1B Hydraulic System Mine Water Assessment

Neville Street Mine Water: Outline Design Report

4th April 2008

Notice

This report was produced by Atkins International Limited for CBCL for the specific purpose of the outline design and sizing for the Neville Street Mine Water Treatment Scheme.

This report may not be used by any person other than CBCL without their express permission. In any event, Atkins accepts no liability for any costs, liabilities or losses arising as a result of the use of or reliance upon the contents of this report by any person other than CBCL.

Document History

JOB NUMBER: 5063247			DOCUMENT REF: Document 1			
001	Draft for Client comment	SMB	PT	AMF	AMF	04.04.08
Revision	Purpose Description	Originated	Checked	Reviewed	Authorised	Date

Contents

Section Page

List of Tables

List of Figures

1. Background

1.1 Cape Breton Mine Water Pumping Scheme

The Neville Street well field is located east of Neville Street near the town of Reserve Mines, Cape Breton County, Nova Scotia. The well field forms part of the 1B Hydraulic System, a group of interconnected abandoned coal mines located beneath the towns of Glace Bay, Dominion and Reserve. The coal seams have been extensively mined and dip in a general south to north direction, and extend under the Atlantic Ocean.

The mine workings have been steadily filling with water following the cessation of pumping of the coal mines in the mid 1980s. The current pumping stations are situated in two main groups on the Neville Street well field; these are the southern group and western group. The southern group lie adjacent to the old rail bed and the western wells lie in a line perpendicular to the rail bed. The pumps are operated sequentially to ensure a constant water level within the mines and are operated in an order of best water quality to worst water quality.

The pumped mine water is currently channelled into a combined drainage system and discharged directly in the local river (Cadegan's Brook).

1.2 Mine water data to March 2007

1.2.1 Pumping regime

The pumping regime is currently operated by CBDC on an automated system, based upon the chemical quality of the mine water. The pumps are believed to remove surface water inflow to the mines prior to the water mixing with the deeper mine water. The best quality mine water wells (relating to lowest metals and acidity loading) are operated first, and during periods of high precipitation and/or when the water level rises above the required level (17m to 19m BGL) , the lower quality mine water wells are operated in the order from best to worst quality. A hydrogeological study of the subsurface mine water situation has not been part of Atkins scope for this study.

Average daily pumping rates and the water level within the mine are measured on a daily basis, along with a measurement of precipitation events and snow melt.

1.2.2 Chemical data

Mine water quality is monitored on a two weekly basis from the combined discharge from those wells that are in operation on the sample day, and on a yearly basis from each individual pumping well head.
Chemical testing of the combined discharge commenced on the 28th of April 2003. Currently, there are 7 pumps in operation in the southern group of wells and five in the western group.

Southern Group: The southern group of wells consists of 7 wells that are orientated in a south to north trend along the line of the old rail bed. In general, the metal loading within the mine water deteriorates in a northwards direction away from outcrop. The predominant contaminants in the southern wells are manganese and iron. Iron concentrations have been steadily increasing over the last year, with an average of 0.8 mg/l in March 2007, 1.35 mg/l in February 2008 and 2 mg/l in March 2008. It is not clear if this is seasonal variation as the well head testing is only conducted once a year in the spring.

Western Group: The western group of wells consists of 5 wells that are orientated in an east to west trend that run in a line perpendicular to the line of the old red bed. The mine water is net acidic with an average iron concentration of 9.8 mg/l in March 2007, 20.9 mg/l in February 2008 and 25 mg/l in March 2008. As with the southern wells, it is not clear if this is a seasonal variation.

Combined discharge: The mine water is net alkaline, with an average iron loading of 4.5 mg/l, 6.5 mg/l manganese and 0.2 mg/l aluminium (data averaged from April 2003 to November 2007). The quality of the discharge has been steadily decreasing with respect to an increased metal and acidity loading since the pumping of the wells commenced.

1.2.3 Summary

The main contaminants on the Neville Street well field are iron, manganese, zinc, aluminium and acidity. Over time, there appears to have been a net decline in the quality of the mine water, in that metal loading and acidity have increased. This has serious implications for the treatment of the mine water using a passive treatment system, as net acidic water will have no buffering capacity to neutralise acidity produced during the oxidation and hydrolysis of metals in the treatment system.

