Addressing the environmental effects of mining on the Ngakawau River

D.M. Elder, M.H. Pizey, P.A. Weber, P. Lindsay, P.J. Rossiter, G.A. Rutter, D.G. Thomas, F.M. Crombie, T. Cooper, J.J Wildy

Solid Energy New Zealand Ltd

ABSTRACT

On 17 May 2005 Solid Energy committed to a five-year programme to improve the water quality of the Ngakawau River. Following extensive stakeholder consultation, Solid Energy committed to agreed water-quality targets of pH ≥ 4.7 (99% of the time); Al < 1 mg/L (99% of the time); NTU to be no greater than 25 NTU (based on a 30-day rolling median); and clarity to be >54 cm (NIWA Clarity Tube) > 90% of the time during base flow conditions (base flow is typically observed 70 to 75% of the time).

Significant management systems were developed and infrastructure constructed to achieve these targets including site-wide sedimentation ponds, the Stockton Black Water Treatment Plant; the Mangatini Limestone Dosing Plant; and the Mangatini Sump (900,000 m^3).

For the period January 2011 to September 2011 the target for pH was achieved 97.3% of the time, Al 98.3% of the time, NTU 100% of the time and clarity 89.8%, assuming base flow occurs for 70% of the time. Significant progress has been achieved compare to pre 2005 standards and noteworthy results include the return of *galaxids* inanga (whitebait) in the Ngakawau River. Further work is required to achieve the agreed targets and Solid Energy has plans to mitigate other sources of acid mine drainage and turbidity to the Ngakawau River.

KEYWORDS

Stockton Coal Mine, acid mine drainage, water treatment, erosion, TSS

1 INTRODUCTION

The Stockton opencast coal mine (Figure 1), located on the West Coast of the South Island 35km north of Westport, is owned by Solid Energy New Zealand Ltd and is operated by the Stockton Alliance, a partnership between Solid Energy and Downer EDI Mining New Zealand Ltd. It is the largest opencast mine in New Zealand with an active mining area of ~930 ha; ~180ha of which is rehabilitated. Stockton mine has sufficient economically recoverable resources to continue producing for at least another 20 years and delivers high-quality steelmaking coal for export.

The mine is located on the coastal Stockton Plateau, at 700 to 1100 m above sea level, at the top of a steep scarp that rises almost directly from the coast, <4 km away. Orographic rainfall occurs as prevailing westerly winds that bring moisture-laden air from the Tasman Sea to the mountains. Annual precipitation at the coast is ~3000 mm/year, increasing to ~6000 mm/year at the mine; frequent rain events with daily rainfall exceeding 200 mm can occur at any time throughout the year; and mean annual temperature is ~9°C (Davies et al., 2011). The amount and intensity of rainfall at the mine has significant implications for erosion control of 930ha of disturbed ground and the management of entrained suspended solids within waterways.

Coal on the Stockton Plateau is present within the Eocene estuarine Brunner Coal Measures (BCM) as thick seams of bituminous coal. These coal measures are overlain by marine sediments, mainly mudstones, with some marginal-marine sandstones near the contact with the coal measures. Pyrite is abundant (up to 5 wt%) in the upper portions of the coal measures and the lower parts of the overlying marine sediments (Hughes et al., 2006; Weber et al., 2006; Weisener and Weber, 2010; Pope et al., 2010). Interaction between rainfall, oxygen, and pyritic waste rock results in acid mine drainage or AMD (Alarcon Leon and Anstiss, 2002; Black et al., 2005;

McCauley et al., 2010; Pope et al., 2010). AMD at Stockton contains abundant dissolved Al and Fe, and elevated concentrations of trace metals compared to natural drainages (Alarcon Leon and Anstiss, 2002; Black et al., 2005; de Joux and Moore, 2005).

Several catchments are affected by AMD and elevated total suspended solids (TSS) derived from the Stockton Coal Mine (Figure 1) and earlier mining by Solid Energy's predecessor and a number of private mines. Solid Energy has recognised these adverse effects and the concerns of the local stakeholders. The Mangatini Stream, a significant tributary of the Ngakawau River, was identified as the main source of poor water quality within the Ngakawau catchment and an action plan was established to rectify the issues. Following extensive research into possible solutions and stakeholder consultation (Ngakawau Riverwatch, Buller District Council, West Coast Regional Council, and the Department of Conservation), Solid Energy committed to agreed water-quality targets for the Ngakawau River of:

- pH ≥ 4.7 (99% of the time);
- Al < 1mg/L (99% of the time);
- NTU ≤ 25 NTU based on a 30-day rolling median; and
- Clarity to be >54 cm (NIWA Clarity Tube) > 90% of the time during base flow conditions (base flow is typically observed 70-75% of the time).

To achieve these by the target date of June 2010 significant management systems were developed and infrastructure constructed over the five-year period. Root-cause management systems were put in place to reduce requirements for water treatment, including preventative measures such as staff education and environmental awareness, capping of acid-forming rock to reduce AMD generation, erosion control to reduce sediment loss and revegetation using direct transplants and seedlings to stabilise batter slopes. On the treatment side downstream water treatment technologies were installed, including site-wide sedimentation ponds to capture sediment and coal at the point of generation; the Stockton Black Water Treatment Plant to remove coal fines, sediment, and correct pH; the Mangatini ultrafine limestone dosing plant to increase pH and remove dissolved metals (including aluminium); and the Mangatini Sump to capture AMD sludge, unreacted limestone, and sediment.

This paper presents and discusses the work to date and reviews performance against the agreed targets. Further specific details are available as referenced.

2 METHODOLOGY

2.1 INTRODUCTION

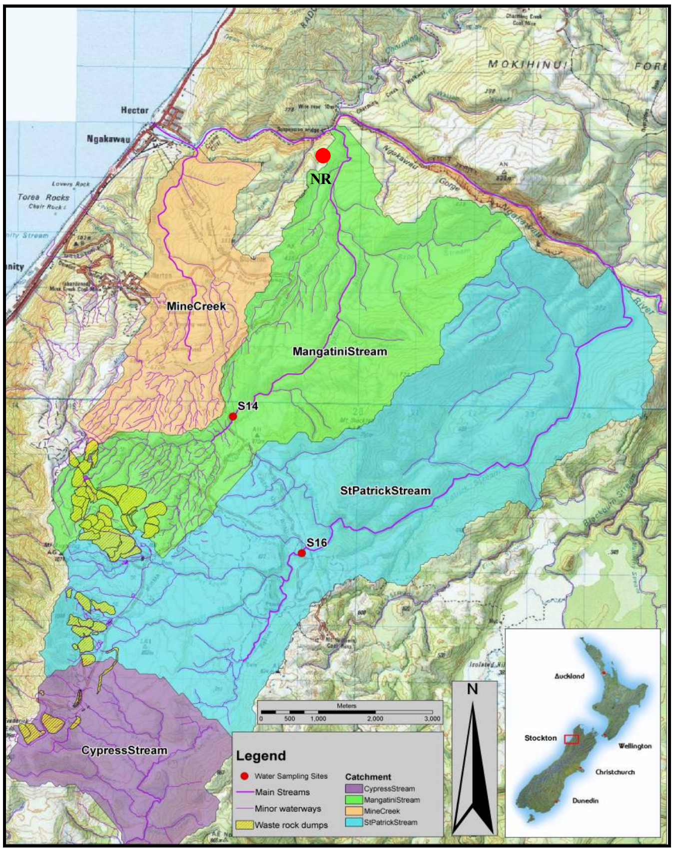
Solid Energy has engaged SGS New Zealand Ltd to undertake the majority of water sampling, in-situ analysis (as required), and laboratory testing as required in accordance with the Australian/New Zealand Standard for Water Quality - Sampling (AS/NZS 5667.1:1998). A number of the water samples are sub-contracted to R J Hill Laboratory in Hamilton.

2.2 ANALYSIS

Water samples were analysed in the field for dissolved oxygen (DO) in accordance with the 4500-OG Dissolved Oxygen Membrane Electrode Method, while the pH, EC, and temperature were determined using a TPS WP 81 pH, Cond, Salinity meter using a TPS pH and conductivity probe, pH electrode double junction with porous Teflon BNC Plug. The meter was calibrated at pH 4 and 7 using TPS or BDH branded buffers weekly.

Acidity (mg L^{-1} $CaCO_3$) was measured by back-titration of a 50 mL aliquot to pH 4, 5, and 7 with 0.1 M NaOH; acidity was then calculated as per the American Public Health Association (APHA 2005). An unacidified sample was filtered through a 0.45 µm membrane filter to remove suspended particulate matter and then sent to R J Hill Laboratory for various parameters. Metals were typically analysed by ICP-MS using the APHA 3125 B 21st ed. 2005 standard method. Ammoniacal nitrogen was determined by phenol/hypochlorite colorimetry using a discrete analyser APHA 4500-NH_3 F (modified from manual analysis) 21st ed. 2005); $CBOD_5$ (chemical biological oxygen demand) was determined by the APHA 5 Day BOD Test, 5210 B, 21st edition 2005).

Figure 1. Catchments affected by mining (Mangatini Stream, St Patrick Stream, and Mine Creek) that drain the Stockton coal mine. *S14, S14b, S16, and NR are standard compliance water-monitoring sites.*



Total suspended solids or TSS was determined by gravimetric analysis of a known representative aliquot of water following filtration and oven drying. Clarity was determined using a NIWA Water Clarity Tube (1000mm long, 44mm internal diameter clear acrylic tube with an adjustable black disk).

Turbidity (NTU) is measured by a HACH 2100N turbidity meter. The unit of measure is NTU (Nephlometric Turbidity Unit). This analysis is undertaken in accordance with Standard Methods APHA 1989 method 2130 B and turbidity is determined by referencing the light scattering properties of a formazin polymer (standard) to the sample being analyzed.

