Hydrodynamic Investigations in the Abandoned Havelock Asbestos Mine, Eswatini, by Means of Tracer Tests

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Abstract

Understanding the hydrodynamics of flooded underground mines is important for assessing residence times, hydraulic connectivity and the movement of dissolved constituents within abandoned mine systems. This paper presents the results of four artificial tracer tests conducted in the flooded Havelock Asbestos Mine near Bulembu, eSwatini. The tests were designed to investigate flow paths, travel times and the degree of hydraulic connection between selected injection points and the mine water discharge. Sodium chloride (NaCl), sodium fluorescein (uranine) and eosin y were used as tracers, and monitoring was undertaken by continuous electrical conductivity (EC) measurements and field fluorometry at the discharge point. The NaCl test did not produce a usable breakthrough curve, which is attributed to the comparatively low tracer mass, the elevated background EC and probable downward movement of the denser tracer into deeper parts of the flooded workings. In contrast, the uranine tests yielded clear breakthrough curves with first arrivals after approximately 1.0 to 1.5 days over distances of 1.1 to 1.4 km. Mean residence times ranged from about 8 to 9 days, and maximum flow velocities ranged between 0.6 and 1.3 m/min. Eosin y was not detected. The results indicate that substantial parts of the flooded mine are hydraulically well connected and that fluorescent dye tracer tests are a suitable method for hydrodynamic investigations in abandoned underground mines.

Keywords: Abandoned mine, asbestos mine, tracer test, uranine, eosin y, hydrodynamics, eSwatini

Introduction

Flooded underground mines are hydraulically complex and evolving subsurface systems rather than static underground reservoirs (Wolkersdorfer 2008; Younger *et al.* 2002). Even after mining has ceased, the voids, stopes, drives, winzes and raises of the mine, as well as fractures, may remain hydraulically connected over long distances (Wolkersdorfer 2008). These flow patterns determine the length of time that water remains in the mine, its contact with reactive rock surfaces, the distribution of dissolved constituents and ultimately the quality and quantity of water discharged from the flooded mine pool (Mugova *et al.* 2024).

Therefore, hydrodynamic investigations form a central part of mine water studies. However, compared to hydrochemical sampling and water level monitoring, direct hydraulic investigations in abandoned mines are still relatively rare. Among the available methods, tracer tests are one of the most robust tools for identifying flow paths, estimating mean residence times and assessing hydraulic connectivity. In flooded mines, however, tracer tests are far from trivial. Density stratification, inaccessible injection points, uncertain flow geometry, tracer losses and restricted access to discharge points can all complicate the design of the test and interpretation of the results. The overall intention of the mine water tracer tests described here was to provide additional background data for the question of whether underground mines can be modified such that artificial density stratification occurs, which can then be used for in situ mine water remediation (Melchers *et al.* 2015; Mugova and Wolkersdorfer 2025; Wolkersdorfer 2025).

The abandoned Havelock Asbestos Mine near Bulembu in eSwatini offered a rare opportunity to investigate hydrodynamic processes in an environmentally relevant and logistically challenging flooded mine system. This mine is interesting because it is an abandoned asbestos mine, the mine workings are flooded and mine water discharge from the system may affect the quality of water downstream (Wolkersdorfer *et al.* 2025). As the mine water composition is similar at the point of discharge and a distant location in the mine pool (10E service raise), it was of interest if this results from a hydraulic connection. Furthermore, understanding how mining influenced water (MIW) moves through the mine is crucial for any future considerations regarding flow control, water level management or potential in situ treatment options in flooded underground mines in general.

This paper presents the results of artificial tracer tests conducted at the Havelock mine using sodium chloride (NaCl), sodium fluorescein (uranine) and eosin y. The main objectives were to evaluate if hydraulically distant parts of the mine are connected, to estimate travel times and flow velocities and to identify whether injection locations and tracer type influence the observed breakthrough behaviour. Particular attention was given to whether mine water flow follows a topographic gradient or whether flooded workings also permit counterintuitive flow directions.

