Options for Treating Acid Mine Drainage at Stockton Mine, New Zealand

Phil Lindsay[a)], Mark Pizey[a)], Paul Weber[a)]

[a)] *Solid Energy NZ Ltd, 2 Show Place, Christchurch, New Zealand e-mail: phil.lindsay@solidenergy.co.nz*

Abstract
Acid Mine Drainage (AMD) emanating from Stockton Coal Mine and associated historic mines on Stockton plateau, New Zealand is unique in terms of volume with a mean of approximately 3500 litres a second potentially requiring treatment and peak flows of up to 10,0000 litres a second; and quality with Al:Fe ratios of 3:1. Dissolved Aluminium concentrations in streams at the coal mine licence boundary can be 100 mg/L and pH as low as 2.7.
The site has over 6 metres of rainfall a year and the runoff coefficients are 0.6 to 0.9. The current open cast mine site operator Solid Energy New Zealand Ltd is reviewing the cost, permit issues and practicality of various options to manage AMD including:

1) Piping AMD to ocean via outfall
2) Piping AMD to ocean via a hydroscheme and outfall
3) Active treatment- dosing streams with ultrafine limestone, combined with capping acidic waste rock to minimize acid production
4) Passive Treatment (e.g., engineered wetlands)

The positives and negatives of the four main treatments are discussed in this paper. The results of water quality and stream ecology improvements in the current active treatment with ultrafine limestone dosing direct to stream are detailed.

Key words: acid drainage, ocean piping, passive treatment, active dosing, treatment costs, permitting, saturated covers.

Background
Underground and opencast coal mining has been ongoing since 1896 on the Stockton Plateau, West Coast, New Zealand. Acid Mine Drainage (AMD) from historic and current mine workings has had an adverse environmental impact on the surrounding aquatic environment. Current Stockton open cast mine operations (1944 to present) now cover a total area of some 700 hectares and approximately 800 hectares contain historic (1896-1969) underground workings. Total disturbed overburden due to open cast mining is 140 million tonnes averaging 1% sulfur.
The Stockton Mine is located at altitudes ranging from 700 – 1100m (Fig. 1) and the ocean/sea level is within 2 km of the western mine boundary. The prevailing northwest air stream rising against the coastal range results in six meters of rainfall per annum. The high rainfall and high flashy flows present a challenge for the implementation of AMD control strategies.
Catchments affected by AMD from historic and current mine workings are those of the Mangatini and St Patrick streams and Mine Creek (Fig. 1). These drain to the lower Ngakawau River (site NR, Fig. 1), which has high amenity value.

