abstract. Acid mine drainage, the drainage of metals, and the prediction of mine water rebound after mine closure are major problems for the mining industry. In the literature, the difficulties in evaluating the hydrodynamics of flooded mines are well described, although only a few tracer tests in flooded mines have been published. Increased knowledge about the hydraulic behaviour of the mine water within a flooded mine might significantly reduce the costs of mine closure and remediation. Relatively cheap and reliable results for decision making can be obtained when tracer tests are properly conducted in a flooded mine prior to planning of remediation strategies or numerical simulations. Applying the results of successful tracer tests allows one to optimise remediation designs and thereby diminish the costs of remediation. The paper summarises the results of several tracer tests and draws general conclusions from such tests.

Additional Key Words: mine water, flooded shaft, underground mining, mine water pollution

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Introduction

After mining ceases, a mine site has to be remediated as close as possible to the natural pre-mining conditions. In many cases, the pre-mining conditions can't be met, because the landscape had been significantly modified or the underground workings altered the hydraulic conductivity of the host rocks. Besides that, mining results in close rock-atmosphere contact, which greatly accelerates the weathering of di-sulfides, namely pyrite and marcasite causing acid rock drainage and metal leachate (Nordstrom and Ball 1985). At mines where a mine operator is responsible for water treatment, the environmental impacts of polluted mine drainage can be minimized to an acceptable level by installing active or passive treatment operations. In contrast, abandoned mines very often discharge polluted mine drainage with elevated concentrations of acidity or toxic metal leachate (ERMITE Consortium et al. 2004).

Mine water is commonly treated at the path or target, where the path might be a drainage gallery or an aquifer and the target could be a receiving stream, lake, or drinking water supply. The methods used include active treatment by means of conventional treatment (aeration-liming-sedimentation) and filtration (e.g. nano-filtration, ultra-filtration, reverse osmosis), passive treatment (e.g. constructed wetlands, RAPS [also called SAPS], limestone channels, phytoremediation, reactive barriers), or natural attenuation (Younger et al. 2002; Brown et al. 2002; Wolkersdorfer et al. 2003). Rarely, the mine water is treated *in-situ*; in general, where *in-situ*-treatment has been chosen as a potential option, the results have been unacceptable for the regulators or could only be used at a very small part of the mine (Canty and Everett 1999; Hause and Willison 1986; Jenk et al. 2005).

A prerequisite for successful *in-situ* treatment is a thorough understanding of the hydrodynamic conditions in the flooded underground mine. As has been shown by the published *in-situ*-treatment projects, most of the failures occurred because the mine water did not reach the point of alkalinity injection (either as fly ash, lime, or sodium hydroxide). Even where tracer tests were conducted prior to the alkalinity injection, the results of the *in-situ* treatment were not always satisfying on a long-term basis (Aljoe and Hawkins 1993). In fact, 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.

Tracer tests are well established in ground water studies where they are commonly used to investigate the hydraulic parameters or interconnections of ground water flow (Käß 1998). Most of the techniques used are well described and depending on the aims of the tracer test and the hydrological situation a range of tracers or methods can be chosen. Published results of tracer tests in abandoned underground mines are not common, as already stated by Davis (1994). Therefore, in mine water tracing, less experience exists and the expected results of an individual mine water tracer tests could not always been reached. Summarized, the aims of mine water tracer tests are as follows:

- Testing the bulkheads' (dams') effectiveness
- Investigating the hydrodynamic conditions
- Tracing connections between mine and surface
- Clarifying water inundations

- Mass flow
- Estimate the decrease or increase of contaminants

Historically, the first tracer tests conducted in mines were simply to reveal connections between ground or surface waters and the mine (e.g. Skowronek and Zmij 1977). One of the first tracer tests in a deep flooded underground mine to investigate the more complex hydrodynamic conditions of the flooded mine was conducted in 1995 (Wolkersdorfer 1996).

During the past decade the author has conducted nine tracer tests in abandoned and flooded underground mines with the aim of improving the tracer techniques for underground mines and to understand the hydrodynamic regime of such hydrogeological systems (Wolkersdorfer 2002; Wolkersdorfer 2005b; Wolkersdorfer et al. 2002a). It became clear that from a hydrodynamic point of view there are two different types of mines. The first type can be considered the multiple-shaft mines (MSM) and the second, single-shaft mines (SSM); however, as will become clear, these designations do not necessarily mean, that *more* than two or really *just* one shaft exists (Fig. 1). Because mines usually have a limited number of discharge points or pump sumps, the flow direction of the tracer is usually known before a mine water tracer test is conducted (yet, in the case of the Straßberg/Harz tracer test the mine operator thought the tracer would flow into another direction, but because all potential discharge points were included in the sampling programme, all the injected tracers could be found).

