Downstream geochemistry and proposed treatment – Bellvue Mine AMD, New Zealand

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Abstract Geochemical modelling can predict how treatment of one AMD feeding into a complicated system with multiple AMD sources may change the downstream chemistry and, hence, the potential for an aquatic ecosystem to recover. Current chemistry and flow rates for two AMDs and the receiving streams were correlated with precipitation to identify changes in acid loads and resulting effects on streams during and between precipitation events. Geochemical modelling was then used to predict resulting acid load in streams during and between precipitation events if only one of the AMD sources was treated.

Key words Acid mine drainage, modelling, passive treatment, mussel shells, diversion well, Bellvue Mine

Introduction

Many countries have abandoned mines programmes for assessment and remediation of acid mine drainage (AMD), however, no such programme exists for New Zealand. As part of a research grant focused on understanding and managing environmental impacts of mining in New Zealand, the Centre for Minerals Environmental Research (CMER) is planning remediation of AMD at the abandoned underground Bellvue Coal Mine, West Coast, New Zealand. This project contains methodologies that could be applied to abandoned AMD sites throughout New Zealand.

Previous work found that the Bellvue AMD, and several additional AMD sources downstream, discharge into the nearby Cannel Creek, resulting in significant impact (Trumm and Cavanagh 2006). Approximately 62% of the impact to the creek was found to be caused by the Bellvue AMD, 33% of the impact from the abandoned James Mine AMD (located 550m downstream of the Bellvue Mine) and the remaining 5% from the abandoned Jubilee Mine AMD (located 10m downstream of the Bellvue Mine).

Small-scale remediation trials were completed to identify a suitable remediation technique for the AMD (West 2014); based on this work, an up-flow mussel shell reactor has been selected as the remediation solution. Prior to installation of the system, a geochemical conceptual model was developed to understand the current conditions in Cannel Creek from the two major AMD sources, the Bellvue Mine AMD and the James Mine AMD, to predict how treatment of the Bellvue AMD will change the conditions downstream in Cannel Creek and to ensure treatment will achieve suitable water quality targets. The conceptual model is presented in this work.

Methods

Flow rates were measured in Cannel Creek and James Creek (a tributary to Cannel Creek 150m downstream of the James Mine) using a SonTek FlowTracker. Flow rates were measured in the two AMD sites using a bucket and stopwatch method. An Intech WT-HR 1m datalogger was installed in the Bellvue Mine adit and recorded water height every 30 minutes; these data were correlated with measured flow rates from the AMDs to expand flow rate data. Precipitation data were obtained from the NIWA climatic station Greymouth Aero; these data were correlated with measured flow rates in the streams to expand flow rate data across the timeframe of the datalogger data from the mine pool. Field measurements were collected from the two AMD sources, Cannel Creek and James Creek, using a portable YSI 556 multi-probe system. Samples were collected for laboratory analyses and analysed for major chemical parameters, including pH, acidity, alkalinity, sulphate and metals using APHA methods (APHA 2005).

Geochemical modelling was completed on mixed solutions using PHREEQC (version 2) (Appelo and Parkhurst 1999). In all cases, the model was first run to determine the saturation index of Al-bearing minerals and Fe-bearing minerals. If Gibbsite or Schwertmannite were found to be above saturation, the model was then run again, specifying that these minerals would be at equilibrium with the final solution. In these cases, the resulting pH and metal concentrations were always lower. It is likely that true values lie somewhere between these two extremes for each case.

Results

Bellvue AMD flow rates range between 0.041 L/s and 30.3 L/s with an average of 0.93 L/s. The data is characterised by low base level flows with short duration spikes where flow rates first increase rapidly and then decline back to base level at a somewhat slower rate. Ninety-two percent of the flow rates are less than 2 L/s, with 47% below 0.5 L/s. Flow rates from the James Mine AMD range from 0 L/s to 6.0 L/s with an average of 0.14 L/s and there is a linear correlation between the two AMDs. Flow rates were less than 0.40 L/s 95% of the time and less than 0.06 L/s 50% of the time. Flow rates for Cannel Creek range from 2.7 L/s to a maximum of 3,831 L/s with an average of 50 L/s. Flow rates are characterised by a baseline level with short duration, high flow rates during storm events. Eighty percent of the flow rates are less than 50 L/s, 17% range from 50 to 300 L/s, and 3% are greater than 300 L/s. James Creek shows flow rates 20% to 50% of that measured in Cannel Creek.