Automatic flow meters have been installed at NR, S14, S14b, and S16. Seeps are measure by small Sensus flow meters.

An important aspect of acid-base-accounting to determine AMD potential is total sulfur determination. This was undertaken by both SGS and Amdel Laboratories and total S was also determined by LECO analysis (Crock et al., 1999) whereby the sample is combusted in an O_2 atmosphere at 1370 ^{o}C (V_2O_5 catalyst) to oxidise sulfide and SO_4 to SO_2 and then the S content is measured by a calibrated solid state infrared detector

3 ACID MINE DRAINAGE

3.1 INTRODUCTION TO AMD

Acid mine drainage (AMD) is the result of sulfide mineral oxidation in the presence of oxygen and water (*e.g.,* Equation 1). Pyrite is the most common sulfide mineral in coal measures and four moles of acid are generated for every mole of pyrite oxidised. The acidity generated by pyrite oxidation can be neutralised by materials such as limestone (*e.g.,* $CaCO_3$). Two moles of $CaCO_3$ are required to neutralise the acidity generated by the oxidation of one mole of pyrite (Equation 2).

$$FeS_2 + {}^{7}/_{2}H_2O + {}^{15}/_{4}O_2 \Rightarrow Fe(OH)_3 + 2H_2SO_4 \qquad (1)$$

$$2CaCO_3 + 2H_2SO_4 \Rightarrow 2Ca^{2+} + 2H_2O + 2CO_2 + 2SO_4^{2-} \qquad (2)$$

The potential for a rock to produced acidity (the maximum potential acidity) can thus be determined by the amount of sulfur present (Equation 3), although there are several assumptions and not all the sulfur may be pyritic (see Weber, 2003)

$$\text{MPA (kg } H_2SO_4/t) = \text{wt\% S x } 30.6 \qquad (3)$$

Where 30.6 is the conversion factor and is determined by:

$$CF\left(for\ pyrite\right) = \left[{2moleH_2SO_4 \times 98.076}\Big/{2moleS \times 32.06}\right] \times 10 \quad = 30.6 \qquad (4)$$

Rocks can contain both pyrite and carbonate, which means that although pyrite may be present, if the carbonate content is sufficient, AMD may not occur. In this regard the Net Acid Production Potential of a rock can be determined by the maximum potential acidity less the acid neutralisation capacity (Equation 5):

$$\text{NAPP (kg } H_2SO_4/t) = \text{MPA} - \text{ANC} \qquad (5)$$

Where the ANC is determined by acid digest of the sample followed by back-titration with base to determine the amount of acid consumed (*e.g.,* IWRI and EGi, 2002; Weber et al., 2004)

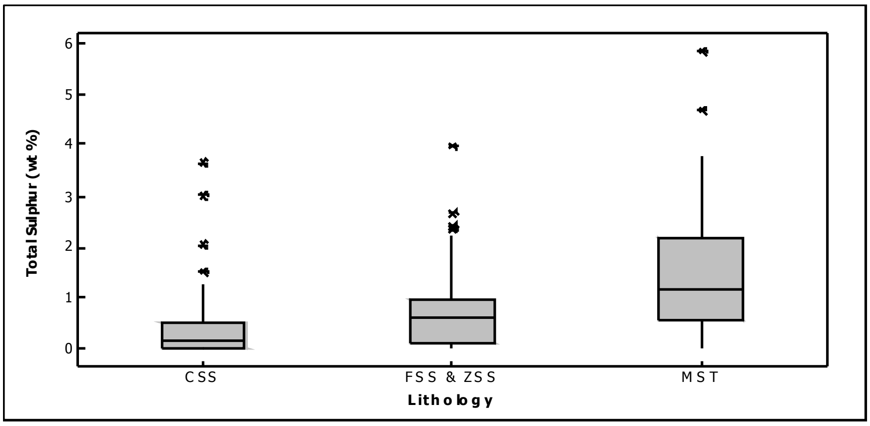
The Brunner Coal Measures (BCM) are often deficient in carbonate minerals, and have very unreactive alumino-silicate minerals (K-feldspar, kaolinite, muscovite) that provide little silicate neutralisation such that the oxidation of pyrite typically leads to the formation of AMD. However, the sulfur content and thus pyrite content of rock varies significantly on a geographic basis and lithologically within the Stockton coal mining area. This is related to the palaeo-environmental setting. Estuarine coal measures tend to have higher pyrite content, whereas fluvial environments are lower in pyrite (see Pope et al., 2010).

Coarse grained sandstones tend to be low in pyrite and thus low acid-forming (LAF) likely due to either deposition in a fluvial (low S) environment or low organic matter availability to convert SO_4^{2-} to H_2S (and thence pyrite). Mudstones and similar lithologies such as carbonaceous mudstones and siltstones tend to be elevated in pyrite which is linked to deposition in a low energy estuarine environment with good sources of Fe, SO_4^{2-}, and organic matter. This lithological variation in sulfur at Stockton coal mine is shown in Figure 2. At the southern end of the mine site within the Mt Frederick mining block the palaeo-environment was fluvial and thus even mudstones can be LAF. This is clearly identified in the tiphead sampling programme dataset where samples are collected daily from active tipheads and analysed for total S (Figure 3).

For AMD management (prevention and treatment) at Stockton the data shown in Figure 3 therefore indicates that the greatest effort to minimise pyrite oxidation and treat AMD formation should be within the northern mining blocks, i.e., the Mangatini Catchment, which will thus provide the greatest water quality improvements in the Ngakawau River where targets have been agreed. This is validated by stream drainage chemistry that indicates seeps discharging from the Mt Frederick mining block to the south have higher pH's and lower acidities (e.g., Herbert Stream seep pH 2.9 – 3.2 and an acidity of 60 -110 mg/L) compared to northern areas that can have pH < 2.0 and acidities > 5000 mg/L (e.g., Collis Seep) (Weber et al., 2008). Similar trends have been identified by McCauley et al. (2010).

Although Mangatini Stream has been identified as the priority catchment for mitigating the effects on the Ngakawau River, Solid Energy has embarked on plans to treat all waterways affected by AMD including Mine Creek, Ford Creek, Fly Creek, and St Patrick Stream.

Figure 2. Total Sulphur of the Brunner Coal Measures (northern sites – does not include Mt Frederick mining block). *CSS = coarse sandstones (104 samples), FSS & ZSS = Fine sandstones and siltstones (145 samples), MST = mudstones (76 samples). The upper whisker shows the highest data value within the upper limit. The top of the box is the third quartile. The median is the middle of the data and this is shown by the line within the box. The bottom of the box is the first quartile. The lower whisker extends to the lowest value within the lower limit. The Asterisk's represent outliers.*



As shown in Equation 1 the oxidation of pyrite releases Fe, SO_4, acidity, and produces low pH in drainage waters. Low pH leads to the dissolution of metals from the surrounding rock. For example, at pH values < 4.5, Al is partially leached from alumino-silicate minerals. The end result is elevated metals (Fe, Al, trace metals) and high acidity in streams draining the Stockton Plateau that have been affected by historical and current mining operations. It was estimated that the Mangatini Stream discharged 756 tonnes of Al, 300 tonnes of Fe, and ~6,200 tonnes of acidity ($CaCO_3$ equivalent) per year (PCE, 2006,) prior to Solid Energy embarking on its 5 year programme to improve water quality in the Mangatini Stream and thus the Ngakawau River. Further details relating to the Mangatini stream geochemistry is available (Davies et al., 2011).