Site Background

The Havelock Asbestos Mine, located in eSwatini (Barton 1986; Hall 1931), is one of the country's best-studied abandoned mine sites. Following its closure in 2001, parts of the underground workings flooded to form a hydraulically connected body of mine water with a volume of 8–11 million m^3. The mine's geometry is complex and includes various access points, including an incline shaft and a main vertical shaft. The horizontal projection of the spatial separation between the injection and sampling points is around 1.1 to 1.4 km (Wolkersdorfer *et al.* 2025).

As with many abandoned underground mines, the Havelock mine cannot be treated as a simple pipe system. The actual flow field in the mine pool is instead controlled by the mine's geometry, partial collapses, local constrictions, flooded stopes, possible density differences and the hydraulic gradients prevailing between connected mine sectors and discharge points. In such a system, assumptions based on maps alone can be misleading. Direct tracer-based evidence is therefore required to identify flow paths (Mugova and Wolkersdorfer 2022; Wolkersdorfer 2002, 2008; Younger *et al.* 2002).

Another complicating factor is that the flooded mine likely contains bodies of water with different hydraulic behaviour at different depths. Previous measurements were inconclusive in this regard, which became one reason for selecting two different injection locations in the mine pool. One tracer (eosin y) was introduced to the surface of the mine water via access through an incline shaft (10 E). The other tracer (uranine) was injected through the main vertical shaft (HVS) into the mine water body at a depth of 107 m below shaft collar (Fig. 1), enabling an initial assessment of the effect of injection position within the water column on the subsequent tracer response.

Materials and Methods

Four separate tracer tests were conducted, each using a different tracer substance, mass combination or injection configuration. One of the reasons for repeating the tracer test was that the tracer breakthrough took more time than the battery in the online fluorimeter lasted or that a tracer could not be detected. No pH adjustment of the MIW was applied, as online detection of fluorescent dyes in the MIW discharge does not permit such a procedure. However, as the pH of the MIW is between 8.6 and 8.7, the recovery of the uranine and eosin y signals would theoretically exceed 100% anyway (Cao *et al.* 2017).

The first test used 2 kg of NaCl as an artificial tracer. The advantages of salt are that it is inexpensive, readily available and easy to detect using electrical conductivity EC (Käß 1998; Leibundgut *et al.* 2009). However, in large, flooded mine pools, substantial quantities of the tracer are often required, particularly where background EC is already high or dilution volumes are large (Wolkersdorfer 1996).

The second test used 503.55 g of uranine injected into the Havelock vertical shaft. This well-established fluorescent dye has been used successfully in surface water, karst and mine water studies and is particularly suited to systems with large dilution volumes due to its low detection limit (Aley *et al.* 2025; Goldscheider and Drew 2007; Käß 1998; Leibundgut *et al.* 2009).

The third test combined 1 kg of uranine and 1 kg of eosin y to test two fluorescent tracers simultaneously and obtain additional information on flow behaviour from different injection locations. One tracer was introduced via the 10E incline shaft onto the surface of the mine water at location 5A, while the second tracer was injected through the main vertical shaft to the mine water surface at a depth of 107 m below shaft collar.

In the fourth test, the same configuration as in test three was used except that the tracer masses were increased to 3,020.09 and 5,026.81 g for uranine and eosin y, respectively. At the underground injection location 10E, the injection was moved 25 m to the south of 5A, into a West–East drift that is better connected to the mine pool.

Figure 1 *Injection (HVS, 10E) and sampling location (HMD) for the tracers at the Havelock asbestos mine. Mine map overlay from Archive Bulembu Mining Museum, base map World Imagery 1.9cm Resolution Metadata.*

Tracer monitoring focused on the only accessible discharge location of the mine, south of the asbestos tailings. Continuous on-site fluorometry (GGUN FL-30, Albillia, Switzerland) was used to establish breakthrough curves for the fluorescent tracers (Lemke *et al.* 2013). For the salt test, EC measurements (van Essen CTD Diver, Netherlands) were used to identify any increase in tracer-related EC values above background levels. Travel times were derived from the time of the first detectable arrival and the mean residence time of the recovered tracer signal. Maximum flow velocities were then estimated by relating the horizontal flow distance of 1.1–1.4 km to the observed travel times using QTRACER2 (Field 2002).

