Leachate generation and nitrogen release from small-scale rock dumps at the Kiruna iron ore mine

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Abstract Two small-scale waste rock dumps have been constructed in Kiruna, Sweden to investigate the dynamics of leachate generation and nitrogen release over the course of several years. The rock dumps have been constructed of low sulfur rock waste which is not acid generating. The results of the study indicate that, for the two years of this study, water is only discharged intermittently from the rock dumps during snowmelt and during more intense rainfall events. During 2016, concentrations of nitrate and ammonium in the discharge waters ranged up to 46 and 0.14 mg N/L, respectively. The average leachate composition (n = 25) was pH 7.8, alkalinity 55 mg/L HCO_3^- and 1011 mg/L SO_4^{2-}, which is quite similar to the composition of water in the clarification pond at the mine site.

Key words neutral mine drainage, nitrate, ammonium, waste rock, sub-arctic

Introduction

The ultimate source of most of nitrogen cycling at a mine site is the ammonium nitrate – based explosives used in the excavation of the mine. Waste rock, a by-product from the excavation of non-metalliferous rock in mining activities, often contains adsorbed nitrogen compounds (ammonium and nitrate) that are residues from the detonation of the explosives. Once the rock waste is deposited on the ground surface, the percolation of rain and snowmelt through the deposit will leach the nitrogen compounds, potentially impacting local recipients.

All mining activities within the European Union are affected by the Water Framework Directive (WFD), which is locally enforced by legislation within member countries. Since the nitrogen compounds originate from the nitrogen-based explosives used for mining, virtually all mines in Europe will have nitrogen discharges; complying with national environmental regulations will hence be an issue for most actors in the raw material sector using explosives. From the perspective of mining in northern Sweden, the release of ammonium is of primary concern as ammonia has potentially toxic effects on aquatic ecosystems; eutrophication is of secondary importance.

The presence and release of nitrogen compounds from waste rock dumps has received increasing attention over the past 20 years, especially in northern Europe (e.g. Forsberg and Åkerlund 1999, Karlsson and Kauppila 2015, Lindeström 2012, Morin and Hutt 2009, VTT 2015, Zaitsev et al. 2008). Bailey et al. (2013) published data from the first large-scale study where the dynamics of nitrogen leaching from waste rock over a period of several years was investigated.

This paper presents the interpretation of two years of monitoring data from small-scale rock dumps. The rock dumps have been constructed with the objective to investigate the dynamics of leachate generation and nitrogen release over the course of several years. This is one of the first studies in Scandinavia that studies nitrogen leaching from rock waste above the Arctic circle, and is important for understanding the potential release of nitrogen into nutrient-poor aquatic recipients.

Construction of waste rock dumps

Between July and September 2014, two small waste rock dumps (called hereafter south and north waste rock dump) were constructed at the Kiruna iron ore mine site in northern Sweden. Prior to construction, the ground surface was prepared by filling a pre-existing pond with waste rock. The ground surface was graded so that the elevation decreased by approximately 0.5 meters over the base of the rock deposit (35 meters) and in the direction of the basal drainage outlets (Figure 1). The basal footprint of the rock dumps were 35 m x 35 m. Each rock dump was completely surrounded by a 2 m high berm consisting of waste rock. Each berm was approximately 5 m wide. The basal areas and berms were covered with an impermeable HDPE geomembrane (1.5 mm thick). To enhance drainage to the corner discharge pipes, perforated pipes were installed along two of the sides of both of the waste rock deposits (Figure 1). Drainage water was then led from the corner drainage pipes to two external leachate collection wells which contained V-notch weirs for the quantification of flow.

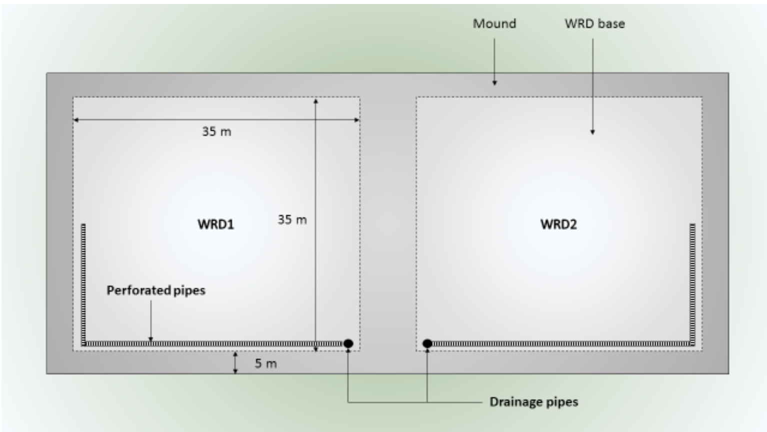

Figure 1 *Dimensions of the basal area of waste rock deposit with drainage. Light gray surface is the inner area, while the dark grey borders are the berms.WRD1 = south dump, WRD2 = north dump.*

After the installation of the geomembrane and overlying geotextile, the basal areas of the waste rock dumps were carefully covered with approximately 30 cm of fine-grained waste rock (0-30 mm diameter), so as to avoid puncturing the geomembrane with more coarse-grained material. The perforated drainage pipes were placed on top of this material. The dumps were then built up by the alternating deposition of 0-30 mm waste rock and 0-200 mm waste rock.