3.2 AMD MINIMISATION

3.2.1 INTRODUCTION

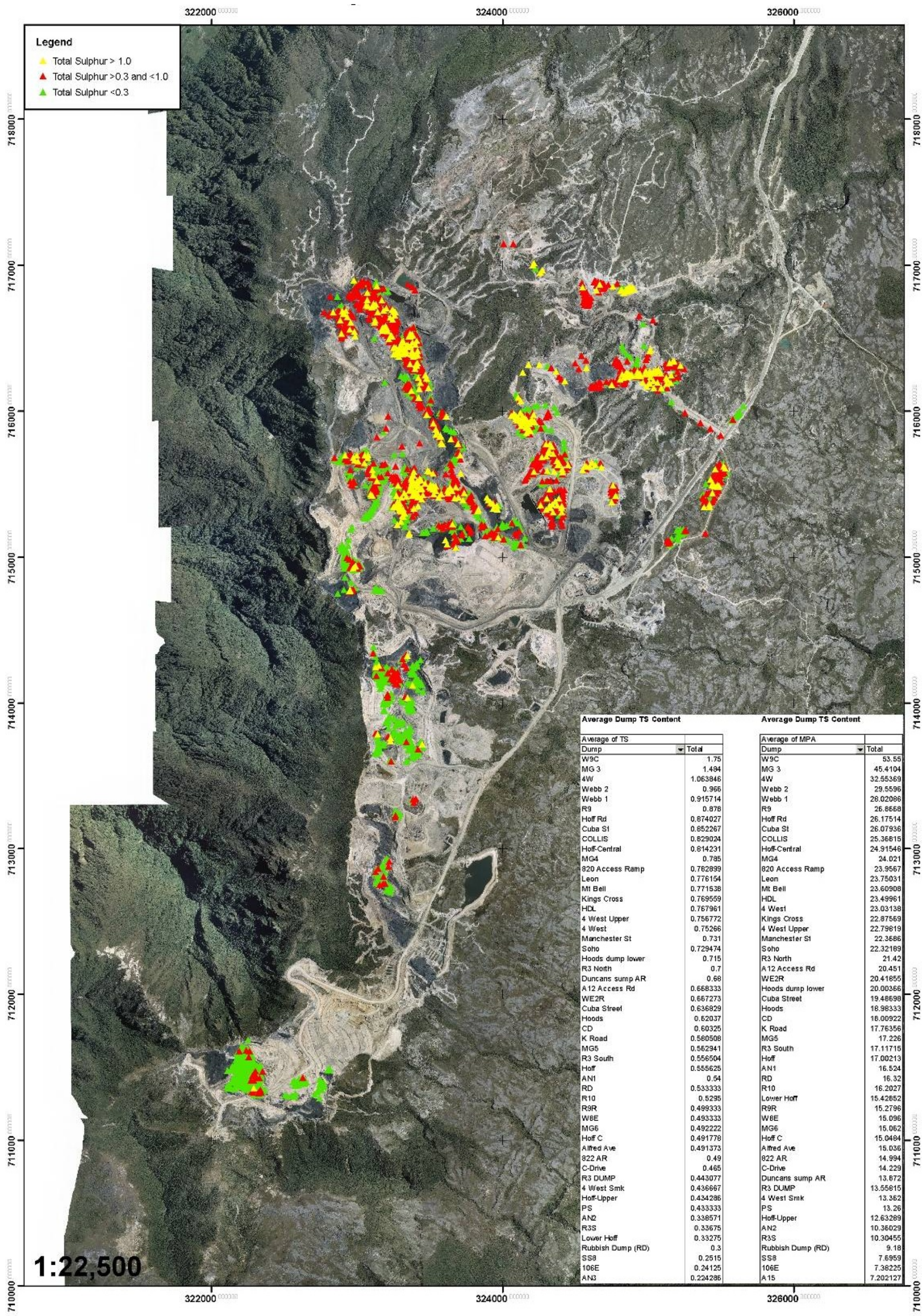
An integral part of the AMD management plan at Stockton is the separation of the overburden rock and the subsequent overburden dumps into their propensity to generate AMD. This is undertaken at the exploration stage whereby drill core is sampled and analysed for total S (to determine MPA) and thence the NAPP determined, with the assumption that ANC is zero for the BCM (see Weber et al 2006). Within the Kaiata mudstone the NAG (Net Acid Generation) test is used (IWRI and EGi, 2002; Weber et al., 2004) as carbonates are also present and need to be accounted for.

For the BCM the non-acid-forming (NAF), low acid-forming (LAF) and potentially acid-forming (PAF) rocks are separated, often based on lithology (Table 1). Conglomerates and granite beneath the BCM are NAF; coarse grained quartz sandstones are often LAF and both are a valuable construction material for roadways and for capping PAF rock within engineered landforms. As shown in Figure 2 the mudstones are typically PAF or high PAF.

Table 1. AMD characterization for the Brunner Coal Measures, Stockton Coal mine.

AMD Classification	**NAPP (kg H_2SO_4/t)**
Non-Acid Forming (NAF)	<0
Low Acid Forming (LAF)	0 - 5
Potentially Acid Forming (moderate) (PAF)	5 - 30
Potentially Acid Forming (high) (PAF)	> 30

Figure 3. Total S content for rock samples collected daily from active tipheads. Data up to 2007.



Average Dump TS Content

Average of TS	
Dump	Total
W9C	1.75
MG 3	1.484
4W	1.063846
Webb 2	0.966
Webb 1	0.915714
R9	0.878
Hoff Rd	0.874027
Cuba St	0.852267
COLLIS	0.829024
Hoff-Central	0.814231
MG4	0.785
820 Access Ramp	0.782899
Leon	0.776154
Mt Bell	0.771538
Kings Cross	0.769559
HDL	0.767961
4 West Upper	0.756772
4 West	0.75266
Manchester St	0.731
Soho	0.729474
Hoods dump lower	0.715
R3 North	0.7
Duncans sump AR	0.68
A12 Access Rd	0.668333
WE2R	0.667273
Cuba Street	0.636829
Hoods	0.62037
CD	0.60325
K Road	0.580508
MG5	0.562941
R3 South	0.556504
Hoff	0.555625
AN1	0.54
RD	0.533333
R10	0.5295
R9R	0.499333
W8E	0.493333
MG6	0.492222
Hoff C	0.491778
Alfred Ave	0.491373
822 AR	0.49
C-Drive	0.465
R3 DUMP	0.443077
4 West Smk	0.436667
Hoff-Upper	0.434286
PS	0.433333
AN2	0.338571
R3S	0.33675
Lower Hoff	0.33275
Rubbish Dump (RD)	0.3
SS8	0.2515
106E	0.24125
AN3	0.224286

Average Dump TS Content

Average of MPA	
Dump	Total
W9C	53.55
MG 3	45.4104
4W	32.55369
Webb 2	29.5596
Webb 1	28.02086
R9	26.8668
Hoff Rd	26.17514
Cuba St	26.07936
COLLIS	25.36815
Hoff-Central	24.91546
MG4	24.021
820 Access Ramp	23.9567
Leon	23.75031
Mt Bell	23.60908
HDL	23.49961
4 West	23.03138
Kings Cross	22.87569
4 West Upper	22.79819
Manchester St	22.3686
Soho	22.32189
R3 North	21.42
A12 Access Rd	20.451
WE2R	20.41855
Hoods dump lower	20.00366
Cuba Street	19.48698
Hoods	18.98333
CD	18.00922
K Road	17.76356
MG5	17.226
R3 South	17.11715
Hoff	17.00213
AN1	16.524
RD	16.32
R10	16.2027
Lower Hoff	15.42852
R9R	15.2796
W8E	15.096
MG6	15.062
Hoff C	15.0484
Alfred Ave	15.036
822 AR	14.994
C-Drive	14.229
Duncans sump AR	13.872
R3 DUMP	13.55815
4 West Smk	13.362
PS	13.26
Hoff-Upper	12.63289
AN2	10.36029
R3S	10.30455
Rubbish Dump (RD)	9.18
SS8	7.6959
106E	7.38225
A15	7.202127

Calculations based on Equation 1, using 10 mg/L oxygen in rainwater indicates that with 5m of rainfall per year at Stockton and an infiltration rate of 0.3 this equates to 25g H_2SO_4 per m^2 per year or 250kg H_2SO_4 per Ha per year and 250 tonnes for 1000ha currently disturbed per year, which is minor compared to the current acid load of ~6,200 tpa for the Mangatini Stream alone. Thus encapsulation of PAF rock by NAF rock and engineered covers must limit the amount of oxygen that can reach the sulfide rich rock and hence the amount of acidity generated (e.g., Equation 1) rather than water exclusion. The following section looks at ways to minimise AMD formation by oxygen exclusion.

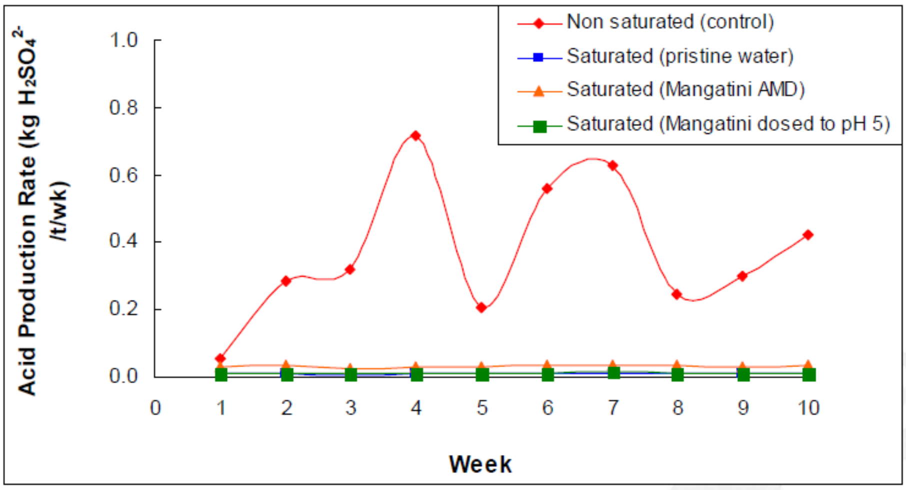
3.2.2 ENGINEERED LANDFORMS

A general requirement for the management of overburden is the need to minimize the time between blasting of the PAF rock and placement within an engineered landform, which minimizes the amount and duration of interaction of the PAF rock with oxygen and water. Overburden rock is then carted to the engineered landform and whenever possible the dumps are constructed by end-tipping where the height of the lift is limited to 5m or less. Heavy traffic thence compacts this lift. End tipping can create fines and coarse rock separation and a chimney effect whereby oxygen flows down the coarse layers enabling deep penetration into the core of the engineered landform (Figure 4). Limiting end-tip height reduces the depth of oxygen penetration. Trials on site have demonstrated that 5m lifts can reduce dissolved aluminium in drainage waters by 10-30% and reduce acidity by 10-15% (pers. comm. Phil Lindsay).

Figure 4. Autopsy of a waste dump constructed by end-tipping. *Note the pathways for oxygen ingress (coarse material). Figure courtesy of Environmental Geochemistry International Pty*

Previous work (see Hughes et al., 2007 for details and methodology) has demonstrated that permanent saturation of PAF rock with rainwater, or even AMD effectively shuts down acid generation by preventing oxygen reacting with the sulfides present in the submerged waste rock (Figure 5). This has important design ramifications for engineered landforms in that many are constructed in old pits and this can provide 2-5% acid reduction by submerging the basal parts of the engineered landform. At Stockton's Cypress resource area, currently in development the plan is to back-fill the pits and bury 10 million BCM beneath the water table.