The flow rate in Cannel Creek, upstream of Bellvue Mine, does correlate to the flow rate of the AMD, suggesting that high flow rates during storm events are not synchronised between the two. During storm events, the flow rate in Cannel Creek peaks approximately 24 hours after maximum precipitation and the flow rate in the AMD peaks an additional 24 hours later. While the AMD flow rate peaks, the flow rate in Cannel Creek has already begun to decline, and can reach baseline levels while the AMD flow rate is still elevated. The relationship of flow rates in Cannel Creek and James Creek to the James Mine AMD shows the same pattern.

The Bellvue Mine AMD has a pH of 2.28-3.01, 69 mg/L Fe, 39 mg/L Al, 0.76 mg/L Mn, 0.32 mg/L Zn and 0.15 mg/L Ni. Water quality does not dilute significantly with increase in flow rate, resulting in an increase in acid load with increase in flow rates (from 6.9 to 918 kg/d). The James Mine AMD has a pH of 2.41-2.80, 148 mg/L Fe, 200 mg/L Al, 6.5 mg/L Mn, 1.21 mg/L Zn and 0.56 mg/L Ni. Similar to the Bellvue Mine AMD, water quality does not dilute significantly with increase in flow rates, and acid load increases with increased flow rate (from 0 to 899 kg/d). A comparison of the acid loads to Cannel Creek from the two AMD sources across the range of flow rates shows that the Bellvue AMD contributes relatively more acidity at low flow than at high flow. At 0.10 L/s, the Bellvue AMD contributes 90% of the sum of the two acid loads. At a flow rate of 1.2 L/s, Bellvue contributes 60% and at a flow rate of 2 L/s, the contribution from Bellvue is only 58%. Since flow rates are less than 1.4 L/s 77% of the time, then the relative contribution to Cannel Creek from Bellvue is mostly 60 to 90% and from the James Mine is mostly 10 to 40%.

Upstream of the AMDs, Cannel Creek has a pH of 4.60-7.28, 0.29 mg/L Fe, 0.14 mg/L Al, and an alkalinity of 3.0-25 mg/L. Downstream of the Bellvue Mine AMD, Cannel Creek has a pH 2.76-4.30, 6.49 mg/L Fe, 5.91 mg/L Al, and 83.4 mg/L acidity. Downstream of the James Mine AMD, Cannel Creek has a pH of 3.11-3.75, 3.3 mg/L Fe, 4.3 mg/L Al, and 42 mg/L acidity. Water quality dilutes with increase in flow rate, however there is some scatter in the data due to the asynchronous flow rates between Cannel Creek and the AMDs during storm events resulting in variable acid load reporting to Cannel Creek. James Creek has a pH of 7.06-7.14, 0.27 mg/L Fe, 0.131 mg/L Al, and 25 mg/L alkalinity. Downstream of the confluence with James Creek, the water chemistry in Cannel Creek improves to a pH of 3.25-4.32, 2.1 mg/L Fe, 3.3 mg/L Al, and 26.4 mg/L acidity.

The asynchronous pattern of the flow regimes in Cannel Creek and the Bellvue AMD during precipitation events has been analysed to determine relative flow rates to be used for geochemical modelling of current stream chemistry and predicted chemistry post treatment of the Bellvue Mine AMD. Data show that for approximately 49% of the time, there has been no precipitation in the previous 24 hours and both Cannel Creek and the AMD are at base flow conditions. The modelled flow rates for this category are 2.7 L/s for Cannel Creek and 0.5 L/s for the AMD. For the remaining 51% of the time, Cannel Creek and the AMD are influenced by precipitation events. These precipitation events have been placed into five categories as follows:

