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High-resolution profiling of the stable isotopes of water in unsaturated coal waste rock

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SUMMARY

Characterization of the rate of water migration through unsaturated mine waste rock dumps is an essential element in assessing the chemical loading from these landforms; yet our understanding of how water moves into, through and out of waste rock is incomplete. To further understand the rates and magnitude of percolation through waste rock, deep high-resolution (every 0.1–4.5 m) depth profiles of the stable isotopes of water (δ^2H and δ^{18}O) at two coal waste rock dumps and a natural alluvial deposit down-gradient of one of the dumps were collected in the Elk Valley, British Columbia, Canada. The profiles were generated using vapor equilibrium techniques applied to continuous core samples collected using dry sonic drilling methods. Elevated core temperatures (up to 80 °C) were measured during sonic coring. The isotopic values of pore waters measured in the core samples were corrected for water loss to the atmosphere attributed to the elevated core temperatures. The average isotopic composition of the core samples were compared to water collected from rock drains discharging from the base of the dumps. The results indicate that high-resolution profiles of δ^2H and δ^{18}O can be measured to depths of 86 m in coal waste rock dumps and, based on the seasonal cycles in the isotopic composition of recharging water, can be used to characterize the migration of recharge water within these dumps. These profiles also suggest that recharge into these dumps occurs from both rain as well as snow melt and may be as high as 400–600 mm/yr (60–75% of annual precipitation). Combined with the relatively low volumetric water contents of these dumps (5–10%) the rates of water migration through the dumps are tens of meters each year.

1. Introduction

Characterizing the volumes and rates of water migration through unsaturated mine waste rock dumps is foundational to an evaluation of chemical loading associated with the flushing of constituents of interest (CI) from these waste deposits. Few large-scale investigations of flow through mine waste overburden dumps have been conducted, and there has been limited success in relating the timing and volume of net percolation (recharge) to rates of water migration through the dump (Anterrieu et al., 2010; Azam et al., 2007; Nichol et al., 2005; Poisson et al., 2009).

Natural stable isotopes of water such as deuterium (^{2}H) and oxygen-18 (^{18}O) have been used as tracers to measure recharge and flow rates in natural profiles of deep unsaturated soil. The isotopic composition of infiltrating meteoric water varies seasonally (wetter vs. drier, colder vs. warmer) while remaining on a local meteoric water line (LMWL). These seasonal cycles in the stable isotope of water signature of infiltrating meteoric water have been used to track recharge (i.e. net percolation) in natural soil profiles (Adomako et al., 2010; Allison et al., 1994; Barnes and Allison, 1988; Gazis and Feng, 2004; Mathieu and Bariac, 1996). Yet the number of studies in which deep (>10 m) profiles of stable isotopes of water have been studied are limited (Bath et al., 1982; Cheng et al., 2014; DePaolo et al., 2004; Gaye and Edmunds, 1996).

There are two particular challenges associated with estimating net percolation rates from deep isotopic profiles: the first is the shift in the signature of recharging water relative to meteoric water as a result of surface evaporation (Allison, 1998; Barnes and Allison, 1988; Melayah et al., 1996) and the second is the loss (dampening) of the seasonal signal as water moves downward through the unsaturated soil profile (Bath et al., 1982). DePaolo et al. (2004) and Singleton et al. (2004) show that in semi-arid

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zones (i.e. high evaporation relative to net percolation) the stable isotope profile in finer textured soils (e.g. clayey silt and silty sand) may only propagate to depths of a few meters, after which the profile tends to become uniform with depth and shifted relative to meteoric water as a result of the fractionation by evaporation during dry seasons. However, in sandy soils under greater rates of net percolation (e.g. >200 mm/y) the seasonal cycles in the isotopic composition of infiltrating water are propagated to greater depths and without a significant (i.e. relative to analytical error) shift in the isotopic profile relative to meteoric water. Cook et al. (1992) and Bath et al. (1982) show that the seasonal fluctuations of isotopic signatures may propagate to great depths (and consequently are representative of sources of surface recharge over a greater time) if the recharge rates are high (>100–200 mm/y) and the volumetric water content within the profile is relatively low (e.g. 0.05–0.1). It is hypothesized that these restrictions are met during the recharge of meteoric waters into waste rock dumps in sub-humid regions of western Canada.

The other major challenge in applying the stable isotopes of water to trace net percolation in mining waste rock dumps is the assumption that flow through these deposits is dominated by preferential flow through the coarser rock and gravel which segregates from the finer matrix of sandy material during placement of the waste rock by dumping. For example, in waste rock dumps associated with coal mining in the Elk Valley of southern British Columbia, the focus of this paper, the predominant dump construction method is by end or push dumping. These methods tend to create particle segregation in which the largest particles (boulders) move to the base of the slope with a mixture of finer and coarse particles retained over much of the slope length (Morin et al., 1991). Piteau (1999) noted that for Elk Valley waste rock dump heights greater than 20 m, a coarse rubble zone is formed at the base of the dumps. The basal rubble zones act as 'rock drains', collecting water draining from the dump as well as water moving laterally into the dump from adjacent natural watersheds, and channeling this water to adjacent surface drainage (Lighthall et al., 1985). Textural breaks can also be created by the layers of coarser and finer material running parallel to the slope as illustrated for a gold mine waste rock dump by Azam et al. (2007). Similar breaks can also be formed as a result of compaction associated with trucks and dozers working along the top of dump surfaces.