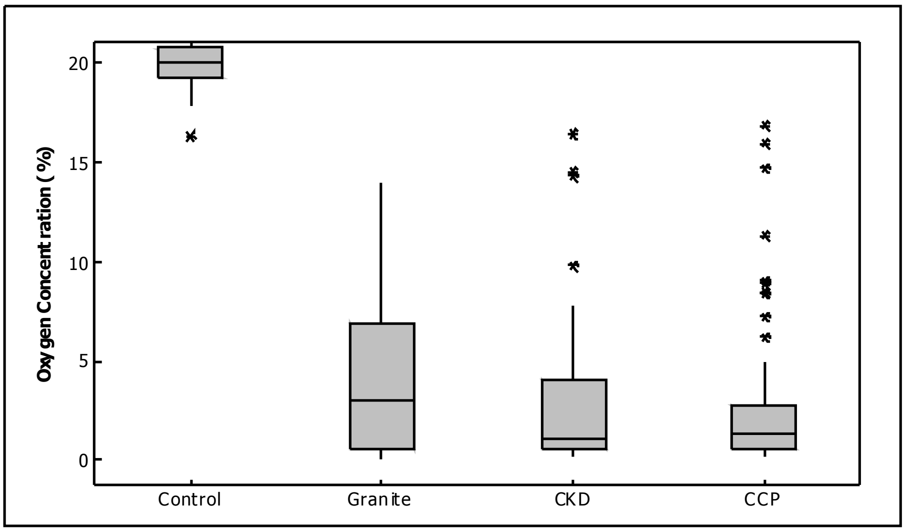
Figure 5. Acid generation for BCM PAF rock laboratory columns submerged under water. *(see Hughes et al., 2008 for further details).*



After reshaping of the engineered landform it is compacted with several bulldozer passes and then 500mm of weathered granite (>5 wt% fines < 63 µm) is compacted above the PAF rock as a low permeability cap. Where LAF is available a layer of this rock is wrapped over the PAF core. The granite cap is compacted to a permeability of < 1 x 10^{-6} m/s as measured by the double ring infiltrometer and is designed to be saturated to reduce oxygen ingress. 400mm of topsoil is then placed over the surface of the granite to act as a growing medium, which is then replanted.

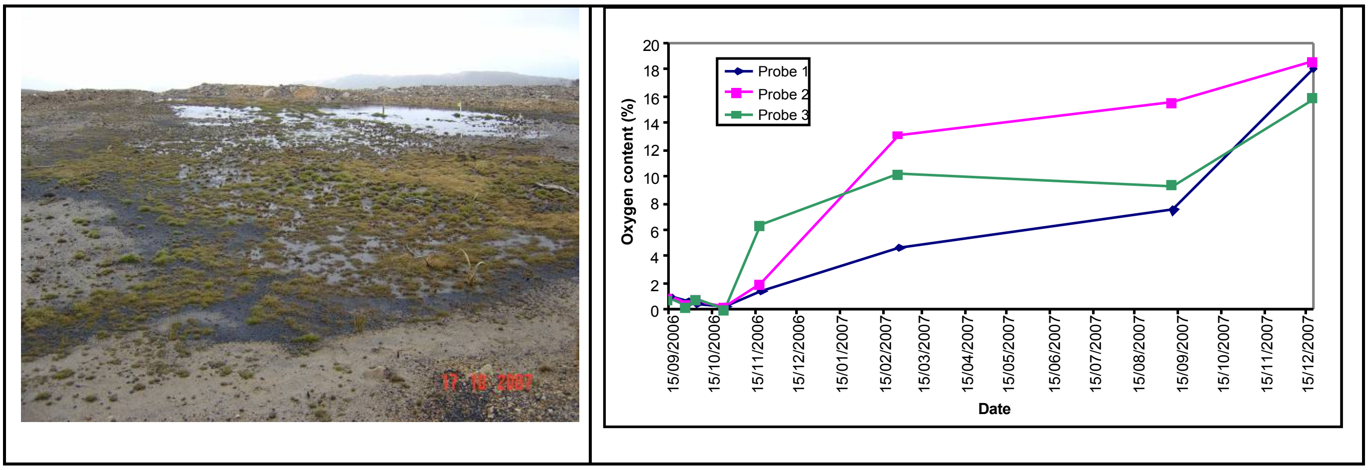
Other options for engineered caps have been developed, including alkaline covers using coal ash and cement kiln dust (CKD) having ANC values of 100 – 700 kg $CaCO_3$ respectively that both exclude oxygen and release alkalinity to the underlying PAF rock (Weber et al., 2008). Results demonstrating oxygen ingress are shown in Figure 6. These opportunities are limited by product availability and flat dump surfaces as, on dump slopes, the CKD and coal ash could produce slip planes.

Figure 6. Oxygen Concentration measured beneath various capping materials*. The granite oxygen probes were located at WE8 overburden area and C drive; CKD caps, CCP (coal ash) caps, and the control were from the Egypt trial pads.*



Mining guidelines developed at Stockton recommend that dumps are capped within 2 months to minimise oxidation. However, because this is often impractical, and interim solutions have been developed. Silt pond fines (SPF) disposal requires significant effort and it was believed that this material could be used as a capping material. A 40m by 20m trial site was selected on the flat C-drive overburden area and was bunded 300mm high to which SPF were added. Oxygen probes (2m depth) were inserted to measure oxygen content. They are essentially a PVC pipe designed to extract oxygen from a certain depth and remain sealed by a ball valve hooked up to an air hose fitting).

Figure 7. Silt pond fines trial site and oxygen content monitoring results. *Atmospheric oxygen content = 20.6%.*



Results shown in Figure 7 indicate that the saturated cap worked exceptionally well for the first three months and then failed. This is associated with the silt pond fines drying out. Thus they are not a long-term capping solution as the pond will require continual topping up every few month with additional SPF. Nevertheless they still have potential as a short term solution for AMD control prior to final capping and also the management of SPF.

3.3 AMD TREATMENT

Although prevention technologies for AMD will reduce acid loads within the engineered landforms, some treatment is still needed. It is anticipated that treatment will be required at Stockton for at least 100 years as disturbed overburden and the inherent pyrite continues to oxidise. Research into treatment processes that could treat this long-term liability commenced in 2005.

3.3.1 LIMESTONE NEUTRALISATION OF THE MANGATINI STREAM

A cost analysis indicated that the cheapest long term solution for the treatment of AMD was limestone (provided reasonable dissolution efficiencies could be obtained). A pilot-scale plant that could dose ultra-fine limestone (UFL) into the Mangatini Stream was constructed in 2006 and was run as batch trials. Several different limestones were tested and reactivity was variable due to ANC content and crystal structure of the limestone. It was demonstrated that UFL (90% < 100 µm) from Murchison Lime Quarry was reasonably efficient (50-70%) when at least 60 minutes rapid in-stream mixing was available (~400m stream length) and could raise the pH to > 6, which was sufficient to achieve water quality targets in regards to dissolved aluminium and pH.

Monitoring data obtained from downstream pH and turbidity loggers picked up pulses of neutralised water moving downstream. The pH profile at monitoring site S14B in the Mangatini Stream (4.1 km downstream of the dosing station) and site NR in the Ngakawau River (9.4 km downstream of the dosing station) is shown in Figure 8. Compared to the Mangatini Stream, there was a smaller pH increase in the Ngakawau River, which is expected considering the greater flow rate of the Ngakawau River, and thus dilution of the lower volume, higher pH Mangatini Stream.

Figure 8. pH Levels in the Mangatini Stream and Ngakawau River after UFL dosing.

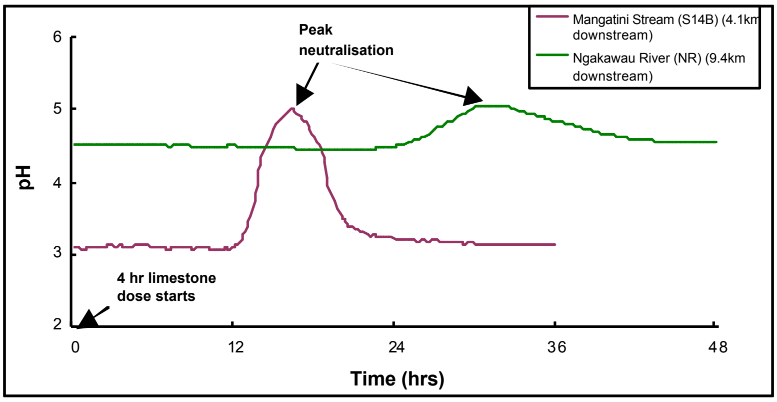


Figure 9. pH, dissolved Al, and dissolved Fe levels at site S14A (400m downstream of the dosing plant) after limestone dosing.

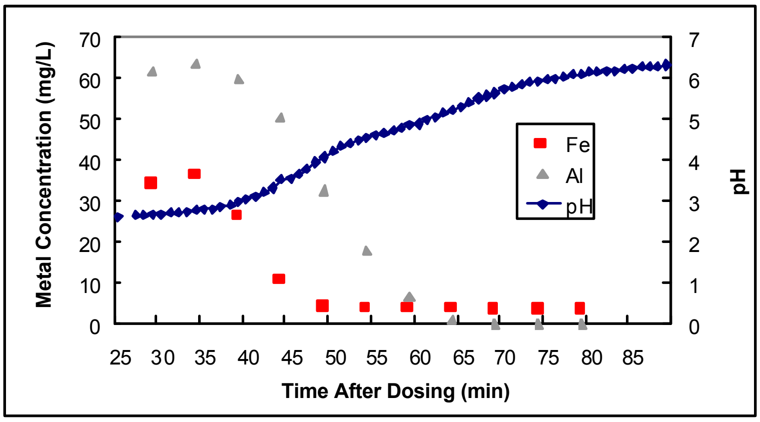


Figure 9 shows the pH, Fe, and Al concentrations in the Mangatini Stream recorded at a site 500 m downstream of the limestone dosing plant. From these results it can be observed that pH levels started to increase 30 minutes after dosing started and increased to pH 6.3 after 90 minutes. The precipitation and removal of dissolved Fe between pH 2.8 – 3.3 and dissolved Al between pH 4.3 – 5.0 buffered the rate at which pH increased due to the associated lewis acidity. Most of the dissolved Fe and Al was removed from the stream at approximately pH 3.5 and pH 5.0 respectively. Thus these results confirmed that at base flow conditions using 1.5 tonnes of fine limestone (90% < 100 microns) the fine limestone could be effectively used to raise the pH of the Mangatini Stream and reduce the aluminium load to levels that met with the Solid Energy's commitment to water quality in the Ngakawau River. This provided the science and confidence to construct a full scale plant.

