Characterisation of Fanny Creek catchment acid mine drainage and optimal passive treatment remediation options

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Abstract

Fanny Creek drains from Island Block, an inactive open cast coal mine near Reefton on the West Coast of the South Island, and is impacted by acid mine drainage (AMD) resulting in elevated metal concentrations and low pH. Water sampling between 2008 and 2009 characterised Fanny Creek AMD, with elevated dissolved metal concentrations averaging 6.0 mg/L for Al, 1.3 mg/L for Fe, 3.1 mg/L for Mn, 0.49 mg/L for Zn, and 0.14 for Ni. pH ranged from 3.58 to 4.51. Flow rate varied considerably, averaging 12.5 L/s, (1.5 - 30 L/s), but drainage chemistry is not significantly affected by rainfall dilution.

To determine optimal AMD remediation strategies for Fanny Creek the effectiveness of four different 'bench' scale passive AMD treatment systems was assessed in a laboratory. Treatment options trialled include a sulfate reducing bioreactor (SRBR), a limestone leaching bed (LLB), an open limestone channel (OLC), and mixing with adjacent alkaline Waitahu River water. Trial AMD was sourced from Fanny Creek, and treatment system influent flow rates were regulated to assess performance at different hydraulic retention times (HRT). The SRBR and LLB performed best, with pH raised to 7.12, and above 6.01, respectively. At optimal HRTs the SRBR removed $\geq$92.5% of all elevated metals, except for Mn (60.4%). The LLB removed $\geq$86.3% of all metals, apart for Ni (50.0%) and Zn (73.6%), with Mn precipitation catalyzing greater removal of Ni and Zn. The OLC had lowest metal removal, and only raised pH to 5.65. Mixing AMD with Waitahu River water can adequately neutralize AMD and requires only 140 L/s of river water. Results suggest optimal passive AMD treatment options for Fanny Creek are either a limestone leaching bed, or the Waitahu River Mixing option due to treatment effectiveness, size requirements, and simplicity.

Key words; Passive AMD treatment, sulfate reducing bioreactor, limestone leaching bed, open limestone channel

Introduction

Island Block opencast coal mine is located in the Garvey Creek Coalfield, near Reefton on the West Coast of the South Island of New Zealand. Island Block is owned by Solid Energy New Zealand Ltd (SENZ) and is currently inactive, although historic mining activity causes acid mine drainage (AMD) in Fanny Creek which drains the mine site. Island Block coal mine sits on the hilltop between the Inangahua and Waitahu river valleys and Fanny Creek drains steeply down to the relatively flat Waitahu Valley floor where it travels through sedimentation basins before it enters the Waitahu River. There is however no detectable affect on river water quality downstream of the coal mine (Raj, 2002).

Coal mines hosted in the Brunner Coal Measures on the West Coast can generate AMD (Pope et al., 2011). Acid mine drainage is most often caused by weathering of pyrite (FeS_2) after exposure by mining activities (Brown et al., 2002). Pyrite oxidation releases dissolved iron, sulfate and acidity into the aquatic environment along with other metals (Stumm and Morgan, 1996), which can adversely affect the fresh water ecology of New Zealand streams (Winterbourn et al. 2000).

Treatment of AMD is categorized as either 'active' or 'passive'. Passive AMD treatment systems utilise naturally occurring geochemical and biological processes to neutralise acidity and remove dissolved metals from mine water, and require only infrequent maintenance (Younger et al., 2002). Conversely, active treatment systems require constant input of energy and neutralizing agents, and are often more expensive to operate. There are limitations to passive AMD treatment however, such as clogging and armouring of limestone by metal precipitates, which can result in ineffective treatment of AMD. However, when selected and designed appropriately passive systems can successfully mitigate AMD and this can be achieved using a 'phased' design approach with small scale testing performed prior to construction of a full-scale treatment system (Trumm, 2007). Passive treatment systems are relatively cheap to operate if successfully implemented.

A number of studies document AMD on the West Coast and its effects (Lindsay et al., 2003; Harding and Boothryd, 2004; de Joux & Moore, 2005; Trumm, 2005); however not many focus on its treatment and remediation. There is limited geochemical and environmental data available for Garvey Creek Coalfield, especially for Fanny Creek, and this information is essential to select and design successful passive AMD treatment systems (Watzlaf et al., 2003).

The objectives of this research are:

- To characterise Fanny Creek drainage chemistry and flow regime.
- To identify suitable passive AMD treatment options for Fanny Creek and to conduct laboratory scale trials of these systems.
- To interpret and evaluate the effectiveness of laboratory scale passive AMD treatment systems.
- To determine optimal passive treatment options for remediation of Fanny Creek AMD for future pilot or full scale application.

Methods

Characterization of Fanny Creek AMD and Flow Regime

Measurement and sampling of physiochemical properties for Fanny Creek was completed on a monthly basis from 2 February 2008 to 13 January 2009. Monitoring involved measurement of pH, electrical conductivity (EC) and dissolved oxygen concentration (DO) using calibrated portable instruments, and water samples collected for alkalinity, acidity, metal and sulfate analysis at R.J Hill Laboratories Ltd. Flow rate was measured by either V-notch weir or bucket and timer method, but had to be estimated during high flow conditions (>20 Ls).