(a) Start of Precipitation: Cannel Creek is at moderate flow; AMD is at base flow
(b) Middle Precipitation-1: Cannel Creek is at high flow; AMD is at moderate flow
(c) Middle Precipitation-2: Cannel Creek is at high flow; AMD is at high flow
(d) End Precipitation-1: Cannel Creek is at moderate flow; AMD is at moderate flow
(e) End Precipitation-2: Cannel Creek is at base flow; AMD is at moderate flow

The results of the modelling predict a current pH of 2.95-4.76 in Cannel Creek downstream of the Bellvue AMD, depending on relative flow rates of the stream and the AMD and depending on if Fe and Al minerals are at equilibrium with the water (tab. 1). The lowest pH and highest metal concentrations occur at the very end of precipitation events, when Cannel Creek is near base flow conditions and the AMD is still at moderate flow ("e" category). The next lowest pH occurs during low flow conditions between precipitation events ("No Precipitation" category). The next lowest pH condition also occurs near the end of precipitation events when moderate flow in Cannel Creek is influenced by moderate flow from the AMD ("d" category). The other three modelled conditions, during the start and middle of precipitation events when the flow rate of Cannel Creek is substantially greater than that of the AMD, show relatively high pH in the stream and dilution of metal concentrations reporting from the AMD.

Modelling was completed again for all six flow categories assuming up to 1 L/s of the Bellvue AMD was treated and then discharged to the stream (tab. 2). For the categories where the AMD flow rate was greater than 1 L/s (all flow conditions with the exception of "No Precipitation" and "a" category), the modelling included mixing of the untreated AMD with the treated AMD prior to mixing with Cannel Creek. The results show that overall, 88-91% of the time the pH in Cannel Creek is greater than 5 and 9-12% of the time it is less than 5. The lowest pH is predicted when both Cannel Creek and the AMD are at high flow conditions ("c" category). During this stage, the pH is predicted to be 4.19-4.28. The effects of a typical storm event in the area lasts for approximately three days, from start of precipitation to end of precipitation and return of flow rates to near base level conditions. Once treatment of the Bellvue AMD commences, the category with the lowest resulting pH in Cannel Creek ("c" category) is predicted to last for approximately 13 hours during each storm event and is expected to occur 9% of the time.

Modelling predicts a current pH of 2.87-4.25 in Cannel Creek downstream of the James Mine AMD, depending on relative flow rates of the stream and the AMD and depending on if Fe and Al minerals are at equilibrium with the water (tab. 3). When comparing precipitation categories, the pattern of the severity of impact on pH to Cannel Creek is identical to that from the Bellvue Mine AMD. The lowest pH and highest metal concentrations occur at the very end of precipitation events.

Once treatment of up to 1 L/s of the Bellvue AMD begins, modelling predicts that overall, 49% of the time the pH in Cannel Creek downstream of the James Mine AMD is greater than 5, 29% of the time the pH is between 4 and 5, and 22% of the time the pH is between 3 and 4 (tab. 4). The lowest pH is predicted for the "e" category. During this stage, 1 L/s of Bellvue AMD is being treated but 0.5 L/s is not being treated and 0.25 L/s of James Mine AMD is discharging to Cannel Creek, and the resulting pH is 3.30-3.47. During a typical storm event, this category is predicted to last for approximately four hours and is expected to occur only 3% of the time.

Modelling predicts a current pH of 2.98-6.49 in Cannel Creek downstream of James Creek, depending on relative flow rates of the two streams and the two AMDs and depending on if

Fe and Al minerals are at equilibrium with the water (tab. 5). When comparing precipitation categories, the pattern of the severity of impact on pH to Cannel Creek is identical to that from the Bellvue Mine AMD and James Mine AMD. The lowest pH and highest metal concentrations occur at the very end of precipitation events.

Once treatment of up to 1 L/s of the Bellvue AMD begins, the results show that overall, 78% of the time the pH in Cannel Creek downstream of the tributary is greater than 6, 19% of the time the pH is between 4 and 6 (as high as 5.29), and 3% of the time the pH is between 3 and 4 (tab. 6). The lowest pH is predicted for the "e" category, when Cannel Creek and James Creek have returned to near base-flow flow rates and both the Bellvue Mine AMD and James Mine AMD are still flowing at moderate flow rates.