From 2007 a temporary limestone dosing plant has been operating at Mumm's bridge dosing directly to the Mangatini Stream (see Weber et al., 2008 for details) with significant improvements in water quality (Fe, Al, pH) although clarity has been poor due to direct dosing of the limestone to the stream and the formation of Fe and Al hydroxide precipitates. This has been partially resolved by dosing of limestone into the Mangatini Stream above the Mangatini Sump, although further optimization is required.

The final stages of project involves a dosing plant that will be constructed in the upper catchment of the Mangatini stream in early 2012. This plant will have the capacity to dose both UFL and $Ca(OH)_2$ and will be fully automated to receive tanker deliveries of product and dose to the sump based on inflow pH meters calibrated against flow rate.

3.3.2 PASSIVE TREATMENT

Passive treatment is a system that uses a leach bed or reactor using limestone, organic material, or a combination of the two to treat AMD. A number of papers have been published on passive systems for Stockton (e.g., Weber et al., 2008; McCauley et al., 2009, 2010; Crombie et al., 2011). Passive treatment has limited treatment capacity (<40 L/sec in general). Crombie et al. (2011) identified the best place for a passive system using waste mussel shell is for low volume water discharging from AMD seeps where TSS is low to prevent clogging up of the passive treatment system.

An operating full scale passive system has been installed to treat the Manchester Seep (0.04 – 0.6 L/sec; pH 2.8; acidity ~400 mg/L $CaCO_3$). During high rainfall events the overflow (> 0.6L/sec) discharges via a spillway. The system has been operating for approximately 2 years with significant results (Table 2). pH has increased from 2.8 to 7, acidity has been removed, and all metals have been reduced to very low levels. Based on these results more of these passive systems re-using a waste product are planned for areas that cannot be treated by UFL dosing where the flow and water quality are appropriate.

Table 2. Influent and effluent water analysis for the mussel shell passive treatment system.

	Al (mg L^{-1})	Fe (mg L^{-1})	Ni (mg L^{-1})	Zn (mg L^{-1})	pH	EC (µS cm^{-1})	Acidity (mg L^{-1} $CaCO_3$)	DO (mg L^{-1})	Ammoniacal Nitrogen (mg L^{-1})
Influent									
Min	<0.003	0.81	0.10	0.5	2.1	332	240	2.1	0.037
Mean	51	29	0.27	1.18	2.8	1246	422	8.5	0.15
Median	54	23	0.24	1.0	2.9	1311	430	9.4	0.12
Max	80	140	0.5	2.2	4.0	1621	790	10.2	0.32
Effluent									
Min	<0.003	<0.02	<0.0005	<0.001	6.2	943	0	0.5	0.06
Mean	0.013	0.17	0.028	0.008	6.9	1445	0.3	2.8	7.81
Median	0.004	0.04	0.0062	0.004	7.0	1463	0	2.4	3.9
Max	0.21	0.92	0.038	0.045	8.6	2110	9.9	6.1	46

4 EROSION

4.1 INTRODUCTION

With up to 6000mm of rainfall per year and 930 ha of disturbed or recently rehabilitated ground at Stockton the management of erosion and the subsequent suspended sediment in waterways is a challenge. Typically during rain events soil armouring processes occur whereby fine soil particles are eroded quickly, leaving a coarse surface layer of rock and gravel. This coarse layer provides protection to the underlying soil, reducing further erosion. However, field observations have indicated that up to 50mm of soil can be lost from engineered landforms following topsoil respreading prior to the effect of armouring occurring. This equates to 500m^3 per Ha of sediment that is lost from slopes. Better management solutions were required to minimise fines loss and the following section looks at the activities undertaken at Stockton to minimise sediment loss that thence generates elevated TSS within waterways.

4.2 EROSION MINIMISATION

4.2.1 INTRODUCTION

The most effective means of minimising erosion is to minimise the amount of area disturbed within a mining block and the first step of this is accurate delineation of the mining area. All clean water is diverted, where possible, away from the mining block to minimize scouring and sediment entrainment. The following activities look to minimize the subsequent loss of sediment from the mining block and from the rehabilitated landform.

During the design and construction of engineered landforms consideration should be given to final slope gradient. The lower the angle of the slope the less erosion prone it will be. This, however, is often counterproductive as greater area is required for the dump and thus the disturbed area foot print is larger. Hence a balance must be struck. Design of engineered landforms should also look at maximum slope length between benches, diversion of drains away from slopes to remove high energy point sources of water-flow, and the ability to start progressive rehabilitation. One of the most important aspects of erosion management is monitoring, review, and maintenance of erosion control systems and structures.

4.2.2 SLOPE STABILISATION

Successful rehabilitation of engineered landforms (ELFs) at Stockton Mine relies on the retention of remaining soil once it is re-applied at the completion of the mining process. The soil is important as a growing medium and also as a cover to the underlying granite cap that that been constructed to reduce oxygen ingress into the underlying PAF rock. Following placement of the soil the area is planted out with native seedlings (25 different species) at a rate of 5,000 – 15,000 stems per ha as a standard approach (Rodgers et al., 2011). However, prior to canopy closure this leaves a significant area of ground without any vegetative cover and the potential for significant erosion.

Researchers have shown the effectiveness of straw mulch to control erosion (*e.g.,* Meyer et al., 1970; Jennings and Jarrett, 1985; Benik et al., 2003; Shadbolt and Weber, 2007). Hydro-seeding, like straw mulching, had also been used for erosion control (e.g., Albaladejo Montoro et al., 1999). Six plots (each ~ 217m^2) were established in May 2006 on the Collis Dump with 5m long erosion gutters placed at the base of the plot to capture sediment runoff (Figure 10). Straw and hydro-seed was applied to the plots:

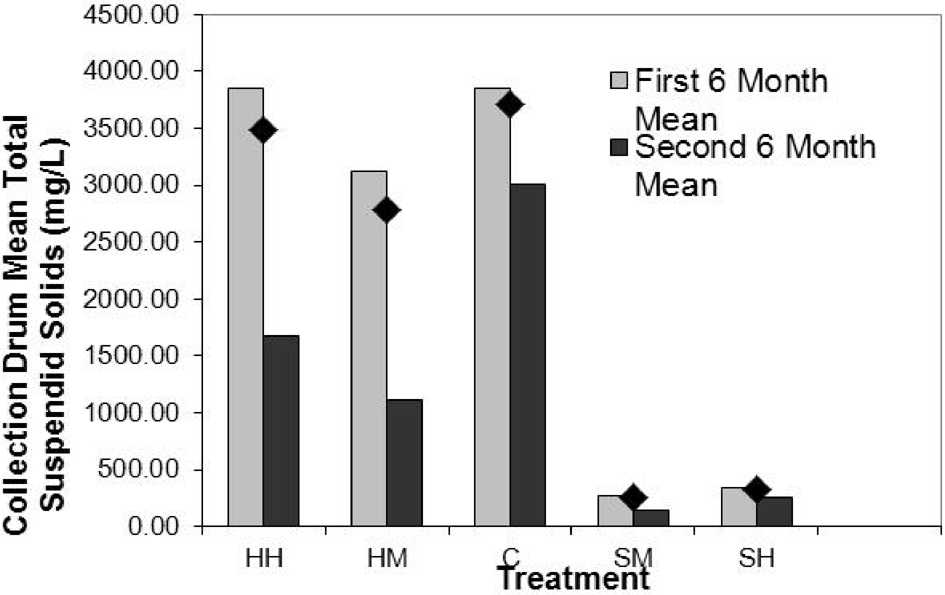
- Plot 1 – Hydro-seeding; paper 1t/ha, Browntop 5kg/ha,Yorkshire Fog 5kg/ha, Tama Ryegrass 25kg/ha, DAP 400kg/ha, **(HH – hydro-seeding high rate)**
- Plot 2 – Hydro-seeding; paper 1t/ha, Browntop 2.5kg/ha, Yorkshire Fog 2.5kg/ha, Tama Ryegrass 8kg/ha, DAP 400kg/ha, **(HM – hydro-seeding medium rate)**
- Plot 3 - Control plot; bare soil **(C)**
- Plot 4 - Straw mulching; wheat straw 3.5t/ha **(SM – straw medium rate)**
- Plot 5 - Straw mulching; wheat straw 5t/ha **(SH – straw high rate)**

Results (Figure 11) demonstrated that straw was the most successful method to mitigate erosion. The ability for hydro-seed to work was initially compromised by poor winter growth but sediment loss was significantly reduced once the grass had established in the second 6 month period. After one year the straw had started to break down and was no longer as efficient at retaining sediment whereas the grass established by hydro-seeding had greater longevity.

As a result of this research Solid Energy has implemented a procedure whereby straw is applied (4 tonnes/ha) as soon as practical to areas rehabilitated with respread soil and hydro-seed is also applied before seedlings are transplanted.