Monitoring focused on Fanny Creek AMD immediately before settling basins (site R12) on the Waitahu Valley floor. This is the preferred locality in the catchment for AMD treatment because the surrounding large flat area provides a suitable space for a full scale passive AMD treatment system. Other sites in the catchment relevant for characterizing drainage chemistry were also monitored.

Laboratory Trials of Bench Scale Passive AMD Treatment Systems

Selection

Four treatment options for Fanny Creek AMD were trialed at laboratory scale. A selection flow chart (Trumm, 2007) identified three potentially suitable treatment options:

- Limestone Leaching Bed (LLB),
- Open Limestone Channel (OLC)
- Sulfate Reducing Bioreactor (SRBR)

The fourth, site specific option trialled (Waitahu River Mixing) involved investigation of the neutralizing capacity of the Waitahu River, to potentially mix buffered river water with Fanny Creek AMD.

Design and Construction

The trial SRBR, LLB and OLC treatment systems, and the Waitahu River Mixing option were 'bench top scale' and trialled in the CRL Energy laboratory in Christchurch (Fig 1) and Reefton, respectively. The AMD used for the trial was sourced from Fanny Creek and designed to simulate treatment of worst likely AMD at the remediation site; therefore, AMD was collected upstream of site 'R12', prior to dilution sources, and transported back to the laboratory (~ 14 000 L collected).

The experimental design for the trial SRBR, LLB and OLC treatment systems was based on hydraulic retention time (HRT). HRT is a measure of the average length of time AMD is in contact with the reactive treatment materials within remediation systems, and was systematically decreased for each bench scale system throughout the trial. The SRBR had an initial HRT of 56 hours, while the LLB and OLC started with a HRT of 14 and 15 hours, respectively. Hydraulic residence times were decreased periodically as the trial proceeded to a minimum of 5 hours HRT for all treatment systems. Each HRT operated for a prescribed time period, ranging from 12 days initially, to three days at the end of the trial for the highest flow rates because the supply of AMD was limited. Optimal HRTs, operating ranges, and failure thresholds for the trial systems were identified by analysis of effluent water quality at the end of each HRT period. The SRBR operated for 116 days, and the LLB and OLC operated for 112 days.

The AMD supply to trial SRBR, LLB and OLC systems was gravity fed from a header tank via plastic tubing with metal clamps attached to regulate influent flow rate. The SRBR system employed a vertical down-flow configuration in a 90 L plastic container (570 mm long, 380 mm wide, 400 mm high). The SRBR reactive substrate had a volume of 50 L (231 mm thick) and consisted of mussel shell fragments (30%), wood chips or 'post peel' from fence post manufacture (35%), Pinus radiata bark (20%), compost (10%), and SRBR substrate (5%) previously used by McCauley (2009). The SRBR substrate was underlain by a 70 mm thick drainage gravel layer, and overlain by a 30 mm thick post peel layer to promote uniform flow into the SRBR. The LLB and OLC treatment systems had horizontal to sub horizontal flow configurations, respectively. The LLB system was in a 100 L plastic container (645 mm long, 400 mm wide, 385 mm high) and composed of individual limestone clasts (10 - 30 mm in length) with a total volume of 50 L, making a 190 mm thick limestone bed. The OLC system was constructed from PVC roof guttering mounted onto a wall in three tiers (90 mm wide, 120 mm high, 12 m long in total) and AMD flowed from one end to the other. The OLC used the same sized limestone clasts as the LLB, placed one deep along the channel, and had a limestone material volume of 21.6 L. Perforated inflow and outflow PVC piping and valves were placed to evenly distribute AMD flow of AMD through treatment systems, and the SRBR and LLB were configured to enable vertical 'flushing' of systems. Each bench scale treatment system discharged into a separate 12 L container to simulate a final settling pond commonly employed in full scale passive treatment systems.

The water quality of settling pond effluent was used to assess the performance of each bench scale treatment system. Water samples of influent AMD and treatment system effluent were collected after each HRT period and laboratory analysed for dissolved Al, Fe, Mn, Cu, Ni, Zn, SO4, while acidity (to pH 5) and alkalinity (to pH 3.7) were measured. Measurements of pH and dissolved oxygen (DO) were also taken using portable instruments at the time of sampling. Treatment systems were 'flushed' (rapid vertically drainage) at the end of the trial and total (particulate) metal analysis completed for effluent.