The two waste rock deposits were built to an approximate height of 8 m over the basal liner, by a combination of end-dumping, push-dumping, and free dumping. Waste rock was unloaded using dumpers, either directly at the crests of the waste rock piles (and distributed at the sides by gravity) or at their side and later moved to the crests using a wheel loader. The technique used for construction of the waste rock piles can give rise to structural features that can influence water flow.

Methods

The water level on the upstream sides of the V-notch weirs was measured using pressure transducers that also measured water temperature. Two Campbell Scientific CS451 pressure transducers were connected to a CR1000 data logger in May 2015, and set to store average water levels every 30 minutes. In order to establish a relationship between water level and discharge, the discharge at each weir was manually measured on 27 occasions during May – August 2016 and coupled to a corresponding water level. The measured discharges were used to establish rating curves for both weirs (showing discharge as a function of water depth) by fitting the measured values with the following equation:

$$Q=\left(\frac{8}{15}\right)\cdot\mu\cdot\tan(\alpha)\cdot\sqrt{2g}\cdot h^{(5/2)}$$

where μ is the weir constant, α is the angle of 90°, *g* is the gravitational constant, and *h* is the water depth in the v-notch. However, because of the high variability in measured discharge and water level, it was not possible to accurately fit one distinct rating curve to the measured values. Instead, a stochastic method was applied where 2000 rating curves were constructed by varying the weir constant μ. For each realization, the absolute sum of the residuals between the measured and modeled values was calculated; lower residuals were accredited with better fits and are color-coded accordingly in the resulting rating curves. The rating curve for the north rock dump weir is depicted in Figure 2.

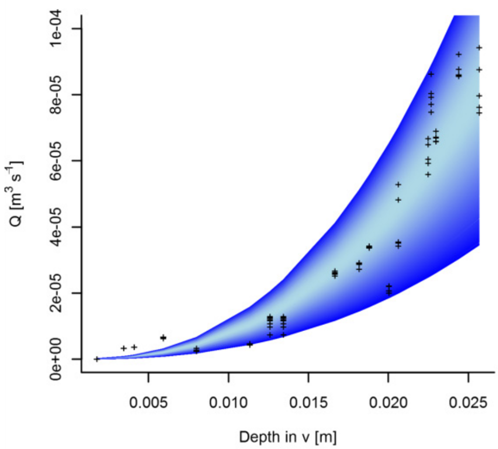

Figure 2 *Rating curve for discharge from the north waste rock dump. Lighter blue indicates the lowest absolute sum of residuals, i.e. the best fit to data, while the darker blue is a poorer fit.*

When water flow occurred from the waste rock deposits, waste rock leachate was sampled and analyzed once a week for NO_3^-, NO_2^-, NH_4^+, SO_4^{2-}, Cl^- and pH. Water samples were analyzed by LKAB's accredited water chemistry laboratory.

Results and discussion

Leachate generation

During the period from May 2015 to October 2016, leachate only flowed intermittently from the waste rock dumps (Figure 3). During the first operational year, leachate discharge was very low from both rock dumps; since the rock waste was deposited in a relatively dry state in 2014, most of the infiltrating water during 2015 accumulated in the pore spaces until the field capacity for the material was exceeded. During the second operational year, when water content was significantly greater in the rock dumps (data not shown), peak flows from the dumps were at least an order of magnitude greater (see Figure 3). This is further illustrated in Figure 4 where the cumulative leachate generation is much greater during 2016 than during 2015.

It should be noted that leachate generation is much greater from the south dump compared with the north dump (Figures 3 and 4), even though the discharges should be very similar. During the construction of the rock dumps, the intention was that the basal slope of each dump was to be graded so that basal drainage from the rock dumps would be directed to the vertical drainage pipes (Figure 1). However, because of inadequate grading, it is likely the water along the base of the north rock dump does not flow directly to the drain, but rather to the eastern side of the rock dump. This requires that a large quantity of leachate must accumulate along the base of the north rock dump before it flows to the basal drain.