*Figure 10. **Erosion control gutter used to measure sediment loss from trial plots.** Further details of the design, methodology, and results are available (Shadbolt and Weber, 2007).*

Figure 11. TSS (mg/L) for all trial plots divided into 6 monthly intervals



4.2.3 VEGETATION DIRECT TRANSFER (VDT)

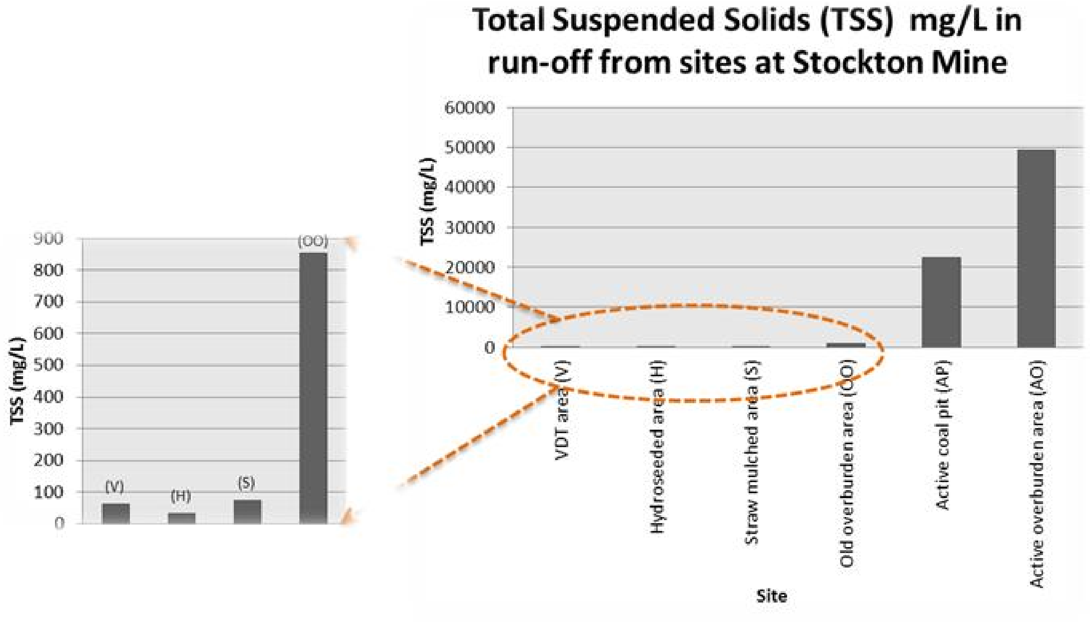
Vegetation Direct Transfer (VDT), also called ‘habitat-’ or ‘community-translocation’ is a method whereby intact mats or sods of vegetation and the attached soils are removed and relocated to sites which have been prepared for rehabilitation (Figure 12). VDT minimises structural damage, enabling the salvage, relocation and reuse of the biotic layers (i.e. vegetation, topsoil, intact root structures, plant litter, seed and seedling banks, microbial and mycorrhizal root associations, and invertebrates) in a way that preserves the potential for natural regeneration (Rodgers et al., 2011). VDT has been developed at Stockton Mine since 1998 and has become the preferred rehabilitation method for rehabilitating high-value, low-stature ecosystems.

Figure 12: VDT bucket salvaging thin sods from pavement. The bucket has a cutting front edge and flat base

A field study carried out in May 2011 demonstrated the greater effectiveness of rehabilitation, including VDT, in limiting sediment run-off (Figure 13). The study was carried out during a moderate rainfall event (80mm in 24 hour period), with water samples collected from rehabilitated slopes with three different rehabilitation treatments (VDT, hydro-seeding, straw mulching), and from three non-rehabilitated areas (old overburden area, active overburden area, active coal pit). The grab samples were analysed for total suspended solids (mg/L) and visual clarity (Bonisch and Rossiter, 2011).

All three rehabilitated slopes generated run-off with high clarity and comparatively low TSS: (61 mg/L for VDT; 31 mg/L for hydro-seeded slope; 74 mg/L for straw mulched slope). By comparison, the non-rehabilitated slopes had poor visual clarity and very high TSS: (854 mg/L for old overburden dump; 49,260 mg/L for active overburden dump; 22,348 mg/L for active coal pit) (Figure 13).

Figure 13. Total suspended solids (mg/L) in water run-off from sites under different treatments.



Thus VDT also provides an immediate ground cover which reduces TSS in run-off to levels comparable with hydro-seeding and straw mulching. The direct costs of VDT are highly variable (~$40,000 – $200,000 per ha) and are greatly influenced by the capital cost of machinery used to transport the VDT, the distance and elevation between VDT source and destination (rehabilitation) areas, and the proportion of down-time the fleet spends not transporting or loading sods. However, in comparison with traditional soil spreading and planting techniques, VDT is overall less expensive when considering the 'life-cycle' costs involved in conventional rehabilitation, which include erosion control (such as hydro-seeding and/or straw-mulching and/or silt fences to retard sediment mobilisation), weed monitoring and control and on-going management. VDT also reduces the time required to achieve closure criteria (such as vascular plant cover and height and species assemblages). Further information on VDT is available (Rodgers et al., 2011)

4.2.4 SEDIMENT CONTROL

As a first line of defence against the transport of sediment from active mining areas into waterways the site uses silt fences to trap water and entrained sediment. The fences are installed prior to mining in the area (Figure 14). The fences are reinforced with wire to support, intensive, overland flow and sediment loads. Site personnel undertake checks of these fences as part of a monthly maintenance programme and after each significant rainfall event (i.e. >50mm in any 24 hour period). Erosion Control Tubes (ECT) or strawbales are also used and enable rapid filtration of water unlike silt fences that are designed to stop water flow.

Road side check dams (Figure 15) are installed on roads with a life of > 3 months and their purpose is to reduce the velocity of concentrated flows, thus providing some sediment control from roadside runoff and reducing the effects of scouring on the drain (and hence more sediment generation). The distance between check dams is based on the gradient of the slope:

- Gradient steeper than 10%: check dam separation to be no more than 30m
- Gradient flatter than 10%: check dam separation to be no more than 45m

Figure 14. Since fence installed prior to mining.

Figure 15. Roadside check dams at Stockton Mine.

4.3 TREATMENT

4.3.1 SEDIMENT PONDS

As shown in Figure 13 the greatest sources of sediment from the mine site are active pits and overburden areas. Because only 180 ha of the 930ha disturbed by mining is rehabilitated there is a significant amount of sediment created. The first line of treatment is sedimentation ponds.

In-pit sediment sumps or dams are an essential water management tool for Stockton. They provide primary settlement of medium–coarse sediment in medium and high flows and significant settlement of fine sediments in low flow situations. Typically the structures are 2.5m in depth (and no more than 3m) and are designed to have a length to breadth ratio of greater than two to be most effective at settling sediments than an impoundment with irregular shape and/or a length to breadth ratio of less than two where short circuiting can occur.

Discharge from the sediment sumps is either by a spillway or floating decant. Sumps are sized based on the upstream catchment and the following general rules apply:

1. Sumps without a floating decant require a surface area of $500m^2$ per ha of catchment
2. Sumps with a floating decant require a surface area of $200m^2$ per a of catchment

Sumps are inspected weekly and any maintenance or sediment removal is scheduled with operations as a priority. The sediment excavated from the sediment ponds is carted to a nearby fines disposal area that prevents the fines from being remobilized. Other options for reuse of this material have been discussed in Section 3.2.2.

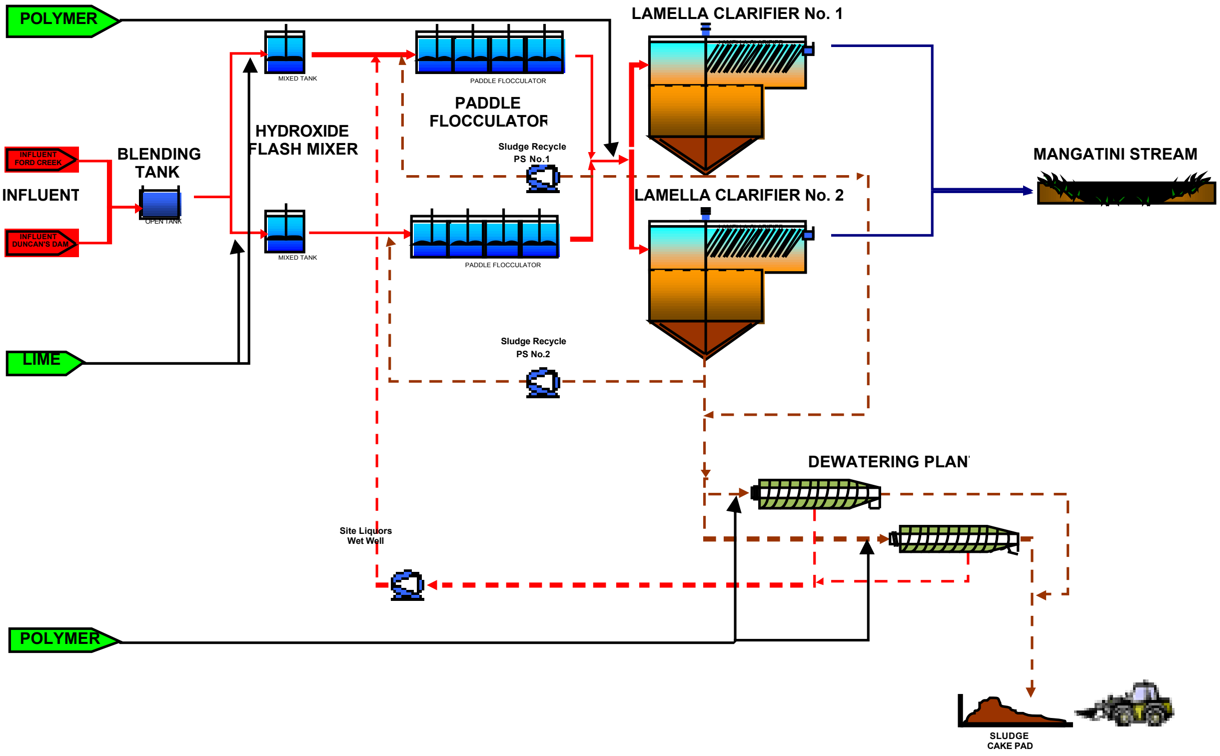
4.4 STOCKTON BLACK WATER TREATMENT PLANT

Part of the water management approach at Stockton is to separate black-water (containing coal fines from mining pits, ROM pad, and processing site) and brown-water (containing general mining sediment other than coal) at the source of generation and transport them to the treatment plant. The reason for this is that the removal of fine suspended coal is inherently more difficult. This is a function of the lower specific gravity of coal compared to mineral sediment, which results in differential settling rates that result in a higher concentration of coal fines remaining in suspension (Kingett Mitchell, 2005).