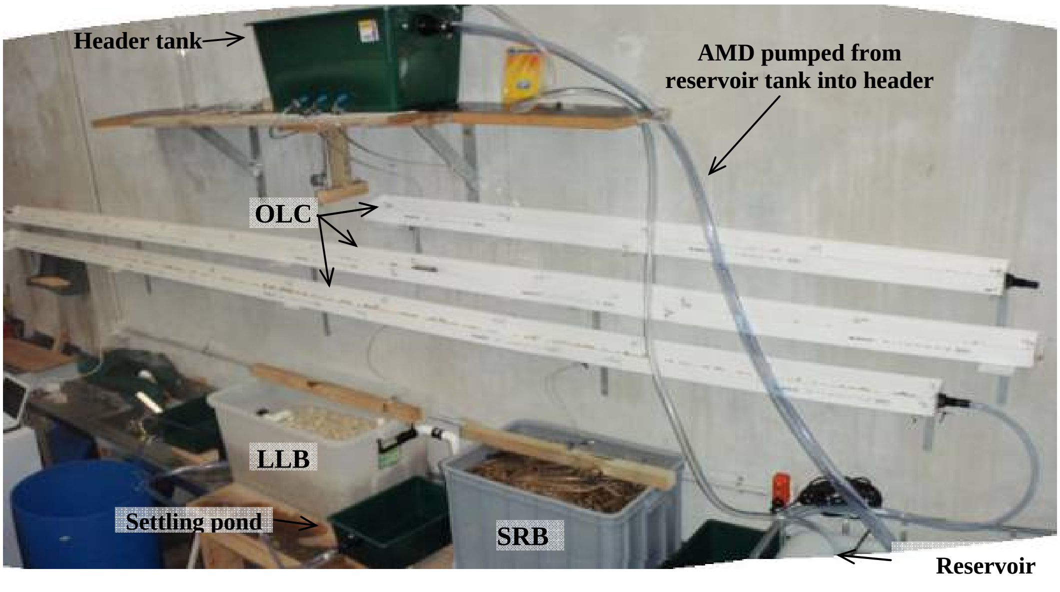

Figure 1: Experimental set up of bench scale SRBR, LLB, and OLC trial treatment systems in the Christchurch laboratory.

The Waitahu River Mixing option was assessed by compilation of monthly acidity and flow rate data from monitoring Fanny Creek, along with alkalinity data from the Waitahu River upstream of Island Block. A ratio of river water required to neutralize Fanny Creek AMD to pH 5 was calculated, and combined with Fanny Creek flow data to determine the volume (L/s) of Waitahu River water required to buffer acidity at the treatment site. Evaluation of this option also accounted for likely worst AMD conditions, therefore minimum Waitahu River alkalinity data was combined with maximum Fanny Creek acidity (upstream of site R12) and flow rate data.

Results and Discussion

Fanny Creek AMD

Drainage chemistry of Fanny Creek at the treatment site shows little variation, although flow rate varied considerably (Fig 2). Average flow rate measured 12.5 L/s, (1.5 L/s to ~30 L/s). Average pH was 3.95 (3.58 - 4.51), and measured acidity (to pH 5) averaged 24.2 mg $CaCO_3$/L (10 - 32.5 mg $CaCO_3$/L). EC averaged 755 µS/cm (460 - 1550 µS/cm) and DO averaged 7.98 mg/L (4.96 - 8.93 mg/L). Elevated metals compared to ANZECC water quality guidelines include Al, Fe, Mn, Cu, Ni and Zn. Average dissolved metal concentrations measured 6.0 mg/L Al (4.9 - 7.8 mg/L), 3.1 mg/L Mn (2.0 - 4.1 mg/L),1.3 mg/L Fe (0.64 - 2.5 mg/L), 0.49 mg/L Zn (0.41 - 0.59 mg/L), 0.14 mg/L Ni (0.11 - 0.17 mg/L) and 0.0071 mg/L Cu (0.0042 - 0.0084 mg/L). Sulfate concentrations averaged 298 mg/L (225 - 360 mg/L).