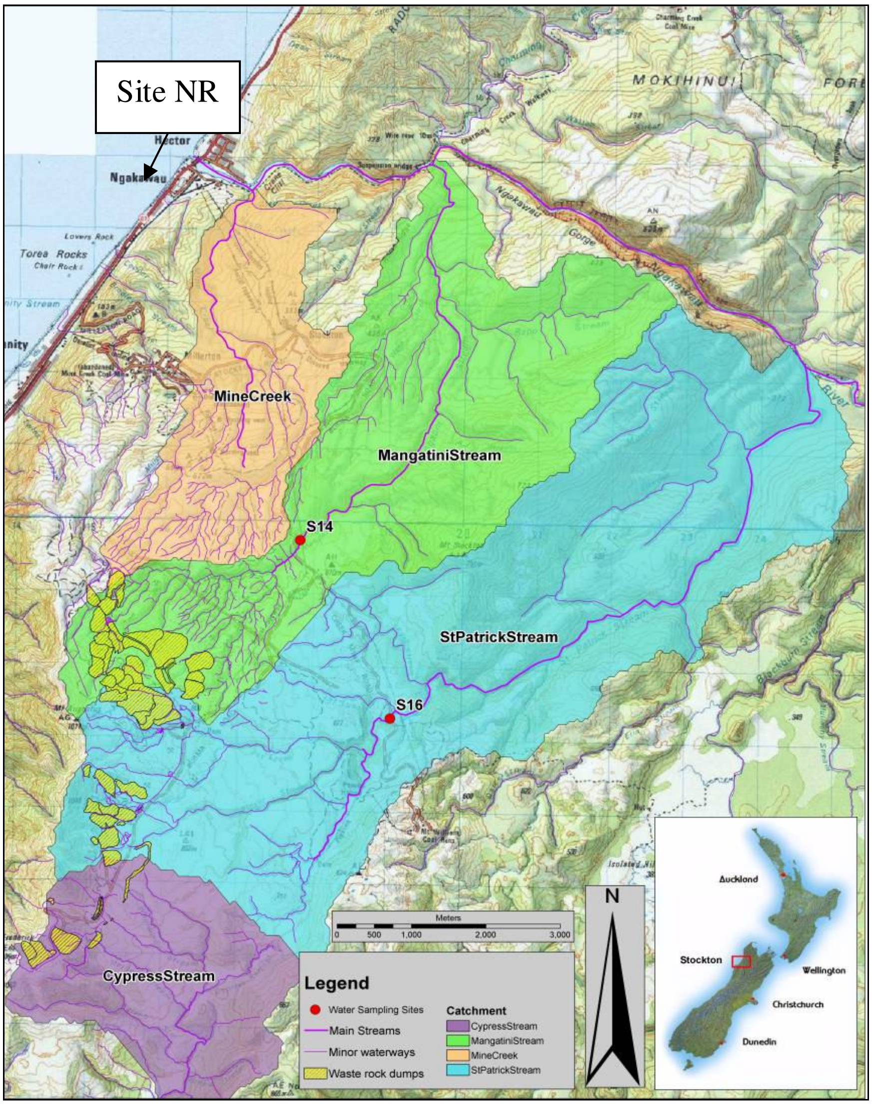
Objective
Improve water quality in the Ngakawau River and tributary streams (Mangatini; St. Patricks and Mine Creek, Fig. 1) to sustain native fish (whitebait (*galaxiids*)) life. Key criteria derived from ecotoxicology test work on native fish, mayfly and caddis fly larvae are as follows:

- pH>4.7
- Dissolved Aluminium <1 mg/L
- Turbidity <25 NTU for >80% of the time (Richardson *et al*, 2001)

Current solution
9,000 tonnes per year of ultrafine limestone (90% <0.1 mm, neutralization efficiency 60-65%) has been pumped in continuous slurry into the Mangatini stream at site S14 (see Fig. 1) since April 2007.

Resulting pH and dissolved Aluminium at site NR is meeting criteria for whitebait recruitment and migration for >90% of the time (Fig. 2).

Figure 1 *Location map of the Stockton opencast coal mine and drainage catchments.*



In addition to the limestone dosing, acidic waste rock is being capped at rates of 25 Ha a year. Capping with 400 mm of weathered granite to permeability of 1 x 10-7 m/s and covered with 300 mm of top soil provides a capillary break with the underlying acidic waste rock (permeability 1 x 10^{-4} to 1 x 10^{-5} m/s) and the high rainfall (6 m/year) allows for a saturated cap to be maintained and a reduction in oxygen ingress and acid generation.

Oxygen probes through the capped waste rock indicate that oxygen conditions can be reduced from 21% to consistently less than 10% and with a median of <5% and minimum of 1%. Laboratory test work using homogenized acidic waste rock samples with oxygen pumped through at rates similar to diffusion rates measured in the field and constant concentrations of 1, 10 and 21 % oxygen indicated reductions in acid production of 90% and 60% in the columns with 1% and 10% oxygen respectively.

Figure 2 *Improved dissolved Aluminium conditions at site NR, lower Ngakawau River due to continuous ultrafine limestone dosing to Mangatini Stream*