The total leachate production from the south waste rock dump is in the range 390 – 800 m^3 for two hydrological years (cf. Light blue areas on Figure 4). For the Kiruna mine site, the average annual precipitation is 490 mm/year (Kiruna airport, 1961 – 1990). Precipitation falling over an area of 35m x 35m (basal footprint of rock dump) would produce a water volume of 600 m^3/year. Considering that most infiltrating water accumulated in the rock dumps during the first year, and that evaporation from the rock dumps is relatively low in the subarctic climate of the region, the measured and calculated leachate production values are in good agreement with each other.

Nitrogen release

The concentrations of dissolved constituents in the rock dump leachate varied over time but did not exhibit any identifiable trend. Average leachate concentrations for the 2016 operational year are shown in Table 1. The leachate concentrations are similar to the concentrations of dissolved constituents in the Kiruna clarification pond (see Nordström and Herbert, 2017, this volume).

Over the two year period reported in this study, 2.4 – 3.2 kg N and 12.3 – 25.3 kg N were leached from the north and south waste rock dumps, respectively; the range of values re-

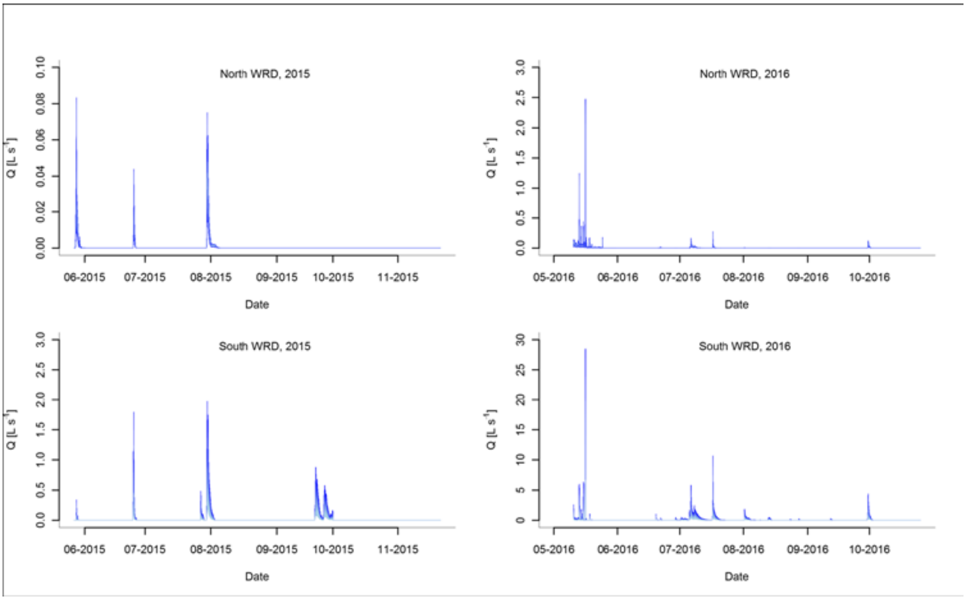

Figure 3 *Leachate discharge from north and south waste rock dumps, calculated from rating curves and measured water levels. Note that discharge scales are different for each diagram.*

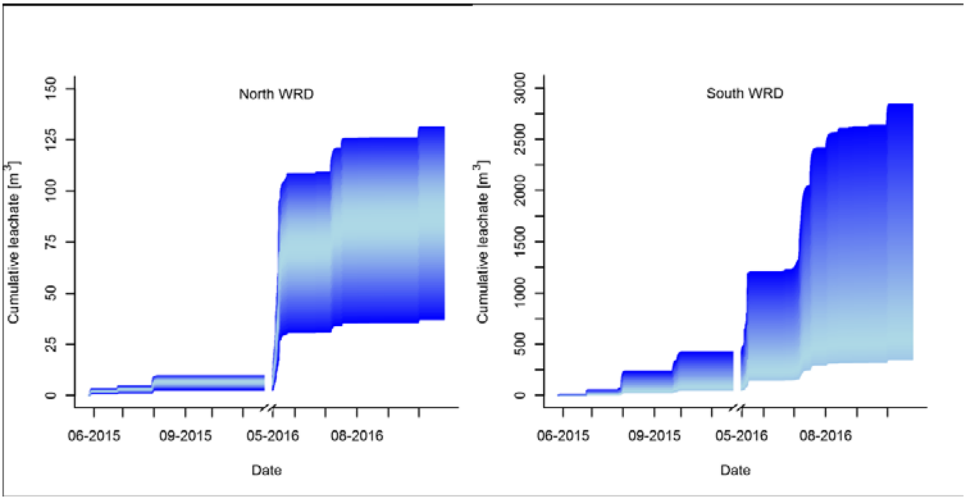

Figure 4 *Cumulative leachate generation from north and south waste rock dumps. Color-coding is based on rating curves where lighter blue indicates the lowest absolute sum of residuals, i.e. the best fit to data.*

flects the uncertainty in the rating curve for discharges from both deposits. If each rock dump contains ca. 3267 m^3 of material, then these exports correspond to a leaching of 0.74 – 0.98 and 3.77 – 7.70 g N/m^3 waste rock