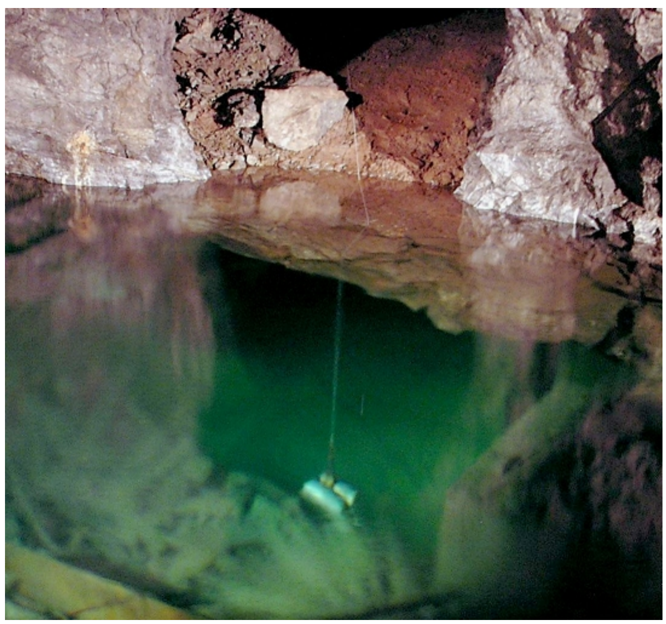

Figure 1. Felsendome Rabenstein/Germany tracer test with the open tracer probe hanging above the flooded inline drift to the 3rd and 4th working levels. The green cloudily colour comes from the Na-fluorescein (250 g)

This paper summarizes the results of different mine water tracer tests conducted during the last decade and draws conclusions from the main points of those tests. Furthermore it is assumed that the reader has a basic knowledge about tracer tests in general. Therefore, the detailed methodology, investigations and results of the single tests will not be described here. Instead, a synopsis of the key findings will be given and such it shall become clear why mine water tracer tests are a necessary tool to support any remediation procedures. To understand the flow in flooded mines a short introduction to the different possible flow scenarios in a flooded underground mine is provided as well.

Acid mine drainage and At-source Control

Mine drainage is one of the great sources of surface and underground water pollution (ERMITE Consortium et al. 2004); the term "mine drainage" includes all types of polluted water emanating from mine sites, including water that is acidic or alkaline and water that contains elevated levels of metals or sediment. Because the four basic equations commonly cited to describe the formation of acid mine drainage and the consequences of that process can be found in nearly every paper about the subject, they will not be repeated here. Instead, the interested reader is referred to any other paper about acid mine drainage in this volume or to one of the excellent descriptions of the process in the literature (e.g. Stumm and Morgan 1996, Nordstrom 2003).

As pyrite is oxidized, the pH of mine water is lowered; the acidity (base capacity) increases and many minerals dissolve. As a result, the biodiversity is decreased downstream, though some rare species are favoured by the new conditions (Johnson 2003; Batty 2005). The polluted mine water causes a threat to the environment and the regulators – and they are perfectly right to do so – ask for immediate action to reduce the concentrations or loads of the contaminants. Everybody working in the mine water field knows about the basic mine water treatment options (Walton-Day 2003), which can be summarized as being both expensive and labour intensive. Though researchers have tried to improve the effectiveness of active and passive mine water treatment we are still far away from economic, reliable, or walk-away options.

One option to reduce the pollutant load discharging from flooded underground mines is to retain the polluted mine water within the mine. In many cases, the oxygen-depleted conditions of a flooded underground mine reduce the pollutant load significantly, as the first reaction step of the di-sulfide weathering is brought to a halt or at least hindered (Fernández-Rubio et al. 1987). A key concern is if this process can be optimized by *in-situ* techniques or if *in-situ* treatment procedures could be applied to treat the mine water close to its source. Such procedures have been attempted in the past (e.g. Fytas and Bousquet 2002, Houston et al. 2005), but without trying to understand the hydrodynamic regime governing the flow of the mine water in the flooded mine workings. If the flow and its response to *in-situ* treatment options were known more precisely, *in-situ* treatment options could be used more efficiently than to date.