Tracer recovery was calculated from the monitored tracer concentrations. As with all tracer tests, these recovery rates must be interpreted with caution because they are influenced by analytical precision, incomplete mixing in the mine pool, temporary storage in stagnant zones, sorption and uncertainties in the measured discharge volumes.

Results

Sodium chloride test

The NaCl tracer test did not result in a usable breakthrough curve. This was because no tracer response could be distinguished from the natural EC variability, though an increase of about 50 µS/cm would have been expected. There are several possible explanations for this outcome: Firstly, the amount of tracer used may have been insufficient for the size of the flooded mine and the resulting dilution. Secondly, the salt may have sunk into deeper parts of the mine pool and thus not reached the point of discharge within the observation period. Thirdly, the monitoring period may have been too short to detect a delayed response. In the flooded Havelock mine with its complex void geometry, all three explanations are plausible, and they are not mutually exclusive. Based on the uranine tracer results, the most likely explanations are insufficient tracer mass and sinking of the tracer into deeper parts of the Havelock vertical shaft.

Fluorescent dye tests

In contrast to the salt test, the fluorescent dye tracer tests were successful (Fig. 2). Uranine was clearly detected at the monitoring location in all investigations using fluorescent tracers. The first arrivals appeared after approximately 1–1.5 days. This comparatively rapid response time for a flooded underground mine over the given travel distance already indicates a good hydraulic connection between the injection and the sampling locations.

The calculated mean residence times ranged between 8 and 9 days. Despite the rapid initial arrival after one day, these values

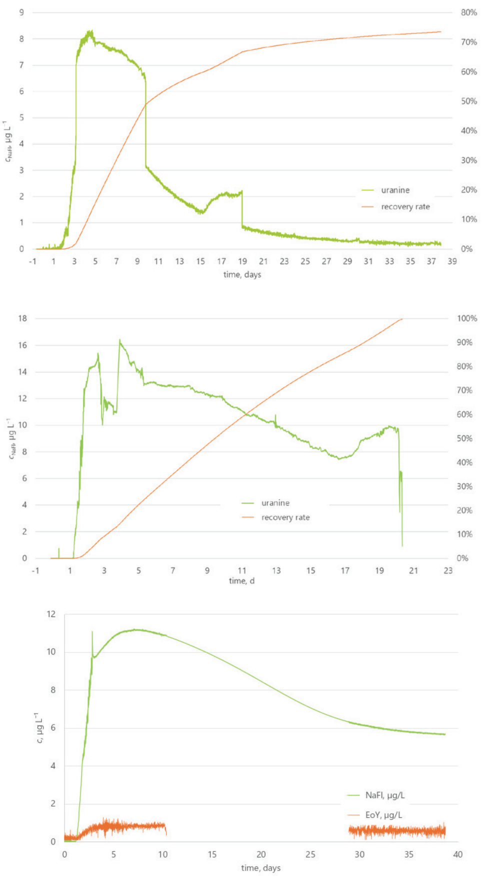

Figure 2 Results of the 2023, 2024 and 2026 dye tracer tests at the Havelock mine, eSwatini (missing 2026 data interpolated).

show that the tracer remained in the flooded mine for a much longer period. This is typical for a mine with a combination of preferential pathways and slower exchange with less mobile zones in stopes or other galleries.

Recovery rates were high, though the battery of the data logger only lasted for about 4 to 6 weeks. The 2023 investigation yielded a recovery rate of 74%, while the 2024 investigation yielded one of 99%. At the time of writing this paper, the 4th test was not finished. These values suggest that the monitored discharge point captured most of the tracer mass during the observation period of the fluorescent tests. They also support the interpretation that the mine levels, stopes and drifts involved in the test were hydraulically well connected.

Maximum flow velocities between 0.6 and 1.3 m/min were calculated for the uranine tracer on the basis of the horizontal distance of 1.1 to 1.4 km and the observed arrival characteristics. The average flow velocity was around 0.1 m/min. This is close to the worldwide median flow velocity of 0.15 m/min reported for flooded underground mines, placing the Havelock results well within the range observed elsewhere.