It is often assumed that water migration through unsaturated mine waste rock is dominated by non-capillarity or macro-pore dominated water migration (Beven and Germann, 1982). There is, however, evidence that even relatively coarse textured soils will exhibit 'soil-like' capillarity depending on gradation. A commonly used threshold for this behavior is given by a soil having greater than 20% by mass finer than 2 mm (#10 U.S. Standard sieve) or 40% finer than 4.75 mm (#4 U.S. Standard Sieve) (Holmquist et al., 1983; Smith et al., 1995; Strohm et al., 1978). Recent studies by Nichol et al. (2005), Neuner et al. (2013), and Blackmore et al. (2014) as well as literature recently synthesized by Amos et al. (2014), highlight that in waste rock dumps comprised of these 'soil-like' textures, the dominant mass transport is through matrix flow with relatively high levels of leaching efficiency. The qualitative definition of leaching efficiency being used here is the proportion of a conservative Cl, initially contained within the pore water, that is removed by the first pore volume of flushing.

In dumps in which water migration occurs primarily through matrix flow, deep profiles of the stable isotopes of water should provide valuable information on the source, distribution and rate of water movement through the dumps. The application of stable isotopes of water to track water migration has seen limited use in waste rock dumps. Marcoline et al. (2006) applied a ^{2}H spike to the top of a 5 m high test pile constructed earlier by Nichol et al. (2005) in order to track water movement by collecting samples by trenching and hand sampling. The results were difficult to interpret; however, due to the small volume of the spike water addition, fractionation due to evaporation during sampling, and dump heterogeneity. Sracek et al. (2004) collected water samples from a full-scale dump (30–35 m) using suction lysimeters installed in the dump and from a water well in the underlying saturated zone. These isotope data suggested an equal contribution of snowmelt water and spring rainfall to recharge. One observation of particular interest was the apparent fractionation due to evaporation that occurred at depth in the dump. This internal evaporation was suggested to be due to the convective flow of atmospheric air into the dump near the toe of the slope.

As surface mining has continued to expand, there have been increasing calls to understand the fundamental hydrology of waste rock dumps and how they interact with the surrounding catchment hydrologic and hydrogeologic systems (INAP, 2009, 2015). The goal of this study is to apply isotopic hydrological approaches to better understand water migration in and through mine waste rock. The specific objectives of this work are as follows:

1. Develop field sampling methods to measure high spatial resolution profiles of the stable isotopes of water through coal mine waste rock and natural alluvial deposits down gradient of a waste rock pile.
2. Evaluate the accuracy of these profiles by comparing the average isotopic composition of the water in the waste rock to that measured in adjacent natural soil profiles using coring and water well samples, as well as the isotopic composition of effluent collected from rock drains.
3. Estimate the magnitude (volume) of annual recharge and the rate of water migration through coal mine waste rock based on the patterns (seasonality and magnitude) of the high spatial resolution profiles of the stable isotopes of water.

2. Study sites

The sites for this study are located at two Teck Resources mines along the Elk River watershed (Fig. 1) in southern British Columbia, Canada: the West Line Creek (WLC) watershed and waste rock dump at the Line Creek Operation (LCO-WLC); and the Bodie dump at the Elk View Operation (EVO-BRD). These mines extract coal from the Mist Mountain formation which is comprised of siltstones, mudstones, and sandstones with coal seams up to 18 m thick (Gibson, 1985; Ryan and Dittrick, 2001).

Teck Resources initiated a multi-disciplinary research and development program in 2012 based on the recommendations of a Strategic Advisory Panel (SAPSE, 2010). This ongoing research has been incorporated into the Elk Valley Water Quality Plan as approved by the provincial government (EVWQP, 2014). The focus of this research program is to find methods of managing water quality, including methods of controlling water and chemical migration from waste rock dumps. This paper presents work undertaken to characterize the source, distribution and rate of water movement through coal waste rock dumps.

The WLC watershed is approximately 10 km^2 in area (Shatilla, 2013; Wellen et al., 2015) and ranges in elevation from 1450 to 2650 m. The dump covers approximately one quarter (2.7 km^2) of the eastern flank of the watershed (Fig. 2a). The dump was constructed over the last 35 years and has surface elevations ranging from 1500 m in the south to more than 2140 m in the north, with a maximum waste rock thickness of approximately 255 m and an average dump thickness of approximately 115 m. The dump extends from the north of the watershed to within 0.5 km of the southern end of the watershed where the rock drain and creek drain into Line Creek. The Bodie dump (Fig. 2b) covers approximately 1.22 km^2 of the original Bodie Creek pre-mining watershed,