Tracers and Tracer Tests in Underground Mines

Most tracers commonly used for tracing ground or surface waters are unsuitable for conditions in an underground mine (Wolkersdorfer 1996), because they are unstable under acidic conditions or where strong oxidants are abundant (Käß 1998). Furthermore, if multiple tracer tests have to be conducted or a tracer test repeated, only a limited number of tracers can be used and those tracers usually are labour intensive and therefore expensive. Finally, most attempts to conduct tracer tests in underground mines injected the tracer at the surface of a mine pool or at a place or depth that was not exactly pre-determined (for a review of such tests, see Wolkersdorfer 2002). Because mines are – from a hydraulic point of view – quasi-karst systems with a triple porosity (the term mine aquifer should be used in addition to porous, fracture, and karst aquifer), techniques established in the karst aquifer research should be used.

Furthermore, to understand the upward or downward flow of the mine water, tracers must be injected into the mine water body at different depths and different locations. The techniques for doing so have been established in the recent years and proved to be suitable for the rough conditions in an underground mine. It is now possible to trace flooded underground mines with up to 6 different tracers at different locations and depths in a multi-tracer approach (Wolkersdorfer and Hasche 2004). In the past, *Lycopodium clavatum* (club moss) spores proved to be a suitable tracer for underground mines, but microspheres provided even better results if a multi-tracer approach is to be used. Yet, because the concentration of the microspheres is usually very low, the tracer has to be concentrated in filter nets (Fig. 2; Wolkersdorfer et al. 1997a; Wolkersdorfer et al. 1997b; Feldtner and Wolkersdorfer 1998). Microspheres are colloidal tracers that are chemically stable in the mine water environment and have also been applied in ground water tracer studies (Fig. 3; Harvey and Harms 2002, Niehren et al. 1995). The microspheres used in mine water tracing are small particles made of polystyrene, stained with fluorescent dyes and with a diameter of 15…30 µm. Because they are produced in up to 8 different colours they could theoretically be injected at up to 8 different locations during one single tracer test. Yet, due to spectral overlaps, only 6 tracers can be used at the same time.

Figure 2. Sampling equipment (Multiple Filter Storage Tool: MeFiSTo) for a multi-tracer test with microspheres including flow-meter and electronic control device.

Figure 3. Bottle of 15µm microspheres used as a tracer for mine water investigations.

Hydrodynamics of Flooded Underground Mines – A short Introduction

This paragraph will give a short introduction on the types of flow that can occur in flooded vertical, horizontal or cave-like mine voids (shafts, inclines; adits, galleries; stopes). Because the subject of non-Darcy flow, especially when it comes to convective flow, is very complex, some basic hydrodynamic understandings will be required. Detailed descriptions of the theoretical hydrodynamic background can be found in the relevant literature (e.g. Gebhart et al. (1988), Landau and Lifschitz (1991), Batchelor (2000), Oertel (2001), Drazin (2002), and many others).

Three different types of non-Darcy flow or combinations of them might occur within the open voids of flooded underground mines: laminar or turbulent Poiseuille flow, laminar or turbulent convective flow, or more or less no flow (except Brown molecular forces or diffusion). Free convective flow in vertical enclosures only occurs in systems, where the Rayleigh number Ra is larger than the critical Rayleigh number Ra_{kr} (Landau and Lifschitz 1991).

Furthermore, the flow regime might be characterized by free flow (buoyancy driven, also called natural flow) or forced flow. Free flow establishes, when the density differences $\Delta\rho$ within the fluid are the only driving forces of the flow, while forced flow establishes, when external forces cause the fluid to flow. However, free and forced flow does not exclude each other and in many cases of practical interest both effects are of significant magnitude (Gebhart et al. 1988). Such cases, with both flow characteristics involved, are called mixed convection flow.

In the case of flooded underground mines it must be assumed, that all combinations of the above listed flow types exist at the same time. Changes of flow type might occur within short distances and short time intervals, too. Even if Darcy flow in flooded mines is of minor importance, such flow characteristics will occur wherever the water flows through backfill, downfall, or goaf material (the latter case was numerically modeled by Jäger et al. 1990).