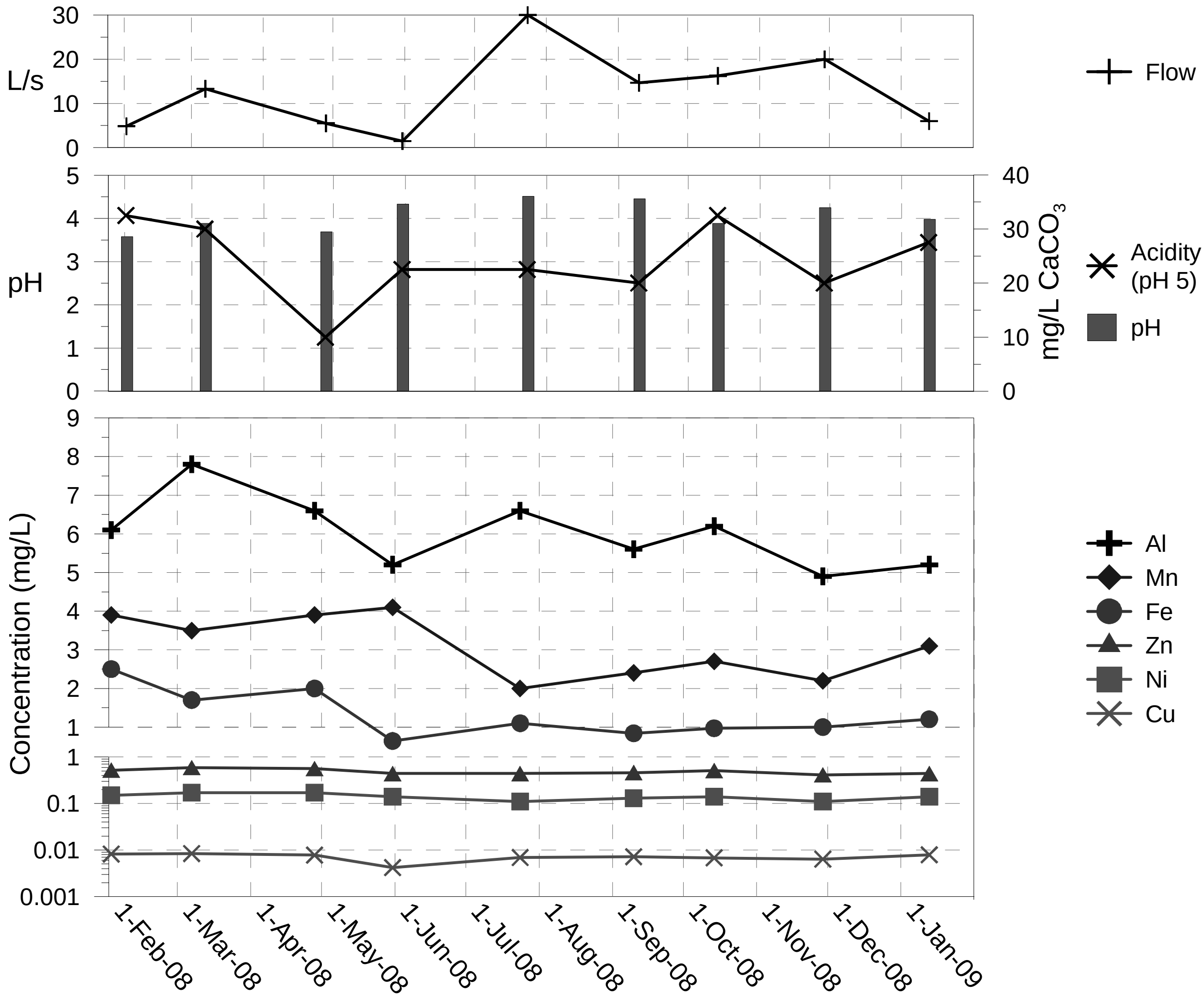

Figure 1. Fanny Creek monthly flow rate, pH, acidity (to pH 5) and dissolved metal concentration data at the proposed treatment site (R12) between 2 February 2008 and 13 January 2009.

Drainage chemistry at R12 is relatively consistent despite considerable difference in flow rate (1.5 L/s - 30 L/s), with AMD not affected greatly by rainfall dilution. Therefore, drainage chemistry in Fanny Creek is largely independent of flow rate. This suggests the rate at which acidity and metals are generated from Island Block mine is proportionate to the amount of flow in the catchment. This is likely caused by a ‘flushing’ effect, where pyrite weathering products are stored in waste rock during fine weather conditions but become dissolved during rainfall and higher flows, releasing acidity and metals into Fanny Creek.

Bench Scale SRBR, LLB and OLC Passive AMD Treatment Systems

Influent AMD

The AMD used for the bench scale treatment system trial is slightly more acidic than at the proposed treatment site (R12) and representative of worst likely AMD to be treated. Influent AMD averaged 11.5 mg/L for Al, 0.59 mg/L for Fe, 4.0 mg/L for Mn, 0.12 mg/L for Cu, 0.24 mg/L for Ni, 0.87 mg/L for Zn, 407 mg/L for SO4, and pH and acidity (pH 5) averaged 3.46 and 63.5 mg/L $CaCO_3$, respectively.

SBRB, LLB, OLC Effluent

Treatment system effluent water quality results are presented for each HRT in chronological order, and show changes in treatment performance as the HRTs for the SRBR, LLB and OLC decreased and influent AMD flow rates increased. Results for dissolved metal and sulfate analysis are presented in terms of removal efficiency (percentage removed by treatment systems) to standardized treatment performance of each trial system at each HRT tested.

In general, greater, more effective metal removal (almost 100%) occurs at longer HRTs tested for each treatment system (Fig 3). In certain systems at shorter HRTs, net export of metal occurs (effluent concentrations are greater than influent AMD) which is indicated by negative removal efficiencies.