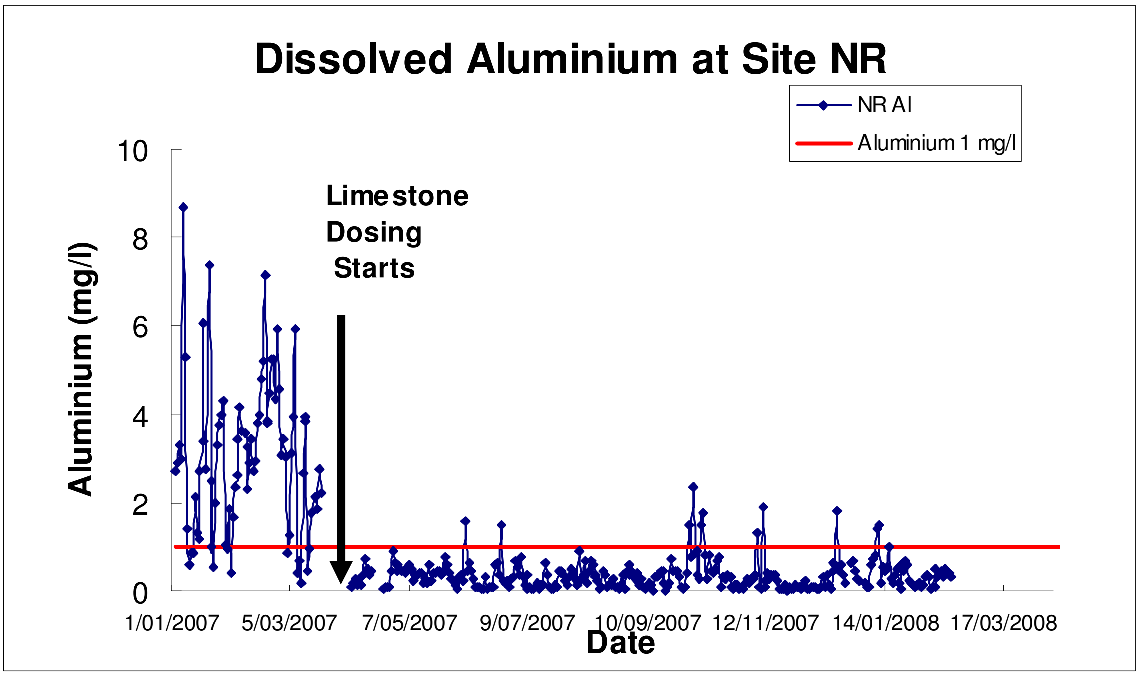
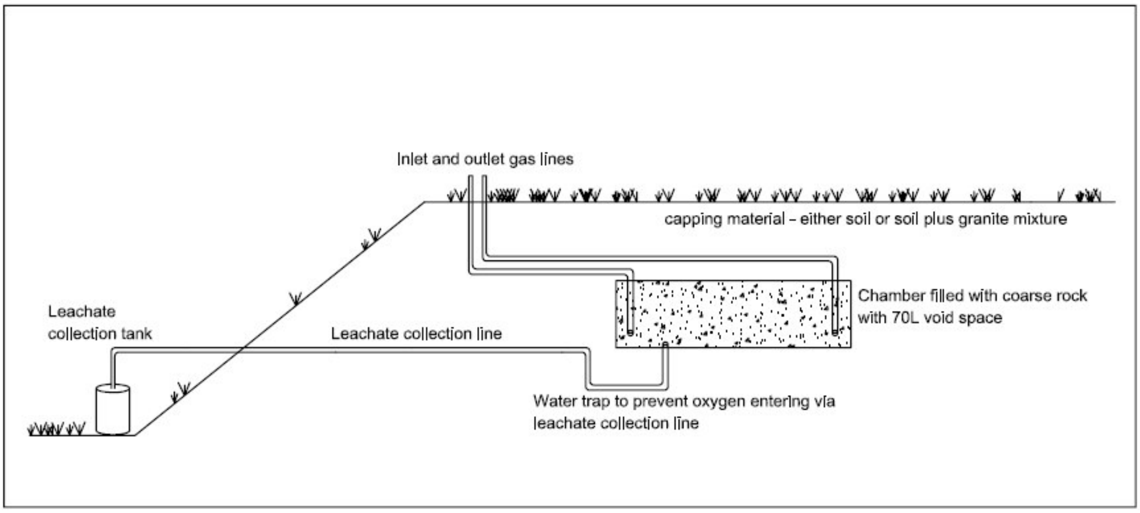


Table 1 *Water quality related to chronic fish (whitebait) 30 day survival ecotox tests. In St. Patrick's stream (S16, Fig. 1) mortality was 100%. Survival in Ngakawau River (NR), Mangatini stream (1000 m downstream S14) was 100% and was higher than control pristine river (Orowaiti). Metals in water are reported as dissolved fraction*