Besides the channel flow within the voids, fracture and porous flow through the rock matrix occurs as soon as all the voids are filled with water (Norton and Knapp 1977, Jäger et al. 1990, Wolkersdorfer 1996). The rock permeability decreases with the mine's depth (Nordstrom et al. 1989, Wolkersdorfer 1996) and also depends on the thickness of the disaggregation zones around the voids ranging between 0 and 3 m with maxima of 8 m (Müller-Salzburg 1978, Militzer et al. 1986, Jacobi and Everling 1981, Stoll and Bauer 1991). Whilst those fractured zones, where the water-rock interactions occur, are important for the chemical composition of the mine water, they are of minor importance for the flow within the voids. Reasons for forced flow within flooded mines can also be as the result of wrongly calculated wear heights for controlling the water flow within adjacent mine parts. Water levels in a pipe system are only similar in those cases, where the density in the water body is similar, too.

Wolkersdorfer (1996), Kolitsch et al. (2001), and Johnson and Younger (2002) conducted *in-situ* measurements of mine water velocities in flooded shafts, where they observed characteristic oscillations of velocity and temperature. Such oscillations with extremely irregular and unsystematic temporal variation in velocity and temperature are characteristic for a developed turbulent flow regime with high Reynolds or Rayleigh numbers Re and Ra (Landau and Lifschitz 1991). Bau and Torrance (1981a, 1981b, and 1983) studied open and closed fluid loops, which can be compared to the situation in flooded underground mines with two or more shafts. They found out, that those systems, when turning turbulent, are of chaotic nature and that the flow starts depending on critical heating situations and values as well as perturbations and eventually can reverse. Furthermore, they concluded that "free convection loops provide a means for circulating fluid without the use of pumps" (Bau and Torrance 1981b); this chapter is based on the author's habilitation thesis which will be published in 2006).

Summarized Results

Results and conclusions from tracer tests

The first mine water tracer test in which tracers were placed into predefined depths of a flooded mine shaft was conducted in the abandoned Niederschlema/Alberoda U mine (Wolkersdorfer 2001). The mine consists of about 50 working levels, 50 shafts and a total volume of 36 · 10^6 m³. Interestingly, the effective velocities were significantly higher than calculated from the pumping rates at the time of the tracer test. Based on the pumping rate and a laminar plane Poiseuille flow (Landau and Lifschitz 1991; better known as "piston flow") approximation, the breakthrough was expected 10—14 days after tracer injection. In fact, the tracers appeared only one day after their injection revealing a mean effective velocity of 6—8 m min^{-1} (Wolkersdorfer et al. 1997a). Similar results were obtained at the abandoned Straßberg/Harz fluorspar mine with 3 main shafts, 9 working levels and a total volume of about 277,050 m³. Again, the breakthrough in the main shaft (Fluor-Schacht) was expected 7—10 days after tracer injection but the tracer breakthrough appeared after 1—2 days indicating a maximal mean effective velocity of 0.2—0.3 m min^{-1} (Wolkersdorfer and Hasche (2001); Fig. 4).