Dissolved metal removal for the SRBR treatment system is greatest for Al (99.8%), Fe (>97.1%) and Zn (99.6%) at HRTs $\geq$8 hours, and for Ni (98.7%) and Mn (70.9%) at the longest HRT (56 hours), while Cu removal is effective (99.3%) at the shortest HRT tested (5 hours) (Fig 3). Removal of Al and Fe decreases markedly at HRTs shorter than 8 hours, declining to 29.6% and 42.9%, respectively, while for Zn net export occurs (-15.4%). Removal of Ni and Mn decreases steadily at shorter HRTs, to a minimum of 15.0% for Ni, and net export of Mn occurs (-8.3%) at 10 hours HRT. For the LLB treatment system removal of Al, Fe and Cu is effective at all HRTs tested ($\geq$5 hours), with maximum removal efficiencies of 99.8%, >98.4%, and 97.1%, respectively. Removal of dissolved Mn, Ni and Zn is initially poor, with minimum efficiencies of 5.7%, 6.3% and 36.7%, respectively, but at shorter HRTs removal increases to maximums of 67.5% for Ni, 89.1% for Zn, and 97.1 % for Mn. Dissolved metal removal for the OLC treatment system is greatest for Al (99.4%), Fe (>98.5%), and Cu (88.0%) at HRTs longer than 13 hours, but removal declines as HRT is shortened, to minimum efficiencies of 37.1% (Al) 74.7% (Fe) and 19.7% (Cu). Removal of dissolved Mn, Ni and Zn by the OLC system is poorer than by the SRBR and LLB systems, with maximum removals of only 14.6%, 26.7% and 33.8% respectively, while net export of these metals occurs at HRTs shorter than 11 hours.

Sulfate removal only occurs for the SRBR treatment system, with a maximum of 18.8% at 51 hours HRT, but at shorter HRTs removal decreases and net export occurs (up to -8.3 %).

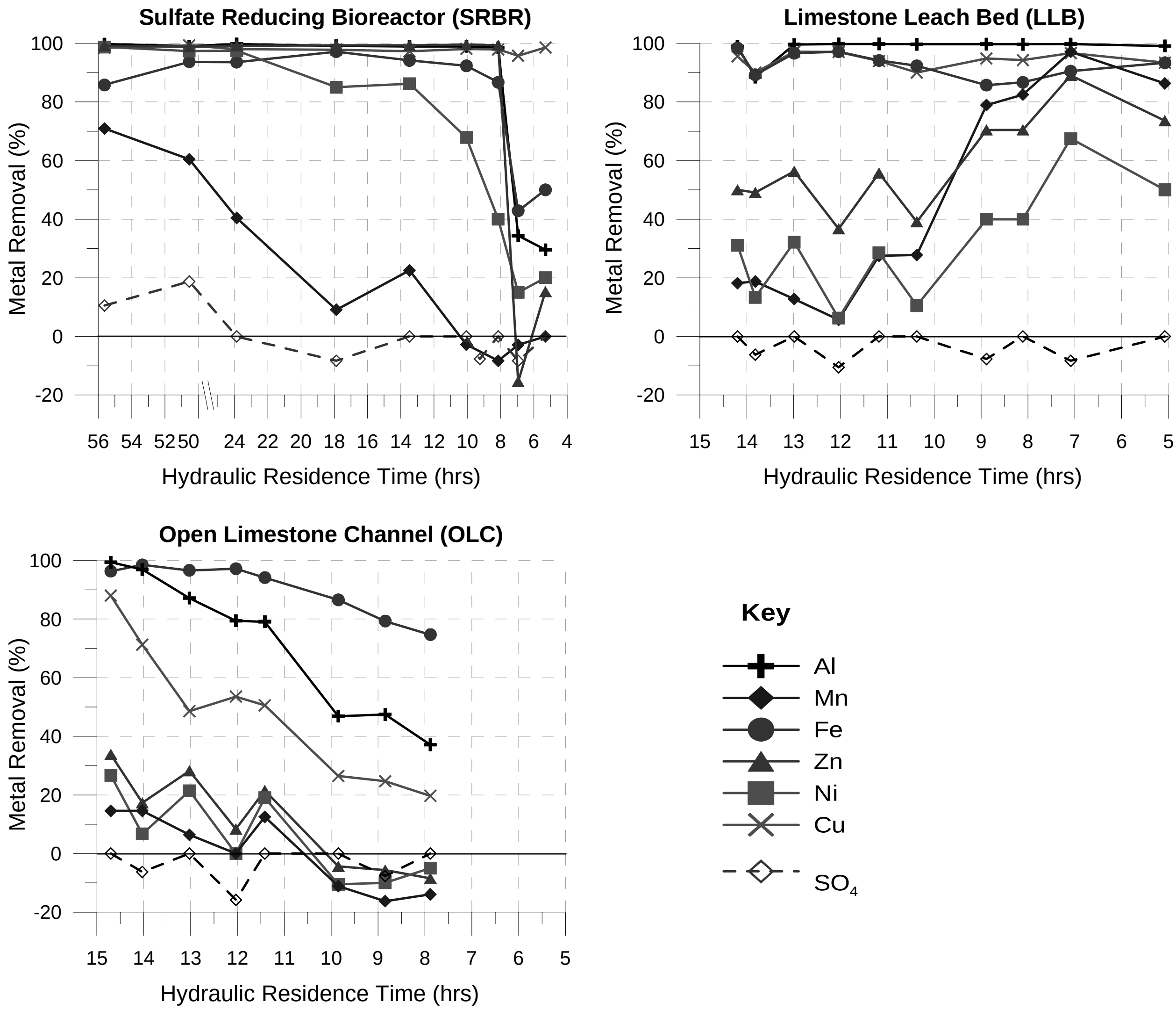

Figure 3: Dissolved metal and sulfate removal efficiencies (%) of effluent discharged from bench scale SRBR, LLB and OLC treatment systems at different hydraulic retention times (hours).