Water sample site	pH pH Units	Al (g.m-3)	Fe (g.m-3)	Cd (g.m-3)	Cu (g.m-3)	Ni (g.m-3)	Zn (g.m-3)
Ngakawau River	5.7	0.06	0.046	0.00029	0.0021	0.031	0.17
Orowaiti River	7.6	0.26	0.12	<0.000050	<0.00050	<0.00050	0.0026
St. Patrick's stream	3.5	6.0	0.85	0.00031	0.0029	0.026	0.15
Mangatini stream	6.9	0.061	<0.020	0.00052	<0.00050	0.1	0.052

Table 1 indicates that water quality in St. Patricks stream will not sustain fish life. Solid Energy is reviewing options to treat AMD in St. Patricks and Mine Creek streams.
Oxygen flux rates through the granite caps were obtained from a field experiment as per figure below. At the beginning of each test the chamber which is filled with non-acid gravel is purgesd with nitrogen gas to remove any oxygen. The oxygen concentration in the chamber is then measured over time to determine the oxygen flux through the capping material

Figure 3 *Field test set up to measure ingress of oxygen through saturated cap material*



Maximum oxygen flux rates through the cap were of the order of 8.6 x 10^{-6} litres/O_2 per m^2/sec. Capping resulted in a maximum acid production rate of 1.2 kg H_2SO_4/m^2 per year. This rate was less than 20% of the maximum acid production from uncapped waste rock.

It is recognized that diffusion; advection due to thermal gradients and/or wind pressure gradients and advection due to barometric pumping can all contribute oxygen to a waste rock pile and lead to pyrite oxidation and acid production.

In addition, dissolved oxygen within water percolating through the caps into the waste rock is another source of oxygen.

Advection from thermal gradients is weak within the Stockton waste rock piles. Monitored temperature increases in the waste rock piles are less than 5° compared with ambient air temperature. The mean height to width ratio of the waste rock piles is between 1:20 to 1:30 and this limits the potential for advective air movement. In addition new waste rock piles are being constructed in 5 m high compacted lifts to reduce oxygen ingress.

Mixing Tests on Stockton Acid Mine Drainage with Seawater

Mixing tests using Stockton AMD treated with limestone and untreated Stockton AMD noted that with a diffusion rate of 100 times dilution that there was no significant physical (turbidity improvement) or chemical benefit in prior treatment of AMD before ocean disposal (Tables 2, 3 & 4).

Table 2 *Dilution of untreated Mangatini Stream AMD (S14 – 24 February 2007) with seawater*

Analytes	Units	ARD 24 Feb 2007 Raw	ARD 24 Feb 2007 10x	ARD 24 Feb 2007 50x	ARD 24 Feb 2007 100x	ARD 24 Feb 2007 200x
pH	pH units	2.9	6.9	7.6	7.8	8
Conductivity	mS/m	139	4860	5200	5240	5260
Acidity to pH 5.0	g/m^3 as $CaCO^3$	402	< 10			
Acidity to pH 7.0	g/m^3 as $CaCO^3$	464	< 10			
Total Dissolved Solids	g/m^3	828	37900	37000	40000	40400
Total Suspended Solids	g.m-3	4	32	11	8	7
Turbidity	NTU	4.3	38.2	2.8	1.9	3
True Hazen Colour		< 5	< 5	< 5 *	< 5	< 5 *
Iron Total	g/m^3	18.6	1.86	0.448	0.332	0.19
Iron Dissolved	g/m^3	16.5	0.006	< 0.004	< 0.004	< 0.004
Aluminium Total	g/m^3	72.8	6.25	1.43	0.72	0.39
Aluminium Dissolved	g/m^3	69.1	0.07	0.19	0.28	0.29
Boron Total	g/m^3	< 0.04	3.89	4.26	4.13	4.15
Boron Dissolved	g/m^3	< 0.04	3.55	3.92	4.01	3.86