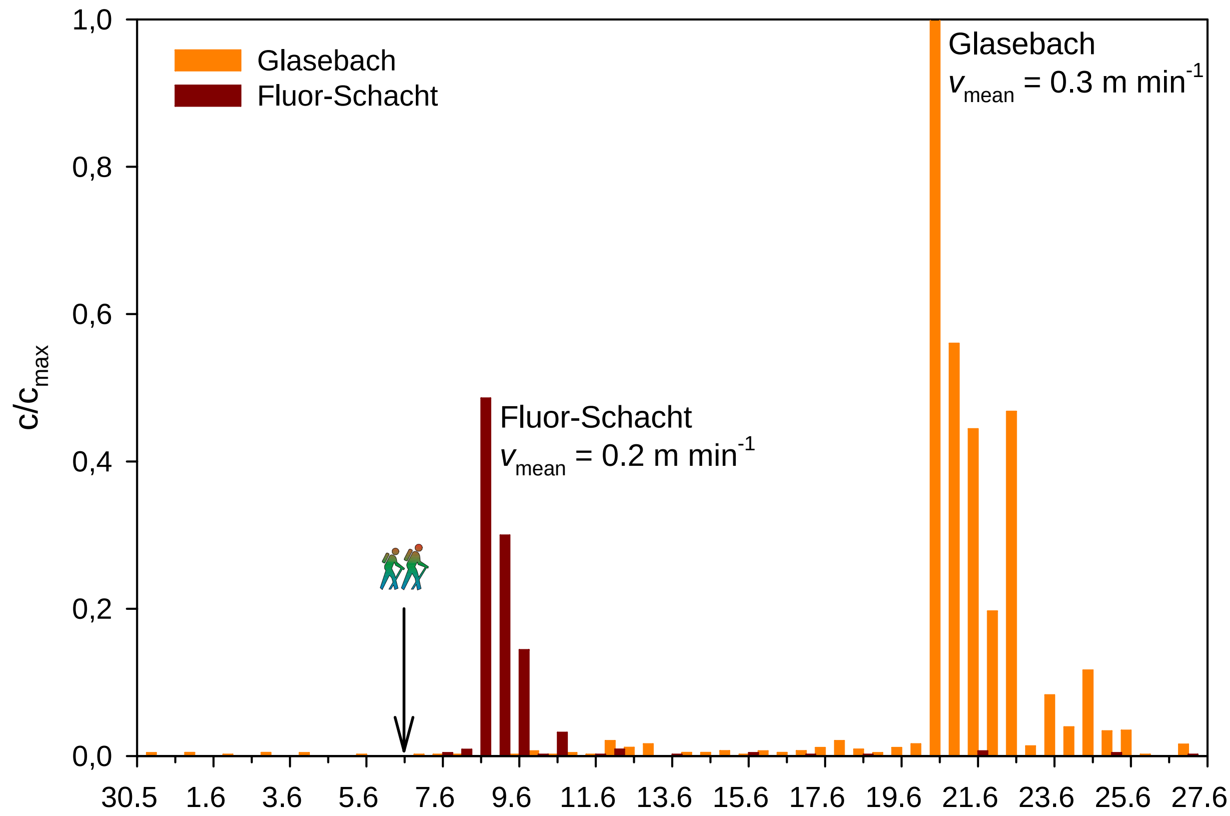

Figure 4. Breakthrough curve of the tracer test with microspheres in the abandoned Straßberg/Harz fluorspar mine (Saxony-Anhalt/Germany), which belongs to the MSM type.

Both mines had many interconnected levels and shafts, and great depth. We therefore concluded that mines with many shafts and levels tend to high effective velocities within the interconnected mine workings and suggested that mines with only one or two shafts and a less intensive connection of the mine workings should have lower effective velocities. Therefore, tracer tests were conducted in the abandoned Georgi Unterbau Ag mine (Tyrol), the abandoned Felsendome Rabenstein limestone mine (Saxony) and the abandoned Ehrenfriedersdorf Sn mine in Saxony (Wolkersdorfer et al. 2002b; Wolkersdorfer 2005a; details of the latter two are unpublished). Whereas the Georgi Unterbau and the Felsendome Rabenstein mines consist of only one or two shafts, the Ehrenfriedersdorf mine belongs to the MSM type. Again, in all three cases, a laminar plane Poiseuille flow approximation was used to estimate the breakthrough of the tracer. For the Georgi Unterbau and the Ehrenfriedersdorf mine, the time of breakthrough was again overestimated by a factor of 5—10, whereas in the Felsendome Rabenstein case, it