***Table 1** Modelling results for Cannel Creek below Bellvue AMD under current conditions.*

Frequency	Condition	Cannel Creek flow (L/s)		Bellvue AMD flow (L/s)		Cannel Creek (just above and just below Bellvue Mine)							
						pH		Fe		Al		Alkalinity	
						Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
49%	no precipitation	base flow	2.7	base flow	0.5	6.09	3.25 3.06	0.30	12.7 2.16	0.09	6.64 6.64	12.76	0
18%	start precipitation	moderate flow	25	base flow	0.75	5.29	4.31 4.11	0.25	2.58 0.067	0.14	1.37 1.37	9.12	0
11%	middle precipitation-1	high flow	100	moderate flow	1.5	5.12	4.76 4.45	0.33	0.81 0.04	0.23	0.56 0.27	3.94	0
9%	middle precipitation-2	high flow	100	high flow	5	5.12	3.96 3.86	0.33	1.71 0.11	0.23	1.42 1.42	3.94	0
10%	end precipitation-1	moderate flow	25	moderate flow	1.5	5.29	3.92 3.77	0.25	3.12 0.15	0.14	2.11 2.11	9.12	0
3%	end precipitation-2	base flow	3.5	moderate flow	1.5	6.09	3.09 2.95	0.30	14.6 4.86	0.09	9.97 9.97	12.76	0

***Table 2** Modelling results for Cannel Creek below Bellvue AMD assuming 1 L/s treatment of Bellvue AMD.*

Frequency	Condition	Cannel Creek flow (L/s)		Bellvue AMD flow (L/s)		Cannel Creek (just above and just below Bellvue Mine)							
						pH		Fe		Al		Alkalinity	
						Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
49%	no precipitation	base flow	2.7	base flow	0.5	6.09	6.04 6.03	0.3	0.89 0.002	0.09	0.16 0.0004	12.76	43 41
18%	start precipitation	moderate flow	25	base flow	0.75	5.29	5.46 5.44	0.25	0.36 0.006	0.14	0.15 0.002	9.12	15 14
11%	middle precipitation-1	high flow	100	moderate flow	1.5	5.12	5.09 4.95	0.33	0.33 0.01	0.23	0.28 0.01	3.94	4 2
9%	middle precipitation-2	high flow	100	high flow	5	5.12	4.28 4.19	0.33	1.02 0.05	0.23	1.18 1.18	3.94	0 0
10%	end precipitation-1	moderate flow	25	moderate flow	1.5	5.29	5.25 5.14	0.25	0.24 0.01	0.14	0.43 0.01	9.12	8 6
3%	end precipitation-2	base flow	3.5	moderate flow	1.5	6.09	5.63 4.83	0.3	0.22 0.01	0.09	1.53 0.09	12.76	8 0

***Table 3** Modelling results for Cannel Creek below James Mine AMD under current conditions.*

Frequency	Condition	Cannel Creek flow upstream of James Mine		James Mine AMD flow (L/s)		Cannel Creek (just above and just below James Mine)							
						pH		Fe		Al		Alkalinity	
						Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
49%	no precipitation	base flow	3.2	base flow	0.06	3.06	3.02 3.00	2.16	5.1 3.38	6.64	10.5 10.5	0.00	0
18%	start precipitation	moderate flow	25.8	base flow	0.1	4.11	3.94 3.90	0.07	0.66 0.10	1.37	2.20 2.20	0.00	0
11%	middle precipitation-1	high flow	102	moderate flow	0.25	4.45	4.25 4.22	0.04	0.34 0.06	0.27	0.70 0.70	0.00	0
9%	middle precipitation-2	high flow	105	high flow	0.95	3.86	3.65 3.60	0.11	1.59 0.24	1.42	3.39 3.39	0.00	0
10%	end precipitation-1	moderate flow	26.5	moderate flow	0.25	3.77	3.60 3.55	0.15	1.63 0.28	2.11	4.08 4.08	0.00	0
3%	end precipitation-2	base flow	5	moderate flow	0.25	2.95	2.90 2.87	4.86	12.0 9.47	9.97	19.5 19.5	0.00	0