Cadmium Total	g/m^3	0.0034	0.0005	< 0.0002	< 0.0002	< 0.0002
Cadmium Dissolved	g/m^3	0.0036	0.0005	< 0.0002	< 0.0002	< 0.0002
Nickel Total	g/m^3	0.389	0.042	0.013	0.009	0.006
Nickel Dissolved	g/m^3	0.392	0.05	0.02	0.016	0.016
Lead Total	g/m^3	0.013	0.002	< 0.001	< 0.001	< 0.001
Lead Dissolved	g/m^3	0.012	0.001	< 0.001	< 0.001	< 0.001
Chromium Total	g/m^3	0.012	< 0.001	< 0.001	< 0.001	< 0.001
Chromium Dissolved	g/m^3	0.014	0.002	0.001	0.001	< 0.001
Arsenic Total	g/m^3	0.007	< 0.004	< 0.004	< 0.004	< 0.004
Arsenic Dissolved	g/m^3	< 0.004	0.007	0.007	0.005	0.006
Mercury Total	g/m^3	< 0.00008	< 0.00008	< 0.00008	< 0.00008	< 0.00008
Mercury Dissolved	g/m^3	< 0.00008	< 0.00008	< 0.00008	< 0.00008	0.00011
Zinc Total	g/m^3	2.21	0.184	0.022	0.019	0.006
Zinc Dissolved	g/m^3	2.32	0.229	0.041	0.023	0.011
Manganese Total	g/m^3	2.3	0.223	0.044	0.022	0.01
Manganese Dissolved	g/m^3	2.43	0.245	0.053	0.03	0.016
Thallium Total	g/m^3	0.0032	0.0004	< 0.0002	< 0.0002	< 0.0002
Thallium Dissolved	g/m^3	0.0033	0.0004	< 0.0002	< 0.0002	< 0.0002
Copper Total	g/m^3	0.41	0.035	0.007	0.004	0.002
Copper Dissolved	g/m^3	0.394	0.014	0.002	0.003	0.001

Based on ANZECC (2000) guidelines for water quality, the critical contaminants in the Stockton AMD mixed with seawater are Zinc, Copper and Nickel, with 95% protection trigger level of 0.015, 0.0013 and 0.070 mg/m^3 respectively (Table 6). AMD and seawater jar mixing tests show no significant difference in the concentrations of Zn, Cu and Ni from the treated and untreated AMD and therefore no environmental benefits from the limestone treatment of AMD. The results for the 100x dilution meet the 95% trigger ANZECC (2000) criteria.

***Table 3** Dilution of treated Mangatini Stream AMD (to pH 5.0) with seawater*

Analytes	**Units**	**ARD partially treated to pH 5.0 Fully mixed**	**ARD partially treated to pH 5.0 10x**	**ARD partially treated to pH 5.0 50x**	**ARD partially treated to pH 5.0 100x**	**ARD partially treated to pH 5.0 200x**
pH	pH units	5.3	7.6	7.9	8	8
Conductivity	mS/m	114	4870	5220	5270	5280
Acidity to pH 5.0	g/m^3 as $CaCO^3$	<10	<10			
Acidity to pH 7.0	g/m^3 as $CaCO^3$	42	<10			
Total Dissolved Solids	g/m^3	363	54	9	8	5
Total Suspended Solids	g.m-3	966	34400	37900	37500	37700
Turbidity	NTU	82.4	11.5	4.5	3.4	3.2
True Hazen Colour		< 5	< 5	< 5*	< 5*	< 5
Iron Total	g/m^3	20.4	1.88	0.517	0.311	0.164
Iron Dissolved	g/m^3	0.011	0.016	0.007	0.011	0.029
Aluminium Total	g/m^3	72.9	6.18	1.44	0.77	0.4
Aluminium Dissolved	g/m^3	1.68	0.11	0.35	2.35	0.32
Boron Total	g/m^3	< 0.04	3.72	3.94	3.98	3.95
Boron Dissolved	g/m^3	< 0.04	3.81	4.14	4.24	4.29