An analysis of the potential acidity in the mine water from the metal loading has shown a major discrepancy between that measured in the laboratory and that calculated from the concentration of metals (full details are presented in section 2). Recent combined discharge data infers that the mine water is progressing from net alkaline to circum neutral status, as depicted in Figure 1.1.

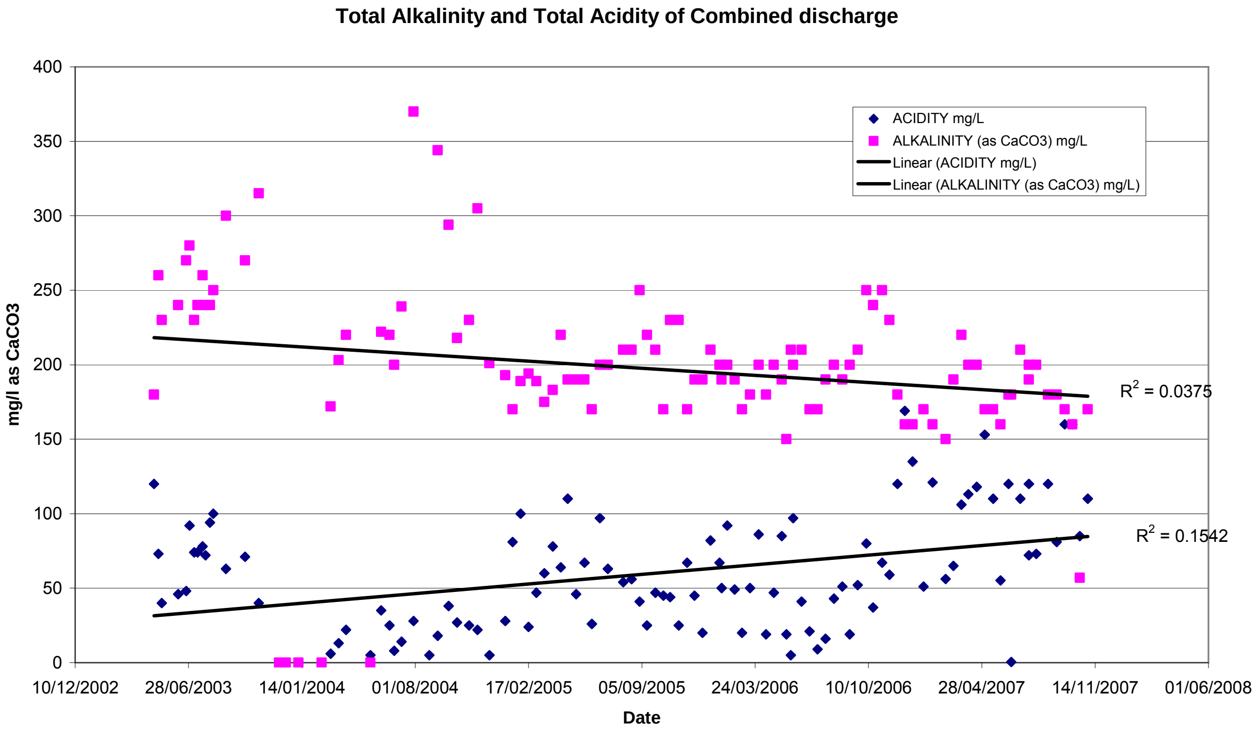


Figure 1.1 – Trends of Total Alkalinity and Acidity over time. Note acidity is increasing and alkalinity is decreasing

2. Carbonate Chemistry

2.1 Alkalinity and acidity in mine water

Understanding the relationship between alkalinity and acidity and how it affects the pH of the mine water is crucial to designing a treatment scheme to treat a metal rich mine water.

Alkalinity is defined as the amount of a strong acid required to decrease the pH of the water to a standard end point (generally 4.5).

Alkalinity can be expressed as the sum of the bicarbonate, carbonate and hydroxide ions minus the concentration of protons.

Alkalinity = $[HCO^-_3] + 2[CO_3^{2-}] + [OH^-] - [H^+]$

Acidity is defined as the amount of a strong acid required to raise the pH of the water to a standard end point (generally 8.3).