***Table 4** Modelling results for Cannel Creek below James Mine assuming 1 L/s treatment of Bellvue AMD.*

Frequency	Condition	Cannel Creek flow upstream of James Mine		James Mine AMD flow (L/s)		Cannel Creek (just above and just below James Mine)							
						pH		Fe		Al		Alkalinity	
						Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
49%	no precipitation	base flow	3.2	base flow	0.06	6.04	5.59 4.99	0.89	2.97 0.010	0.16	4.01 0.030	42.63	29 5
18%	start precipitation	moderate flow	25.8	base flow	0.1	5.46	4.32 4.25	0.36	0.60 0.047	0.15	0.80 0.80	14.82	0 0
11%	middle precipitation-1	high flow	102	moderate flow	0.25	5.09	4.45 4.40	0.33	0.31 0.04	0.28	0.41 0.41	3.91	0 0
9%	middle precipitation-2	high flow	105	high flow	0.95	4.28	3.81 3.74	1.02	1.53 0.15	1.18	3.19 3.19	0.00	0 0
10%	end precipitation-1	moderate flow	26.5	moderate flow	0.25	5.25	3.98 3.89	0.24	1.50 0.10	0.43	2.02 2.02	8.38	0 0
3%	end precipitation-2	base flow	5	moderate flow	0.25	5.63	3.47 3.30	0.22	7.43 0.98	1.53	10.1 10.1	8.02	0 0

***Table 5** Modelling results for Cannel Creek below James Creek under current conditions.*

Frequency	Condition	Cannel Creek flow downstream of		James Creek flow (L/s)		Cannel Creek (just above and just below James Creek)							
						pH		Fe		Al		Alkalinity	
						Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
49%	no precipitation	base flow	3.26	base flow	1.35	3.00	3.21 3.19	3.38	2.5 1.24	10.48	7.5 7.5	0.00	0
18%	start precipitation	moderate flow	25.9	base flow	12.5	3.9	5.30 4.40	0.10	0.16 0.04	2.20	1.52 0.51	0.00	0
11%	middle precipitation-1	high flow	102	moderate flow	50	4.22	6.49 6.45	0.06	0.56 0.001	0.70	0.08 0.0004	0.00	5
9%	middle precipitation-2	high flow	106	high flow	50	3.6	4.42 4.23	0.24	0.25 0.05	3.39	2.35 2.12	0.00	0
10%	end precipitation-1	moderate flow	26.8	moderate flow	12.5	3.55	4.24 4.19	0.28	0.28 0.05	4.08	2.83 2.78	0.00	0
3%	end precipitation-2	base flow	5.25	moderate flow	1.75	2.87	3.02 2.98	9.47	7.2 4.59	19.53	14.7 14.7	0.00	0

***Table 6** Modelling results for Cannel Creek below James Creek assuming 1 L/s treatment of Bellvue AMD.*

Frequency	Condition	Cannel Creek flow downstream of		James Creek flow (L/s)		Cannel Creek (just above and just below James Creek)							
						pH		Fe		Al		Alkalinity	
						Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
49%	no precipitation	base flow	3.26	base flow	1.35	4.99	6.86 6.88	0.01	0.09 0.001	0.03	0.06 0.001	4.73	7 6
18%	start precipitation	moderate flow	25.9	base flow	12.5	4.25	6.13 6.03	0.05	0.12 0.002	0.80	0.58 0.0004	0.00	6 3
11%	middle precipitation-1	high flow	102	moderate flow	50	4.4	6.41 6.43	0.04	0.12 0.001	0.41	0.32 0.0004	0.00	7 5
9%	middle precipitation-2	high flow	106	high flow	50	3.74	4.85 4.27	0.15	0.19 0.04	3.19	2.22 1.54	0.00	1 0
10%	end precipitation-1	moderate flow	26.8	moderate flow	12.5	3.89	5.29 4.44	0.10	0.15 0.03	2.02	1.42 0.54	0.00	3 0
3%	end precipitation-2	base flow	5.25	moderate flow	1.75	3.3	3.53 3.51	0.98	0.80 0.36	10.13	7.6 7.6	0.00	0 0

Discussion

This work shows that the greatest impact to Cannel Creek from the Bellvue Mine AMD and the James Mine AMD occur at the tail end of storm events, when the flow rates in Cannel Creek have returned to near base level but the flow rates in the AMD are still elevated due to the lag in response time to precipitation. This situation may be common for abandoned underground mines that are near the surface and affected by rainfall (through fracturing, etc.), which discharge AMD to surface water streams and may even occur with large overburden dumps. Dilution of the acidity from the AMD by Cannel Creek occurs to some extent during high flow events, however, this is tempered by the increased acid load in the AMD with increased flow.