In contrast to the results of intermittent sampling during the entire 2016 field season (see above), focused sampling during snowmelt in 2016 identified an apparent cyclicity in both leachate generation and nitrogen concentrations. As shown in Figure 5, leachate generation follows the daily cycles in air temperature, with roughly a 12 hour lag time. Maximum flow rates are measured in the late afternoon / early evening when air temperatures are declining, suggesting that a certain amount of time is needed for snowmelt pulses to propagate to the rock dump drains.

Nitrate concentrations in waste rock leachate also exhibit a cyclical pattern during snowmelt (Figure 5), although the relationship with air temperature is not as apparent as it is for air temperature.

Nitrogen transformations in mining environments

Mine water data from a number of Swedish mines (Lindeström 2012, LKAB unpublished data, Nordström and Herbert 2017) generally indicate that >95% of total nitrogen occurs in its most oxidized form, nitrate, in surficial mine drainage. Within an underground mine, a greater proportion of nitrogen may be present as ammonium (LKAB unpublished data), but nitrate is still the predominant nitrogen species. Even though ammonium nitrate explosives contain equal molar amounts of oxidized and reduced nitrogen, the detonation process and oxidizing environment of the mine site favor the occurrence of the more oxidized nitrogen species.

Once released to a surface water environment, either as process water or waste rock leachate, nitrate concentrations will not decrease unless affected by dilution or biological processes (e.g. plant uptake, microbial denitrification). However, denitrification is not expected to be an important process in aerated water. Ammonium concentrations have been shown (Lindeström 2012) to decrease in mine waters during warmer periods as the result of nitrification, which is a strongly temperature-dependent microbial process.

Conclusions

The results of this study clearly demonstrate that waste rock is a source of nitrogen in mining environments. Nitrate concentrations as high as 45 mg N/L were detected in waste rock leachate, while ammonium was detected at concentrations < 0.15 mg N/L. In the subarctic climate of the field site, leachate generation is greatest during snowmelt and in connection with intense rainfall events during the summer. Total annual leachate production is comparable with the annual precipitation falling on the rock dump.

Table 1 *Average leachate concentrations during 2016 operational year. n = 25 samples.*

Constituent	Concentration	Constituent	Concentration
pH	7.8	NO_3^-	32 mg N/L
Alkalinity	55 mg HCO_3^-/L	NO_2^-	0.07 mg N/L
Cl^-	33 mg/L	NH_4^+	0.07 mg N/L
SO_4^{2-}	1011 mg/L	F-	0.6 mg/L

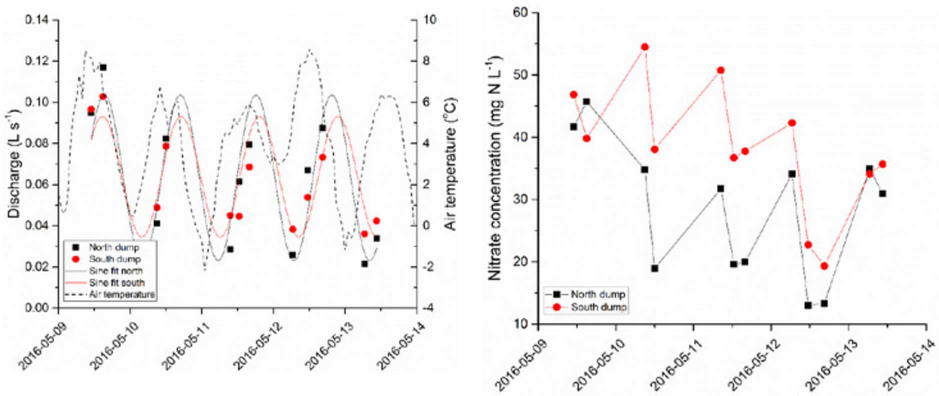

Figure 5 *Left: Leachate discharge from north and south rock dump during snowmelt in 2016. Leachate discharge has been fitted with a sine curve to illustrate the cyclicity in discharge, relative to air temperature (right axis). Right: nitrate concentrations during snowmelt.*

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