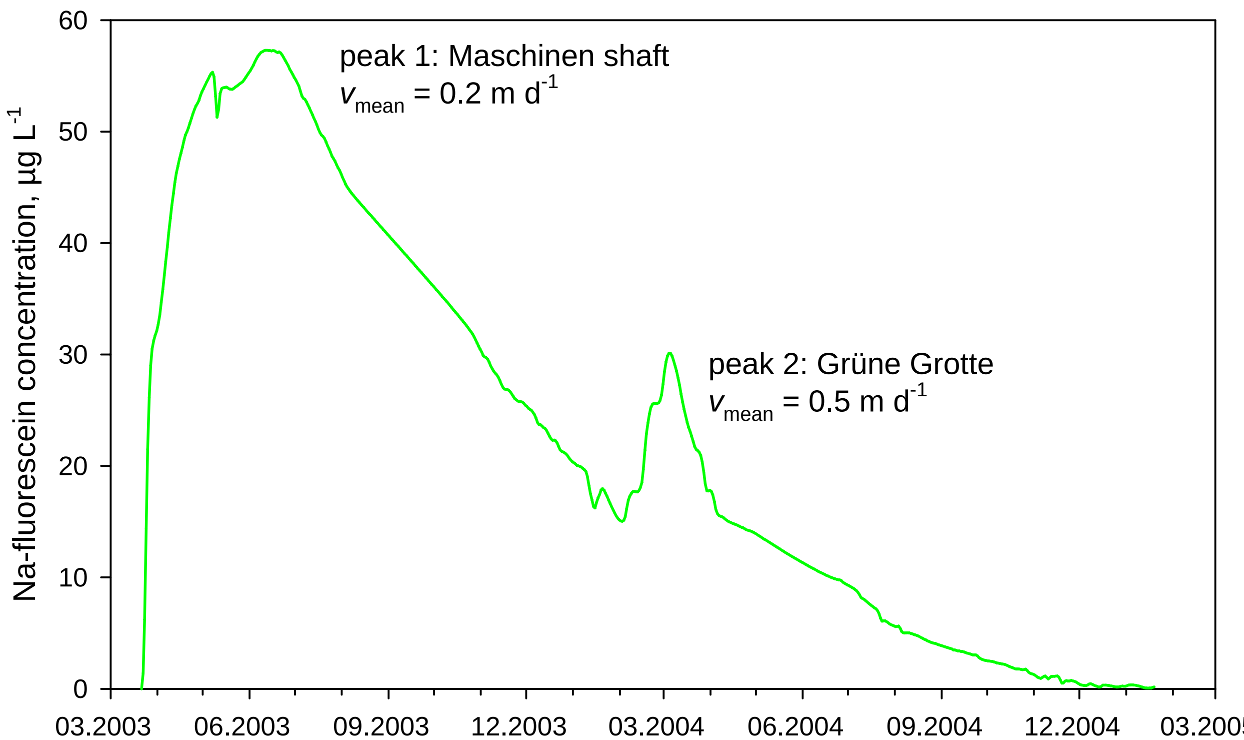

Figure 5. Breakthrough curve of the Na-fluorescein tracer test in the abandoned Felsendome Rabenstein limestone mine (Saxony). 3-min sample interval interpolated to 1 day interval. The mine belongs to the SSM type.

was underestimated by a factor of 2—8; instead of three months, the tracer needed 22 months for complete breakthrough, the longest duration of a tracer test known so far for an underground mine (Fig. 5).

The tracer tests described in the previous paragraph proved the hypothesis that there is a significant difference in the flow velocities of multiple and single shaft mines: MSMs tend to have a fast free or forced convective mixing of the mine water and consequently the pollutants are transported quickly from the investigated mine parts into the anthroposphere (that means the receiving water course). In contrast SSMs are either dominated by diffuse flow or by low levels of free or forced convective flow and low mean effective velocities. In MSMs, the tracers were quickly transported out of the mine and the tail of the breakthrough curve was small, revealing a high Peclet number (Käß 1998) while the SSMs had a long breakthrough curve tail, indicating smaller Peclet numbers. The Peclet number is related to the dispersion coefficient: MSMs have a small dispersion coefficient whereas SSMs have higher dispersion coefficients. Consequently the pollutants in MSMs compared to SSMs are transported faster from the mine into the anthroposphere.

Implications for future remediation strategies

Mine water in MSMs have high effective velocities (above 1 m min^{-1}), whereas mine water in SSMs have lower effective velocities, usually below 1 m min^{-1}. This fact can be used to plan remediation strategies after mine closure. If treatment is to be conducted at an active treatment plant and the duration of the first flush (Younger 2000) shall be relatively short, MSM conditions should be aimed at. However, even so, if locations with elevated concentrations of potentially dangerous metals are known, they should be sealed prior to flooding. This can be achieved by constructing dams or by backfilling those areas with hydraulic backfill.

On the other hand, if passive treatment options are to be implemented after the mine has been fully flooded, it is advisable to establish SSM conditions in the underground mine prior to flooding. Such conditions can be achieved by sealing or grouting shafts, main galleries or other interconnected mine workings. Even if the sealing is not 100 %, the mean effective velocities will be significantly reduced and the discharged annual pollution load and especially the contaminant concentrations can be minimized. To find the appropriate seal location, tracer tests can be used to calibrate the numerical models and shape the decision-making process.

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