Cadmium Total	g/m^3	0.0037	0.0004	< 0.0002	< 0.0002	< 0.0002
Cadmium Dissolved	g/m^3	0.0033	0.0004	0.0003	< 0.0002	0.0002
Nickel Total	g/m^3	0.384	0.041	0.013	0.018	0.007
Nickel Dissolved	g/m^3	0.384	0.035	0.012	0.009	0.007
Lead Total	g/m^3	0.015	< 0.001	< 0.001	< 0.001	< 0.001
Lead Dissolved	g/m^3	0.003	< 0.001	< 0.001	< 0.001	< 0.001
Chromium Total	g/m^3	0.014	0.003	< 0.001	< 0.001	< 0.001
Chromium Dissolved	g/m^3	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Arsenic Total	g/m^3	0.006	0.005	0.004	< 0.004	< 0.004
Arsenic Dissolved	g/m^3	0.004	< 0.004	< 0.004	< 0.004	< 0.004
Mercury Total	g/m^3	< 0.00008	< 0.00008	< 0.00008	< 0.00008	< 0.00008
Mercury Dissolved	g/m^3	< 0.00008	< 0.00008	< 0.00008	< 0.00008	0.00009
Zinc Total	g/m^3	2.1	0.163	0.034	0.017	0.008
Zinc Dissolved	g/m^3	2.04	0.042	0.01	0.017	0.006
Manganese Total	g/m^3	2.31	0.227	0.05	0.025	0.014
Manganese Dissolved	g/m^3	2.22	0.199	0.04	0.02	0.01
Thallium Total	g/m^3	0.0033	0.0003	< 0.0002	< 0.0002	< 0.0002
Thallium Dissolved	g/m^3	0.0032	0.0004	< 0.0002	< 0.0002	< 0.0002
Copper Total	g/m^3	0.111	0.008	0.002	<0.001	<0.001
Copper Dissolved	g/m^3	0.056	0.001	0.001	0.001	0.002

Table 4 *Dilution of treated Mangatini Creek AMD (to pH 4.2) with seawater.*

Analytes	**Units**	**ARD partially treated to pH 4.2 Supernatant**	**ARD partially treated to pH 4.3 10x**	**ARD partially treated to pH 4.3 50x**	**ARD partially treated to pH 4.3 100x**	**ARD partially treated to pH 4.3 200x**
pH	pH units	4.2	7.1	7.8	7.9	8
Conductivity	mS/m	118	4880	5210	5260	5280
Acidity to pH 5.0	g/m^3 as $CaCO^3$	247	<10			
Acidity to pH 7.0	g/m^3 as $CaCO^3$	313	<10			
Total Dissolved Solids	g/m^3	41	24	11	6	7
Total Suspended Solids	g.m-3	1160	35400	37000	47800	38800
Turbidity	NTU	43.6	8.3	2.8	2.8	3
True Hazen Colour		< 5	20*	< 5	< 5	< 5*
Iron Total	g/m^3	9.46	1.01	0.188	0.131	0.052
Iron Dissolved	g/m^3	0.146	0.014	0.014	0.012	0.009
Aluminium Total	g/m^3	68.4	6.66	1.2	0.69	0.37
Aluminium Dissolved	g/m^3	67.6	0.06	0.27	0.39	0.32
Boron Total	g/m^3	< 0.04	3.69	3.86	4	4.08
Boron Dissolved	g/m^3	< 0.04	4.1	4.15	4.13	4.08
Cadmium Total	g/m^3	0.0033	0.0003	0.0002	< 0.0002	< 0.0002
Cadmium Dissolved	g/m^3	0.0035	0.0004	0.0002	0.0002	0.0003
Nickel Total	g/m^3	0.385	0.042	0.013	0.01	0.007
Nickel Dissolved	g/m^3	0.389	0.038	0.011	0.008	0.007
Lead Total	g/m^3	0.012	< 0.001	< 0.001	< 0.001	< 0.001
Lead Dissolved	g/m^3	0.009	< 0.001	0.002	< 0.001	< 0.001
Chromium Total	g/m^3	0.009	< 0.001	< 0.001	< 0.001	< 0.001
Chromium Dissolved	g/m^3	0.004	< 0.001	< 0.001	< 0.001	< 0.001