Alkalinity is greatest for the SRBR system, with effluent containing 250 mg $CaCO_3$/L at the longest HRT, but steadily decreases to $\leq$20 mg $CaCO_3$/L at HRTs <10 hours. Alkalinity concentrations are most steady for the LLB system, ranging between 60 and 90 mg $CaCO_3$/L during the trial, while the OLC system generates least alkalinity ($\leq$25 mg $CaCO_3$/L). The SRBR system increases pH the most (Fig 4), with pH 7.12 at 51 hours HRT; but effluent decreases to <pH 5 at the shortest HRTs. Effluent pH from the LLB system is constant, between pH 6.01 and 6.63. The OLC system increases pH initially (pH 5.7), but effluent drops to <pH 5 at HRTs shorter than 13 hours.

Dissolved oxygen (DO) measurements show effluent directly from the SRBR was mostly anaerobic, with very low concentrations (0.6 mg/L) between 24 and 14 hours HRT, but increased to 3.57 mg/L at shorter HRTs. The LLB and OLC systems did not affect DO concentrations of influent AMD and remained aerobic throughout the trial.

Flushing results indicate that more metal solids were flushed from the LLB system compared to the SRBR system, and metal precipitates were observed to dislodge and become mobile in the limestone bed during flushing.

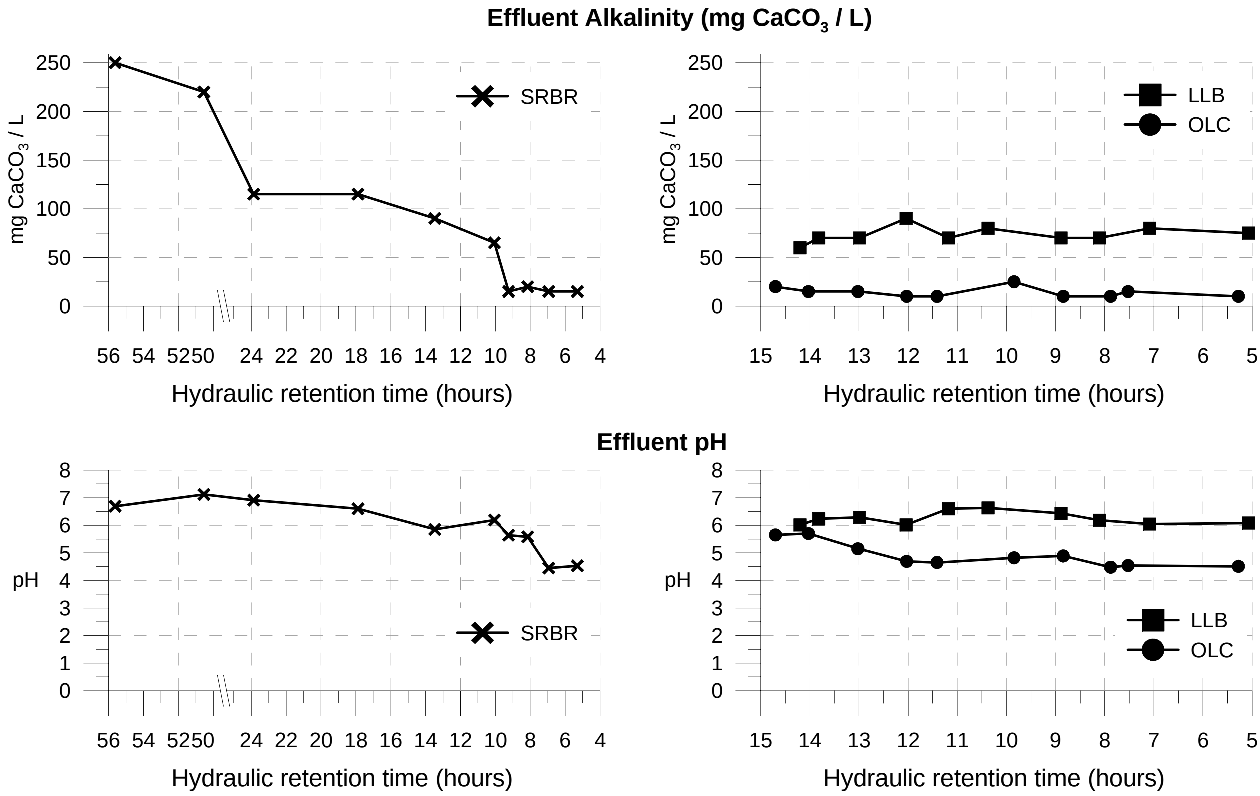

Figure 4: Measured alkalinity (mg $CaCO_3$/L) and pH of effluent discharged from bench scale SRBR, LLB and OLC treatment systems at different hydraulic retention times (hours).