The standard process of sedimentation ponds thus does not achieve the desired water quality for black-water and a black water treatment plant was designed and constructed. The final stages of this plant were completed in 2010. The Stockton Black Water Treatment Plant (BWTP) is an example of a classical active mine water treatment process, which involves, neutralization of the acidity, flocculation of the precipitates and sediment, consolidation of the sludge, and discharge of clean water. A conceptual design is provided in Figure 16; and Figure 17 provides a view of the as-built plant.

In the initial stages of treatment the acidity (H^+, Lewis acidity associated with dissolved Fe and Al) is neutralized by $Ca(OH)_2$ in the flash mixer. $Ca(OH)_2$ is used due to its almost instantaneous neutralization capacity, unlike ultrafine limestone that requires up to one hour of turbulent mixing. A precipitate is formed composed of $Fe(OH)_3$ and $Al(OH)_3$ together with gypsum and any suspended sediment in the flocculator (flocculant is added). Separation of the clean water from the floc occurs in the lamella thickeners and the sludge underflow is sent to centrifuges for further dewatering.

Figure 17. Schematic flow diagram for the Stockton Black water Treatment Plant. *From Ellis (2008).*



Due to the increase in pH and the addition of flocculant a significant component of the dissolved Fe and Al in solution is precipitated together with suspended sediment and coal fines. Results (Table 3) indicate that the BWTP is effectively removing ~99% of the dissolved aluminium and iron respectively and reducing turbidity by ~84%.

***Figure 18. The Stockton Black water Treatment Plant**. Photo from Ellis (2008) prior to the installation of the centrifuges.*

Table 3. Relative improvement in mine water composition following treatment by the Stockton BWTP.

	Units	Mean Influent	Mean Effluent	Percentage Reduction
pH	-	3.4	6.4	-
Turbidity	NTU	19.4	3.19	84 %
Suspended Solids	g/m^3	19.7	8.18	59 %
Dissolved Aluminium	g/m^3	29.8	0.13	99.6 %
Dissolved Iron	g/m^3	15.8	0.07	99.5 %

4.5 THE MANGATINI SUMP

The Mangatini Sump is another significant component of the Stockton Water Management Project aimed at achieving community water quality targets. It has been designed to capture and remove sediment by gravity settlement derived from upstream mining areas and also precipitate AMD sludge created by the upstream neutralisation of acidity. In the near term the sump is intended to provide sediment storage for 10 to 15 years of the mine when sediment rates (TSS) will remain high due to mine disturbance. In the long term, the sump is intended to provide AMD sludge storage capacity from ongoing AMD treatment for up to 100 years. Eventually it is anticipated that the sump will be drained, capped, and integrated into the final rehabilitation plan of the mine.

The sump was excavated entirely below coal floor following mining of the MG05, MG06 and MG07 mine blocks. The total excavation volume from coal floor to the sump bottom (RL 567 m) is approximately 1.8 million BCM, which makes it one of the largest sediment control structure in New Zealand. The total water storage capacity for the normal operating level (RL 593.5 m) is about 900,000 m^3 of which approximately 443,000 m^3 is live storage. Flows of up to ~15 m^3/sec are diverted from the Mangatini Stream into the sump via a low diversion structure located on the Mangatini Stream. A floating decant structure decants treated water from the surface of the Mangatini Sump and conveys it through a tunnel back to the Mangatini Stream.

Figure 19. Aerial view of the Mangatini Sump.

Figure 20. Influent via the Mangatini Stream into the Mangatini Sump. *Note limestone dosing turbidity*

5 RESULTS – IMPROVEMENTS IN WATER QUALITY

The following figures demonstrate the improvements to water quality in the Ngakawau River since limestone dosing started in early 2007. As can be seen significant reductions in the acid load have decreased dissolved aluminium and increased pH. Improvements towards targets for clarity and turbidity (Figures 23, 24) has not been as good as the limestone remained in the stream together with precipitates. However, clarity is significantly improved after June 2010 following commissioning of the Mangatini Sump.

Figure 21. pH results (daily) for the Ngakawau River.

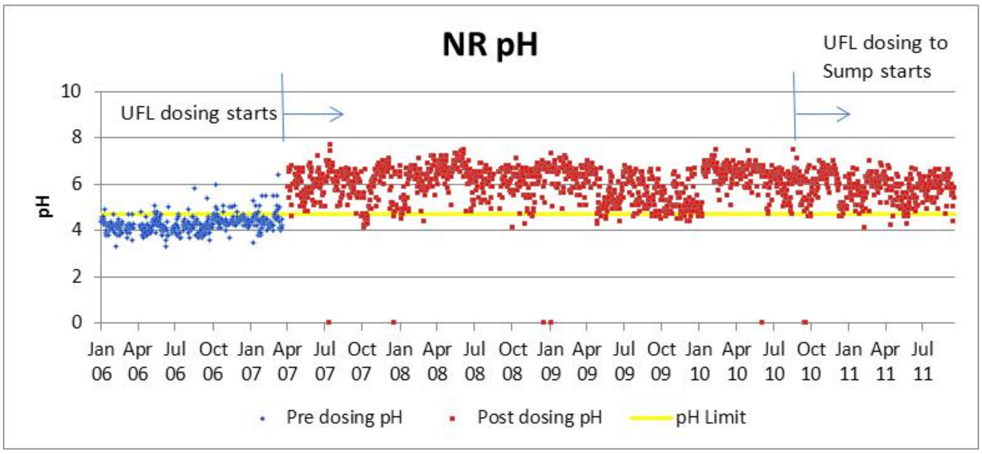


Figure 22. Dissolved aluminium results (daily) for the Ngakawau River.

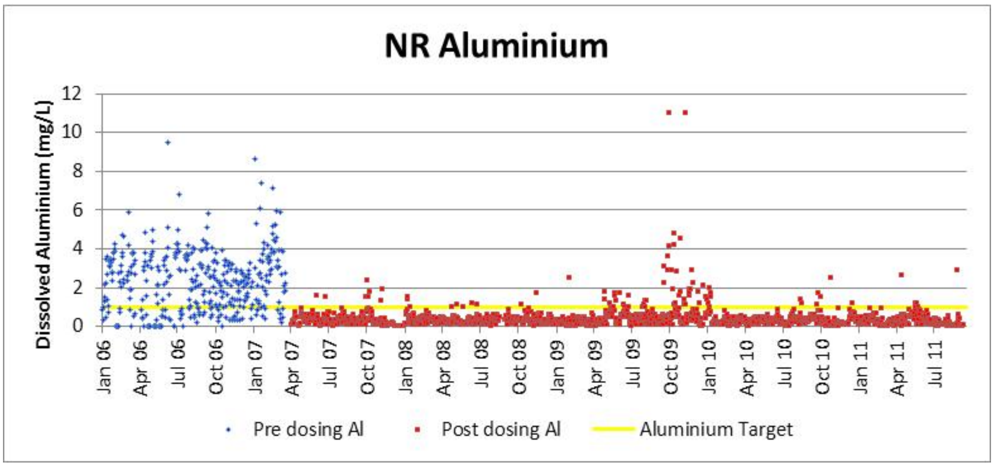


Figure 23. Clarity (cm) results (daily) for the Ngakawau River.

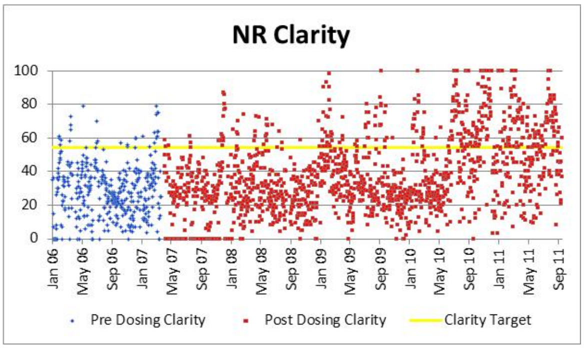
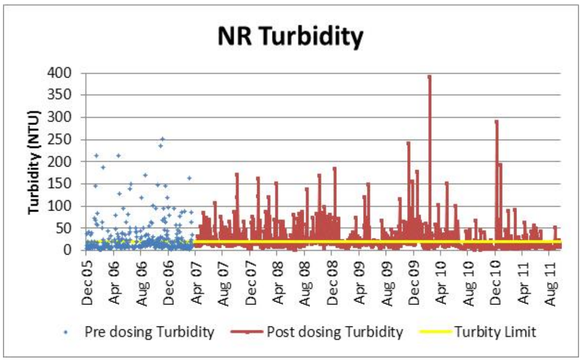


Figure 24. Turbidity for the Ngakawau River.