Arsenic Total	g/m^3	< 0.004	< 0.004	< 0.004	< 0.004	< 0.004
Arsenic Dissolved	g/m^3	0.004	< 0.004	< 0.004	< 0.004	< 0.004
Mercury Total	g/m^3	< 0.00008	0.0001	< 0.00008	0.00009	0.0001
Mercury Dissolved	g/m^3	< 0.00008	< 0.00008	< 0.00008	< 0.00008	< 0.00008
Zinc Total	g/m^3	2.06	0.171	0.034	0.016	0.008
Zinc Dissolved	g/m^3	2.1	0.112	0.024	0.011	0.007
Manganese Total	g/m^3	2.22	0.202	0.044	0.024	0.011
Manganese Dissolved	g/m^3	2.28	0.209	0.044	0.021	0.01
Thallium Total	g/m^3	0.0032	0.0003	< 0.0002	< 0.0002	< 0.0002
Thallium Dissolved	g/m^3	0.0032	0.0003	< 0.0002	< 0.0002	< 0.0002
Copper Total	g/m^3	0.108	0.009	0.002	<0.001	<0.001
Copper Dissolved	g/m^3	0.11	0.002	0.001	0.001	0.001

Recently consented sewage outfall pipeline from Christchurch City in New Zealand allowed for discharge of treated sewage water with dissolved chromium and arsenic at concentrations of 0.079 and 0.006 g/m3 with near field dilution of a minimum of 61x and discharge of up to 6 cumecs . These metal values in the treated sewage discharge are greater than the chromium and arsenic in the raw acid mine drainage.

Table 5 *Analysis of raw seawater*

Analytes	**Units**	**Seawater**
pH	pH units	8.1
Conductivity	mS/m	5280
Total Dissolved Solids	g/m^3	Not provided
Total Suspended Solids	g/m^3	Not provided
Turbidity	NTU	
Total Alkalinity	g/m^3 as $CaCO_3$	115
Color	Hazen units	< 5
Sodium Total	g/m^3	10700
Sodium Dissolved	g/m^3	10600
Chloride	g/m^3	18400
Calcium Total	g/m^3	413
Calcium Dissolved	g/m^3	411
Magnesium Total	g/m^3	1300
Magnesium Dissolved	g/m^3	1270
Sulphate	g/m^3	2530
Potassium Total	g/m^3	393
Potassium Dissolved	g/m^3	398
Iron Total	g/m^3	0.054
Iron Dissolved	g/m^3	< 0.004
Aluminium Total	g/m^3	0.04
Aluminium Dissolved	g/m^3	0.02
Boron Total	g/m^3	4.23
Boron Dissolved	g/m^3	4.07
Cadmium Total	g/m^3	< 0.0002
Cadmium Dissolved	g/m^3	< 0.0002
Nickel Total	g/m^3	< 0.006
Nickel Dissolved	g/m^3	0.013

Lead Total	g/m^3	< 0.001
Lead Dissolved	g/m^3	< 0.001
Chromium Total	g/m^3	< 0.001
Chromium Dissolved	g/m^3	< 0.001
Arsenic Total	g/m^3	< 0.004
Arsenic Dissolved	g/m^3	0.007
Mercury Total	g/m^3	< 0.00008
Mercury Dissolved	g/m^3	< 0.00008
Zinc Total	g/m^3	< 0.004
Zinc Dissolved	g/m^3	0.009
Manganese Total	g/m^3	< 0.001
Manganese Dissolved	g/m^3	0.003
Thallium Total	g/m^3	< 0.0002
Thallium Dissolved	g/m^3	< 0.0002

To help assess the seawater:AMD mixing test results in Tables 2,3 and 4, reference can be made to ANZECC (2000) guidelines, USEPA (2002) water quality criteria and Canadian (1999) Water Quality Guidelines (Table 6). These standards provide guidelines for the maximum concentrations of potentially toxic metals in marine ecosystems, and act as trigger values for water quality. Table 6 shows typical marine water quality standards

Table 6 *Marine water quality guidelines (all units are in µg/L)*

Metal	**ANZECC 99%**	**ANZECC 95%**	**USEPA CMC**	**USEPA CCC**	**Canadian CCME**
As (III)	2.3	-	6.9 (Arsenic)	3.6 (Arsenic)	12.5
Cd	0.7	5.5	40	8.8	0.12
Cr (III)	7.7	27.4			56
Cr (VI)	0.14	4.4	1100	50	1.5
Cu	0.3	1.3	4.8	3.1	-
Pb	2.2	4.4	210	8.1	-
Hg	0.4	0.7	1.8	0.94	-
Ni	7	70	74	8.2	-
Zn	7	15	90	81	-

AMD Long Term Treatment options- relative costs

Four options were considered- three conceptual and the operational current practice in the Mangatini stream of continuous limestone dosing.