Once the Bellvue AMD is being treated, the flow conditions which will have the greatest impact on Cannel Creek will no longer be at the tail end of storm events, but rather, will be during the highest flow events, when a relatively smaller proportion of the AMD is being treated and stream dilution is not adequate. Downstream however, the greatest impact to Cannel Creek from the James Mine AMD will continue to be during the post-storm event periods, even under the Bellvue AMD treatment scenario. This is because no treatment will be undertaken at the James Mine and the post-storm event scenario involves the least dilution effects of the AMD by Cannel Creek. Likewise, recovery of Cannel Creek after the junction with James Creek will be least during these post-storm events. Fortunately, these post-storm event periods only occur three percent of the time and last for approximately four hours each time.

Ideally, pH levels above 4.5 and metal concentrations below 1 mg/L are necessary for the ecology in the stream to recover (Cavanagh et al. 2010). For approximately 49% of the time this condition will be met for the entire Cannel Creek from Bellvue Mine to the junction with the Nine Mile Creek (1.6km). For the other 51% of the time, the section from James Mine to James Creek (150m) will not meet this condition. For approximately 9% of the time the section between Bellvue Mine and the James Mine (550m) will also not meet this condition, and for approximately 3% of the time the section from James Creek to the Nine Mile Creek (890m) will not meet this condition. It is possible that once the ecology has recovered adequately, it can withstand these short duration pulses of acidic water during precipitation events.

The results of this analysis suggest that contingencies for treatment during Bellvue Mine AMD high flow events should be considered to avoid any pH drop in the stream during these events. Likewise, if additional alkalinity can be added to Cannel Creek during post-storm event periods, there would be less of a drop in pH downstream of the James Mine AMD.

Conclusion

The abandoned Bellvue Mine and James Mine both discharge AMD to nearby Cannel Creek. The Bellvue AMD has a pH of 2.28-3.01 and 69 mg/L Fe, 39 mg/L Al, 0.76 mg/L Mn, 0.32 mg/L Zn, and 0.15 mg/L Ni. The James Mine AMD has a much lower flow rate than the Bellvue Mine AMD and has a pH of 2.41-2.80 and 148 mg/L Fe, 200 mg/L Al, 6.5 mg/L Mn, 1.21 mg/L Zn and 0.56 mg/L Ni. Between 60% and 90% of the hydrogen ion acidity contribution from these two sources is from the Bellvue Mine AMD. The water quality in Cannel Creek degrades from near-neutral pH with low metal concentrations to an acidic stream with high metal concentrations. Both AMD sites show a delayed response to precipitation events, resulting in an asynchronous flow rate pattern with Cannel Creek. The greatest impact to Cannel Creek occurs during post-storm event periods, when the AMD flow rates are still elevated but Cannel Creek is returning to base level.

Once planned treatment is installed at the Bellvue Mine, it is expected that the entire length of Cannel Creek from Bellvue to the Nine Mine Creek (1.6km) will be restored to a pH above 5 during low-flow conditions between precipitation events (49% of the time), which should allow the aquatic ecosystem to recover. However, during precipitation events, various sections of Cannel Creek may not meet a minimum recommended pH of 4.5 for a healthy ecosystem. For 9% of the time, the section from the Bellvue Mine to the James Creek tributary (700m) may not meet this condition and for 3% of the time the section from James Creek to the Nine Mile Creek (890m) may not meet this condition. During all stages of precipitation events (51% of the time), the short section between the James Mine and James Creek (150m) is expected to have a pH below 4.5. It is possible, however, that once recovered, the aquatic ecosystem can withstand these short duration pulses of acidic water during precipitation events. As a result of this work, contingencies for treatment during high flow events will be considered.

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