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Assessing subsurface flow hydraulics of a coal mine water bioremediation system using a multi-tracer approach☆

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ABSTRACT

Understanding the hydraulic behaviour of subsurface flow bioremediation systems is a pre-requisite for characterising their biogeochemical functioning, yet it is often overlooked. Using multiple tracers in parallel, considerable hydraulic insight can be gained. A quantitative multi-tracer test was conducted at a passive coal mine water bioremediation system in the UK (Bowden Close Colliery, County Durham) to assess its hydraulic behaviour. Four tracers were used: bromide (Br^-), uranine (Na-fluorescein), lithium (Li^+) and NaCl. The system comprises two parallel treatment streams: one receiving 30–50 L min^{-1} of moderately acidic adit drainage and the other one 90–110 L min^{-1} of strongly acidic spoil leachate. Each of these treatment streams has a separate 'RAPS unit' (Reducing and Alkalinity Producing System) and their effluents are eventually mixed in a single aerobic wetland. The RAPS units are downward-flow porous media with mixed substrates of limestone gravels and compost; RAPS I has a surface area of 1511 m^2 and RAPS II 1124 m^2. The aerobic wetland (990 m^2) is a basin of mineral soil planted with *Typha latifolia* and a shallow (15–50 cm) water level. For the two RAPS units, residence times of 4–5 d and effective velocities of 0.7–0.9 m h^{-1} were deduced. In terms of tracer performance, in contrast to earlier findings, bromide and Na-fluorescein tracers were applied successfully, while NaCl and lithium were found to be least useful, particularly during dilution events caused by intense rainfall.

1. Introduction

Post mining management at sites where no former owner can be held responsible for remediation requires durable low cost solutions. A number of such solutions have been proposed in the past (Brown et al., 2002; Hedin et al., 1994; Younger et al., 2002) and successfully implemented at abandoned mine sites throughout the world. Besides the most commonly applied constructed aerobic and anaerobic wetlands, the technology of RAPS (Reducing and Alkalinity Producing System) is getting more and more attention since its first introduction in the 1990s by Kepler and McCleary (1994). These three types of systems have in common that they are porous media based and their treatment efficiency largely depends on the mean residence time of the mine water in the substrate.

Typically, the design of these porous media treatment systems for polluted waters is based on 'nominal residence times' ('first-order-residence times'), calculated simply from porosities and flow rates (e.g. Langergraber, 2008; PIRAMID Consortium, 2003; Watzlaf et al., 2000). Yet, the problem with this approach is that it assumes piston flow (i.e. plug flow), completely neglecting short cuts within the system or flow retardation and mixing of waters with different residence times resulting in advection-dispersion flow. Kadlec (2000) pointed out the shortcomings of this simple approach and provided solutions to that issue using an example treatment wetland. Younger and Henderson (2014) indicated that the overall removal rate depends also on the hydraulic processes of a passive treatment system, and Persson et al. (1999) investigated the relationship between the pond shape and the system's hydraulic behaviour. They formulated the "hydraulic efficiency" λ (Eq. 5), a coefficient which indicates how efficiently the water flows through a constructed wetland, with $\lambda = 1$ designated to the most efficient flow.

Tracer tests offer one of the best options for obtaining more realistic information about the hydraulics (e.g. advection, dispersion, mixing, hydraulic efficiency) and residence times, with the ultimate goal of improving design criteria. General details about conducting and interpreting tracer tests are given by many scholarly books and papers and shall not be repeated here (e.g. Goldscheider and Drew, 2007; Käß, 1998; Leibundgut et al., 2009; Wolkersdorfer, 2008). Flury and Wai (2003) reviewed a large number of potential dye tracers for the

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☆ Earlier results of this investigation have been published in the 2005 proceedings of the "Berg- und Hüttenmännischer Tag" Freiberg/Sachsen, Germany (Wolkersdorfer et al., 2005).

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vadose zone, of which uranine was chosen for the test described here. In most cases, the cheapest tracer is the common salt NaCl (e.g. Diaz Goebes and Younger, 2004), although simply dosing large quantities of salt into a treatment system has a tendency to create pockets of brine. These density effects of injected tracers have been studied during several tracer tests and indicate that those higher density solutions can behave rather differently to the ambient waters (LeBlanc and Celia, 1991; Schmid et al., 2004). At the Tan y Garn RAPS in Wales, Watson et al. (2009) conducted a series of tracer tests with 0.5 kg of LiBr and 10–20 kg of NaCl with positive results for NaCl. Bromide is a tracer substance that is easy to detect at low concentrations and displays conservative (i.e. non-reactive) behaviour in most tracer test studies (Käß, 1998). It is a common constituent in natural and coal mining impacted water, but commonly has low background concentrations in those environments. Hem (1985) reports background concentrations of 5–150 μg/L in rainwater and LaPierre (1999) reported Br^- concentrations in the range of 50–220 μg/L in shallow and up to 6250 μg/L in deep coal mine waters. Successful applications of bromide as a tracer in wastewater treatment wetlands has already been reported by several authors with recovery rates between 16 and 96% (e.g. Keefe et al., 2004; Kruse et al., 2009; Kusin et al., 2012; Lin et al., 2003; Machate et al., 1998a; Małoszewski et al., 2006; Whitmer et al., 2000). Observed bromide losses might have been caused by plant uptake (Whitmer et al., 2000). Another tracer successfully used in subsurface flow constructed wetlands is lithium (King et al., 1997) and Cheong et al. (2011) used a green food dye for a RAPS tracer test. Although uranine (Na-fluorescein) is often assumed to be an unsuitable tracer for wetlands and similar systems because of its potential decomposition at low pH-conditions, microbial activity or photodecomposition (Behrens and Teichmann, 1982; Gutowski et al., 2015; Käß, 1998; Machate et al., 1998a, b; Sayer, 1991), some investigators reported comparatively good recoveries of 14–50% in constructed wetlands (Machate et al., 1998a; Netter and Behrens, 1992). Rigorous testing in an experimental subsurface flow passive system at Gernrode (Germany) also showed positive results for that tracer (Hasche and Wolkersdorfer, 2004).