Cost estimates based on pre-feasibility high level costs that include design, construction and consenting costs have been provided in Table 2. The most reliable costs are related to the limestone dosing to sump option that is partially operational and hence based on current operational costs.

Table 7 *Relative NPV AMD treatment cost comparisons using NZ$ per cumec treatment over 100 years at a discount rates of 7.0% and compounded inflation of 2.1% per annum.*

Treatment options	NPV Cost discounted over 100 years (NZ$ to treat one cumec of mine water)
AMD to ocean untreated	0.012
AMD to ocean untreated and via hydroscheme (revenue from hydroscheme included)	0.007
Limestone dosing to sump/pit lake	0.005
Passive Treatment	0.011

The AMD to ocean options are costed as untreated AMD. Jar mixing tests using Stockton AMD treated with limestone and raw Stockton AMD noted that with a diffusion rate of 100 times dilution that there was no physical (turbidity improvement) or chemical benefit in prior treatment of AMD before ocean disposal.

Limestone dosing is the current option and the default. Positives: least expensive (Table 7); abundant local resources of quality limestone that are relatively low cost; proven consenting option. Issues: environmental nuisance of daily deliveries of limestone to site for at least 100 years (up to 25,000 tpa); Water retention structure (sump) maintenance; reliance on sludge held in sump; and requires successful rehabilitation leaving a saturated cap that will maintain integrity for 100 years and provide for at least 60% reduction in acid loads.

Ocean disposal via hydroscheme. Positives: local power generation for the region; lower maintenance and long term disturbance than limestone dosing. Negatives: Economics only viable if do not pre-treat AMD; reliance on large retention structures of the order of 6 Mm^3 capacity; moderate to high consenting issues with AMD to ocean; economics based on 100 year forecast electricity price projections—very difficult to predict; even with large retention structures during large flow events spills would still occur due to 6 m/yr rainfall. Further work modelling the water quality implications of the spill durations and quality are required. However, it is likely some water treatment of the spill mine water would be required.

Ocean disposal no hydroscheme. This is the most costly option (Table 3) and probably the most difficult to consent as there is no obvious benefit to the local or regional community such as electricity.

Passive treatment—this is the second most costly option (Table 3) due to the scarcity of flat land and the construction costs to build flat land for passive treatment systems. It is estimated that between 300 to 350 Hectares would be required to treat 500 L/s of seeps. In addition the water quality of the AMD seeps on site is too aggressive for most passive treatment systems and volumes mean that this option is not a solution for the whole site. Solid Energy intend to use passive treatment to treat some low flow seeps (<5 L/s) with more benign AMD to the south end of the mine site.

The passive treatment option is based on a designed engineered wetland based on a four cell treatment system consisting of a gravel bed, low pH bioreactor cell (for the conversion of ferrous iron to ferric iron), an oxic limestone drain cell to raise pH and allow hydrolysis of ferric iron and aluminium hydroxides to insoluble sludges), and a settling pond (where sludge settles out). Flat land space requirements of 300-350 Ha make this option not practical.

The optimal AMD treatment options in terms of cost and consenting is continuous limestone dosing and precipitate retention.

References

Australian and New Zealand Environment and Conservation Council (ANZECC), (2000) Australian and New Zealand Guidelines for Fresh and Marine Water Quality. http://www.mfe.govt.nz/publications/water/anzecc-water-quality-guide-02/index.html

Richardson, J; Rowe, D.K. & Smith, J.P. (2001) Effects of turbidity on the migration of juvenile banded kokopu (Galaxias fasciatus) in a natural stream. New Zealand Journal of Marine and Freshwater Research, Vol. 35: 191-196