No eosin y was detected during the four-week observation period of the second test and none in the first weeks of the 4th tracer test. This result may indicate that the tracer followed a different flow path, remained in a less mobile part of the mine, underwent stronger retardation or attenuation, or that the injection point was hydraulically less well connected to the monitored discharge. The absence of an eosin y signal despite successful uranine detection therefore suggests that the vertical position of the injection point and the local hydraulic setting can strongly influence tracer behaviour.

Discussion

The Havelock tracer tests show that the flooded mine workings are well connected hydraulically over distances exceeding one kilometre. This is an important finding in itself, as mine maps and topographic gradients often suggest a simpler hydraulic picture than is present. At Havelock, dye tracer tests demonstrated that water could move rapidly through the mine, showing that the effective hydraulic connection between distant mine locations is stronger than one might assume from the geometry alone.

It could be shown that mine water can flow both downstream and upstream within flooded mine workings. This does not contradict hydraulic principles. Rather, it reflects the fact that, in abandoned mines, the flow field is governed by local hydraulic heads, submerged connections, internal mine geometry, and density-related effects. In practice, this means that contaminants released in one part of the mine may flow in unexpected directions. For mine water management, this is a relevant consideration.

The contrast between the unsuccessful salt tracer test and the successful dye tracer tests highlights a methodological point. In large, flooded mine systems with not too acidic mine water, fluorescent dyes are generally preferable to salt tracers when dilution volumes are uncertain and only a few observation points are accessible. Their low detection limits make them more robust under such conditions. At the same time, the failure of the salt tracer test should not simply be viewed as a failure of field execution. It highlights the complexity of the system and the need to carefully adapt tracer choice to site-specific hydraulic conditions.

The non-detection of eosin y in test two is also informative. This suggests that not every injection point within the mine accesses the same active flow domain. This observation is consistent with layered or compartmentalised flow behaviour and may also indicate partial stratification or weak hydraulic exchange between different depths (Wolkersdorfer *et al.* 2007a, 2007b). Since this part of the Havelock mine is not fully accessible, no specific reasons could be determined. Previous studies of other flooded mines have shown that even minor density variations can affect vertical exchange, tracer dispersion and residence time behaviour. The Havelock results fit well within this broader understanding, even though the studies were not primarily designed as a density stratification experiment.

From an applied perspective, the Havelock tracer test results support the view that open discharge adits and controlled discharge points are essential for maintaining a stable mine water level. If such outlets become blocked or restricted, however, water levels may rise and previously disconnected mine sectors may become activated, resulting in unwanted flooding of built-up areas. In this sense, the tracer results are not merely of academic interest. They provide a hydraulic basis for practical mine water management decisions at abandoned mine sites.

Conclusions

The tracer tests at the abandoned Havelock asbestos mine yielded several conclusions:

The study demonstrated that fluorescent dye tracer tests can be successfully conducted in a flooded, abandoned asbestos mine despite the logistical constraints at Havelock. We found no published record of an earlier fluorescent dye tracer test in eSwatini or in an asbestos mine. In addition, the mine workings were found to be hydraulically well connected over distances of 1.1 to 1.4 km. Uranine arrived within 1–1.5 days, with mean residence times of 8–9 days. Maximum flow velocities ranged from 0.6 to 1.3 m/min, averaging about 0.1 m/min. Furthermore, the unsuccessful NaCl test and the successful dye tests demonstrate the importance of tracer selection. For large, flooded mine pools with an uncertain dilution behaviour, fluorescent tracers are clearly preferable. Furthermore, the absence of detectable eosin y during the four-week monitoring period suggests that different injection points within the mine may access distinct hydraulic domains. This suggests internal complexity within the flooded workings, which reflects variable connectivity at different depths.

Finally, the tests confirm that mine water in flooded workings can flow in directions that cannot be predicted based on surface topography alone. Rather, it is important to identify the points of discharge with the lowest hydraulic potential. This has direct consequences for interpreting contaminant transport, hydraulic control measures, and the management of abandoned mine discharges. The Havelock results therefore provide both site-specific knowledge and broader methodological insights for hydrodynamic investigations in flooded underground mines.

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