Analysis of the above results for site NR in the Ngakawau River indicate that between 6 April 2007 and 21 September 2011 the pH was ≥4.7, 96.7% of the time; and dissolved aluminium was < 1 mg/L, 94.6% of the time, which was close to targets. From January 2011 to September 2011 the pH was ≥4.7, 97.3% of the time and aluminium was < 1 mg/L, 98.3% of the time. These results demonstrate that Solid Energy is close to its agreed stakeholder targets and effectively managing the effects of AMD on the Mangatini catchment.

In regards to sediment load (turbidity) and water clarity, which is a function of erosion products, ultrafine limestone dosing, and AMD precipitates, significant improvements have occurred over the last six years, particularly in the last twelve months following commissioning of the Mangatini Sump and upstream UFL dosing. Between 6 April 2007 and 21 September 2011 the target in regards to turbidity was 96.1% (25 NTU, 30 day rolling median); and in regards to clarity was 41.3% (>54cm during base flow). Subsequent to further process improvements (completion of the Mangatini Sump and upstream limestone dosing above the sump) results for the period January 2011 to September 2011 have increased to 100% of the time for turbidity (25 NTU, 30 day rolling median) and clarity has increased to 89.8% (>54cm during base flow assuming base flow is 70% of the time).

6 DISCUSSION AND CONCLUSIONS

As this paper has demonstrated Solid Energy has undertaken a significant amount of work to manage sediment and mitigate the effects of acid forming overburden over the last six years. The capital costs for the Mangatini Sump, BWTP, associated water management infrastructure (e.g., A Drive Dam, Ford Creek Dam, Duncan's Sump), and the temporary limestone dosing plant is close to $45M. Further capital commitments are planned in the future such as the long-term (100 year) Limestone Dosing Plant ($4M) to be built above the Mangatini Sump. The long term limestone dosing plant above the Mangatini sump is expected to improve water quality further.

The results presented have shown a significant improvement in water quality in regards to acid load (pH) and dissolved aluminium and confirm that tackling the Mangatini Stream first was the best option for significant improvements in water quality in the Ngakawau River. Further work is required to reduce suspended solids to improve water clarity. This includes other streams that impacted the quality of water in the Ngakawau River

(Mine Creek, Ford Creek, Fly Creek, and St Patrick Stream) and this work will be undertaken in the next few years.

Acid Mine Drainage (AMD) is a significant environmental liability at the Stockton Coal Mine located on the West Coast of New Zealand. This liability is the product of historical and current coal mining and the associated oxidation of pyrite. Management and treatment of the effects of AMD will last at least 100 years. Management of sediment and TSS will be intensive in the short term but post closure following rehabilitation and canopy closure this will reduce and eventually the adverse effects will be negligible.

Significant progress has been achieved to date and further improvements are planned. It is anticipated that with the improvements to stream health there will be an increase in biodiversity. Noteworthy results to date include the return of *galaxids* inanga (whitebait) in the Ngakawau River (with some good catches being recorded).

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REFERENCES

Alarcón León, E. and Anstiss, R.G. (2002). Selected trace elements in Stockton, New Zealand, waters. New Zealand *Journal of Marine and Freshwater Research* 36, 81 - 87.

Albaladejo Montoro, J., Alvarez Rogel, J., Querejeta, J., Diaz, E. and Castillo, V. (1999). Three hydroseeding revegetation techniques for soil erosion control on anthropic steep slopes. *Land Degradation & Development.* Vol. 11: 315-325 (2000).

Benik, S. R, Wilson, B. N, Biesboer, D. D, Hansen, B. and Stenlund, D. (2003). Performance of erosion control products on a highway embankment. *American Society of Agricultural Engineers* Vol. 46(4): 1113–1119

Black, A., Trumm, D. and Lindsay, P. (2005). Impacts of coal mining on water quality and metal mobilisation: case studies from West Coast and Otago. In: Moore, T.A., Black, A., Centeno, J., Harding, J., Trumm, D.A. (Eds.), *Metals in New Zealand*. Resolutionz press Ltd, Christchurch, New Zealand, pp. 247 - 260.

Bonisch, A. and Rossiter, P. J. (2011). Sediment Run-off from Stockton Mine Landforms. Internal report to Stockton Alliance.

Crock, J.G., Arbogast, B.F. and Lamothe, P.J. (1999). Laboratory methods for analysis of environmental samples. In: Plumlee, G.S., Logsdon, M.J. (Eds.), *Reviews in Economic Geology*, vol. 6A. Society of Economic Geologists, Littleton, CO, pp. 264–287 (Chapter 13).

Crombie, F.M., Weber, P.A., Lindsay, P., Thomas, D.G., Rutter, G.A., Shi, P., Rossiter, P. and Pizey, M.H. (2011). Passive treatment of acid mine drainage using waste mussel shell, Stockton Coal Mine, New Zealand. In *Proceedings of the Seventh Australian Workshop on Acid and Metalliferous Drainage*, Darwin, Northern Territory. 21-24 June 2011 (Eds L.C. Bell and B. Braddock), pp. 393-405, (JKTech Pty Ltd), Brisbane.

Davies, H., Weber, P., Lindsay, P., Craw, D., Peake, B. and Pope, J. (2011). Geochemical Changes during Neutralisation of Acid Mine Drainage in a Dynamic Mountain Stream, New Zealand. *Science of the Total Environment* 409: 2971–2980

de Joux, A. and Moore, T.A. (2005). Geological controls on the source and occurrence of nickel in Rapid Stream, South Island, New Zealand. In: T.A. Moore, A. Black, J. Centeno, J. Harding and D.A. Trumm (Eds.), *Metals in New Zealand.* Resolutionz press Ltd, Christchurch, New Zealand, pp. 261 - 276.

Ellis, M.J. (2008). Stockton Mine Water Treatment Plant – the removal of black water from the Mangatini Stream. *41st AusIMM conference (New Zealand Chapter)*, Wellington, August 31 – 3 September 2008.

IWRI and EGi (2002) *ARD Test Handbook.* AMIRA P387A Project: Prediction and Kinetic Control of Acid Mine Drainage. AMIRA International, Melbourne, Australia.

Hughes, J.B., Lindsay, P., Weber, P.A. and Holman, J.B. (2007). Stockton Mine Acid Rock Drainage Remediation Part 1 – Passive Mitigation. *40th AusIMM conference (New Zealand Chapter)*, Christchurch, August 13-15 2007.

Jennings, G. D., Jarrett, A.R. (1985). Laboratory evaluation of mulches in reducing erosion. *Trans. ASAE* 28(5): 1466–1470.

Kingett Mitchell, (2005). Water management strategy overview for Stockton site. Internal report prepared for Solid Energy New Zealand Ltd by Kingett Mitchell Ltd.

Meyer, L. D., Wischmeier, W.H. and Foster, G.R. (1970). Mulch rates required for erosion control on steep slopes. *SSSA Proc.* 34(6): 928–931.

McCauley, C.A., O'Sullivan, A.D., Weber, P.A. and Trumm, D.A. (2010). Variability of Stockton Mine Drainage chemistry and its treatment potential with biogeo chemical reactors. *New Zealand Journal of Geology and Geophysics Special Edition: Mine Drainage* Vol. 53 (2&3): 211 – 226.

McCauley, C.A., O'Sullivan, A.D., Milke, M.W., Weber P.A. and Trumm, D.A. (2009). Sulfate and metal removal in bioreactors treating acid mine drainage dominated with iron and aluminium. *Water Research* 43: 961-970.

Pope, J., Weber, P., Mackenzie, A., Newman, N. and Rait, R. (2010). Correlation of acid base accounting characteristics with the geology of commonly mined coal measures, West Coast and Southland, New Zealand. *New Zealand Journal of Geology and Geophysics Special Edition: Mine Drainage* Vol. 53: 153-166.

Shadbolt, A.A.K. and Weber, P.A. (2007). Performance of erosion control products at Stockton opencast mine. International Erosion Control Conference, New Plymouth, November 20-21, 2007.

Rodgers, D., Bartlett, R., Simcock, R., Wratten, S. and Boyer, S. (2011). Benefits of vegetation direct transfer as an innovative mine rehabilitation tool. In *Proceedings of the Australian Mine Rehabilitation Workshop*, 16-19 August 2011, Adelaide, South Australia. (JKTech Pty Ltd), Brisbane.

Weber, P.A., Lindsay, P., Hughes, J.B., Thomas, D.G., Rutter, G.A., Weisener, C.G. and Pizey, M.H. (2008). ARD minimisation and treatment strategies at Stockton Coal Mine, New Zealand. In *Proceedings of the Sixth Australian Workshop on Acid and Metalliferous Drainage,* Burnie, Tasmania. 15-18 April 2008. (Eds L.C. Bell, B.M.D. Barrie, B. Baddock, and R.W. MacLean) pp. 113-138 (ACMER: Brisbane).

Weber, P.A., Skinner, W.M., Hughes, J.B., Lindsay, P. and Moore, T.A. (2006). Source of Ni in coal mine drainage, West Coast, New Zealand. *International Journal of Coal Geology* 67: 214-220.

Weber, P. A., Stewart W. A., Skinner W. M., Weisener C. G., Thomas J. E. and Smart R. St. C. (2004). Geochemical effects of oxidation products and framboidal pyrite oxidation in acid mine drainage prediction techniques. *Applied Geochemistry.* 19: 1953-1974.

Weber, P.A. (2003). Geochemical investigations of neutralising associated with acid rock drainage: prediction, mechanisms and improved tools for management. Ph.D. thesis, University of South Australia, Adelaide.