Metal and acidity removal processes

Understanding acidity and metal removal processes provides an insight into effectiveness and longevity of treatment systems, which assists with selection and design of optimal treatment strategies. Criteria for the design and implementation of passive AMD treatment systems are used to estimate the necessary size of a treatment system to adequately remediate AMD (PIRAMID, 2003). After results are interpreted, optimal acid neutralization and metal removal thresholds with respect to HRT are determined for trial treatment systems, which are then used as design criteria for field sized systems.

SRBR treatment systems are designed to immobilize metals and generate alkalinity by chemical and biological processes associated with anaerobic bacterial sulfate reduction. Sulfate removal indicates the extent of sulfate reduction and bacterial activity in SRBRs (Doshi, 2006) and results suggest this process was greatest during longer HRTs (>51 hrs HRT), although continued at shorter HRTs indicated by anaerobic effluent and a smell of hydrogen sulfide (H_2S). At shorter HRTs (<14 hours) however bacterial sulfate reduction likely diminished due to unfavourable redox conditions caused by higher flows forcing dissolved oxygen into anaerobic areas (McCauley et al., 2009), and indicated by a weaker odour of H_2S. This process was likely responsible for removal of iron, however removal of Cu, Ni, Zn and particularly Mn was probably caused by adsorption processes onto reactive substrate materials or Fe and Al precipitates in the SRBR. This explains the marked drop in some removal efficiencies at HRTs <8 hours, because adsorption of cations generally becomes weaker as pH declines, and the pH of effluent drops to below 5 at HRTs <8 hours (Gilbert et al., 2005). Similarly, precipitation of Al as $Al(OH)_3$ requires pH >5 and consequently Al removal declines also at HRTs <8 hours. Neutralization of acidity and alkalinity generation in the SRBR is attributed primarily to dissolution of mussel shells, and is greatest at the longest HRT tested due to more contact time with AMD. The optimal HRT for the trial SRBR system is based on effective bacterial sulfate reduction; therefore, 51 hours HRT (or around two days) is recommended as design criteria for a SRBR system to treat Fanny Creek AMD.

Remediation of AMD in LLB and OLC treatment systems occurs by limestone dissolution that neutralizes acidity and generates bicarbonate alkalinity. This increases pH which promotes removal of dissolved metal such as ferric Fe and Al that are insoluble at pH above 3.5 and 5, respectively (Younger et al., 2002). The trial LLB system neutralizes AMD and generates alkalinity even at the shortest HRT tested. This resulted in circum-neutral effluent (>pH 6.0) (Fig 4) throughout the trial and effective removal of ferric Fe and Al (almost 100% at some HRTs) by hydrolysis and precipitation of oxyhydroxides within the limestone bed. The high solubility of Mn, Ni and Zn can result in poor removal (Watzlaf et al., 2003), however, the LLB system had relatively high removal rates during the latter half of the trial. This is attributed to an autocatalytic process (Stumm & Morgan, 1996; Watzlaf et al., 2003) whereby Mn precipitation is catalyzed by co-precipitation and adsorption to Fe and Mn oxide surfaces. Results suggest Ni and Zn removal is then catalyzed by Mn oxides via the same process; therefore, removal of these metals (Mn, Ni, Zn) accelerates with increased Mn oxide surfaces. This process was observed by the appearance of a black precipitate within the limestone bed and settling pond. The optimal HRT for the trial LLB system is based on effective limestone dissolution, removal of dissolved metals and transport of metal precipitates from the system; therefore, 5 hours HRT is recommended as design criteria for a LLB system for Fanny Creek AMD.

The trial OLC system effectively neutralised AMD at longer HRTs (>13 hours HRT), but unlike the LLB system, treatment performance declines (pH <5) at shorter HRTs due to insufficient contact time for limestone dissolution to neutralise AMD. At longer HRTs a gradual increase in pH along the channel results in precipitation of Fe and Al as their solubility decreases. Aluminium precipitate accumulated clogged the channel around 8 – 9 m due to its rapid precipitation once pH 5 was reached. Iron precipitates also closely adhered to limestone clasts at the start of the OLC, suggesting the initial stages of armouring. As pH decreased at the higher flow rates, less dissolved metal was removed due increased solubility in lower pH, along with the dissolution of previously precipitated metals as shown by net export of Mn, Ni, and Zn at HRTs <10 hours. Optimal HRT for the trial OLC system is based on effective limestone dissolution and removal of dissolved metal; therefore, 15 hours HRT is recommended as design criteria for an OLC system to treat Fanny Creek AMD.

The Waitahu River Mixing Option

Monthly monitoring established the Waitahu River has excess alkalinity, with an average concentration of 23 mg $CaCO_3$/L (15 - 30 mg $CaCO_3$/L) (Table 1). Therefore river water can naturally buffer acidity in Fanny Creek. The average ratio of Waitahu River water required to buffer acidity is 2.7 (almost three times more Waitahu river water needed per unit of AMD), while worst case estimates give a ratio of 4.7. These ratios combined with Fanny Creek flow data indicate on average about 39 L/s of alkaline river water is required to neutralize Fanny Creek to pH 5, ranging from 2.5 L/s (during May) to 120 L/s (during June). However, if lowest Waitahu River alkalinity conditions occur at the same time as maximum Fanny Creek acidity and flow conditions (worst case scenario), a much greater volume of river water is required, with 140 L/s needed to neutralize AMD to pH 5; which represents the design criterion for this treatment option.