The hypothesis for the investigations described here was that the above mentioned tracers can be used for passive subsurface mine water treatment systems and that the observed differences in the remedial effectiveness of the two systems might be explained by differences in the mean residence time in the RAPS units. Therefore, the main aim of the quantitative tracer test was to directly quantify the mean hydraulic residence times in the systems. Based on the results it should be possible for future systems to thoroughly quantify bioremediation processes in this type of passive mine water treatment systems. At the time of the multi-tracer test, no hydraulic investigations of the Bowden Close RAPS system had been conducted. Preliminary results of this multi-tracer test were reported earlier and will be updated and (as regards to flow calibration) partly revised in this paper (Wolkersdorfer et al., 2005).

2. Description of the location and the passive treatment system

Coal mining was one of the most important industrial activities in County Durham/England/UK until the end of the 20th century (Kruse and Younger, 2007) and the remnants of some 72 collieries can be found within a 5 km radius of the Bowden Close study site. The Bowden Close Colliery, located in the West Durham Coalfield, opened in the early 1840s (Fig. 1, coordinates: UTM ETRS 30 582820 6063940, UK national grid NZ 185 357) and is situated at an elevation of 130—140 m above sea level. Both, the Colliery and the associated coke works closed in the 1930s (Durham Mining Museum, 2016; Roy, 2002). Mining took place predominantly in the Carboniferous (Westphalian) Harvey to Main Coal seams of the Lower and Middle Coal Measures with sulphur contents between 0.8 and 3.6% and a mean of 1.9% (Durham Mining Museum, 2016; Fielding, 1982; Turner and Richardson, 2004). These coals where deposited in a fluvio-lacustrine dominated environment in the northern Pennine Basin which encountered frequent marine transgressions (Waters and Davies, 2006). One of the most prominent legacies of mining these coals are surface water bodies impacted by ochreous or acidic mine discharges which usually stain the rivers and brooks with unaesthetic red, yellow and brown precipitates (Kruse and Younger, 2007). These problems commonly prompt the authorities and communities to search for cheap and reliable remediation solutions (Younger, 1995), and a still increasingly favoured option for such abandoned mine discharges is passive mine water treatment (Parker, 2003; Ranson et al., 2000).

In the mid-1970s, Durham County Council reclaimed the mine site by demolishing derelict buildings, reshaping spoil heaps, emplacing top soil and re-vegetating the area (Roy, 2002; Younger, 2000). At that time no investigations of the mine spoil and underground workings were conducted and no measures were taken to minimise infiltration and through-flow of water through the spoil heaps. Hence, acidic metalliferous mine water began emanating from a number of points,

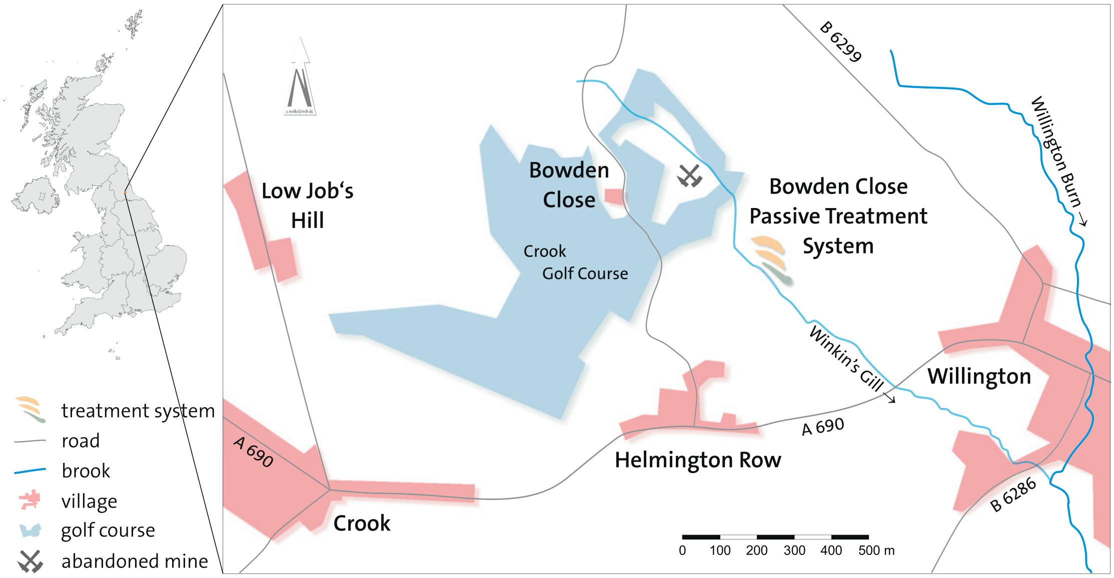

Fig. 1. Location of the Bowden Close mine water treatment system (UTM ETRS 30 582820 6063940, National Grid coordinates NZ 185 357).

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