Table 1: Summary of monthly acidity and alkalinity data, and calculations used to assess the Waitahu River Mixing treatment option.

	Average	Min	Max	Worst case conditions
Waitahu River alkalinity (pH 3.7)	22.8	15	30	15
Fanny Ck acidity upstream of R12 (pH 5)	59.2	47.5	70	70
Fanny Ck flow rate (L/s)	12.5	1.5	30	30
Ratio to neutralise AMD to pH 5	2.7	1.7	4	4.7
Waitahu River volume needed for neutralization (L/s)	**38.9**	**2.5**	**120**	**140**

No metal analysis was completed for the Waitahu Mixing option. However, dissolved ferric Fe and Al will be removed from solution, given adequately sized settling ponds, when AMD is increased to circum-neutral pH. Attenuation of other metals (Cu, Ni, Zn, Mn) by adsorption and co-precipitation with Fe and Al precipitates will also likely occur (PIRAMID Consortium, 2003). The large flow of the Waitahu River (~ 20 cumecs) means it can supply the required flow volume (140 L/s) during worst case AMD conditions, while site topography permits the potential gravity transfer of river water to the proposed AMD treatment area.

Comparison of Treatment Systems and Optimal Remediation Options

Optimal passive treatment strategies for Fanny Creek AMD were determined by comparing treatment performance at optimal HRT design criteria for laboratory trial options, along with scale up implications and long term treatment considerations.

Overall, the SRBR system (at ~2 days HRT) has most effective metal removal, removing $\geq$92.5% of all elevated metals, except for Mn (60.4%). The LLB system (at 5 hrs HRT) was next most effective, removing $\geq$86.3% of all dissolved metals, apart for nickel (50.0%) and zinc (73.6%), but had greatest Mn removal (86.3%). The OLC system performed the poorest (at 15 hrs HRT) with lowest removal for all metals, with around 85% for Fe, Al and Cu, and <34% for Mn, Ni, and Zn. Similarly, at optimal HRTs the SRBR system generated greatest alkalinity (220 mg $CaCO_3$/L) and increased pH the most (pH 7.12), followed by the LLB system with 75 mg $CaCO_3$/L and a pH of 6.08. The OLC system had least effective alkalinity generation (20 mg $CaCO_3$/L) and lowest pH increase (pH 5.65). Treatment effectiveness of the Waitahu River Mixing option can not be quantitatively compared to other trial systems, but Fe and Al removal will be around 100%, and there is capability for dilution to significantly decrease the concentration of other metals.

Scale up implications such as size and construction requirements are important because they relate to AMD treatment costs. Estimates indicate a full scale SRBR system to treat Fanny Creek AMD is about an order of magnitude larger than a full scale LLB system, due to the large difference in HRT design criteria (2 days versus 5 hours HRT, respectively). The design of a multi layered SRBR system is also relatively more complicated than the other options. Therefore, the treatment costs of a SRBR system will be much greater than the other options.

In addition, metal removal in the trial SRBR may involve short-term adsorptive processes, thus long term effectiveness is uncertain. Other factors such as reactive material depletion, clogging and compaction are also possible limitations. Results from the LLB and OLC system suggest armouring of limestone clasts and clogging could limit long term effectiveness of a system, but such problems can be more easily mitigated, such as by periodic system flushing.

Therefore, the optimal passive treatment options for remediation of Fanny Creek AMD are:
- Limestone leaching bed; or
- Waitahu River Mixing

These options are chosen because they have the capability to adequately neutralize acidity and remove metals, are relatively simple, and likely offer most cost effective AMD treatment. On site pilot scale trials of these options are recommended to more accurately determine size and design criteria for optimal Fanny Creek passive AMD treatment strategies.

Summary

Fanny Creek is impacted by acid mine drainage from Island Block opencast coal mine. Monthly monitoring of Fanny Creek between February 2008 and January 2009 characterized drainage chemistry and flow regime. Drainage contained elevated concentrations of Al, Fe, Mn, Cu, Ni and Zn, and was not significantly diluted by rainfall due to a flush effect of stored minerals from pyrite weathering. Potentially suitable passive AMD treatment systems for Fanny Creek include a sulfate reducing bioreactor, a limestone leaching bed, an open limestone channel, or mixing with alkaline water from the adjacent Waitahu River. Laboratory scale trials of these options were conducted and their treatment performance assessed, metal and acidity removal processes interpreted and design criteria determined. Results show either a limestone leaching bed system or the Waitahu River Mixing option provide the most cost effective passive treatment solution for Fanny Creek AMD. On site pilot scale testing of these two options is recommended to verify effectiveness and enable better sizing and cost estimates for future full scale passive treatment system strategies.

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