Acidity is a function of the sum of the carbonic acid and proton concentration minus the concentration of carbonate and hydroxide ions.

Acidity = $[H_2CO_3] + [H^+] - [CO_3^{2-}] - [OH^-]$

The alkalinity and acidity are generally expressed as the equivalent concentration of calcium carbonate (as mg/l $CaCO_3$) or as the milli-equivalent of strong acid or alkali required to complete the respective titration (meq/l). If the acidity is higher than the alkalinity, then the water is classed as '*net-acidic'* and if the alkalinity is higher than the acidity, then the water is *'net alkaline'*. The balance between alkalinity and acidity in mine water creates a highly variable and dynamic system, and can be affected by a multitude of factors.

2.2 Mine water acidity

There are several types of mine water acidity that contribute to form the total measured acidity in mine water. These are;

- **Proton acidity**. This is a measure of the protons (H^+ ions) in the water and can be calculated from the pH.
- **Mineral Acidity**. This a measure of the 'potential' acidity in the mine water and can be calculated from the concentration of dissolved metals in the mine water that will generate protons (H^+ ions) when hydrolysed.
- **Carbonic Acidity**. This is a measure of the 'temporary' acidity that is generated in the mine water due to dissolved carbon dioxide in the mine water. This carbon dioxide forms carbonic acid and increases the acidity.

All of these types of acidity contribute to the total acidity; however it is essential to calculate the acidity in the mine water when the water has equilibrated with atmospheric temperature and pressures. This will allow excess carbon dioxide in the mine water to be liberated (de-gas) and allow oxygen to dissolve in the water. When water has equilibrated with the atmospheric conditions, the acidity will often be very different to that measured as the water is pumped from the subsurface.

2.3 Measuring mine water acidity

The proton, mineral and carbonic acidity all contribute to the total acidity.

2.3.1 Total acidity

The total acidity in mine water can be measured by a simple titration with a strong base to an end point pH of 8.5. The end point indicator generally used for the titration is phenolphthalein, which turns pink above a pH of 8.5.

2.3.2 Proton acidity

The proton acidity can be measured by simply measuring the pH of the mine water. The proton acidity is related to the pH of the mine water by the relationship of pH = -log10[H+]. Therefore the proton acidity can be calculated by simply measuring the pH of the water with a pH meter.

2.3.3 Mineral acidity

This is a calculated value based upon those metals that are readily hydrolysed and oxidised within the mine water and includes all those metals that are present at a sufficiently high concentration for to contribute to the acidity. In general these include iron, manganese, aluminium and zinc, however iron often contributes the greatest amount to the mineral acidity. The relationship is defined in equation 1.

Mineral acidity = 50[2(Fe2+/56) +3(Fe3+)/56) + 2(Mn2+/55) + 3(Al3+/27) + 2(Zn2+/65) + 1000(10-pH) (1)

2.3.4 Carbonic acidity

This can be estimated from the difference between the total acidity measured in the mine water prior to the degassing and equilibration with atmospheric levels of carbon dioxide and either the calculated mineral acidity or the acidity in a degassed mine water.

The factors that will affect the mine water acidity are discussed in section 2.4.

2.4 Factors affecting mine water acidity

The main factors that affect mine water acidity are the concentrations of dissolved carbon dioxide and oxygen in the water.

When water discharges from the subsurface (either by natural means via a drainage adit or similar underground drainage structures, or by active means via pumping) the water is saturated with respect to carbon dioxide and depleted in oxygen. When the mine water comes into contact with air it readily equilibrates.

2.4.1 Carbon Dioxide

The concentration of dissolved carbon dioxide in the mine water plays an important role in the acidity of the mine water. This is because higher pressures at depth allow a higher concentration of carbon dioxide to dissolve in the water resulting in the formation of carbonic acid. This is shown in equation 2.

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^- + 2H^+ \qquad (2)$$

However, as the concentration of carbon dioxide in the mine water decreases as carbon dioxide is lost from the mine water at atmospheric pressures, the concentration of H+ ions decreases, which results in a decrease in acidity (and potentially an increase in pH).

2.4.2 Oxygen

The concentration of dissolved oxygen in the mine water plays an indirect role in the acidity of the mine water, as at low concentrations of dissolved oxygen, dissolved metals in the mine water will be in the reduced form. As mine water is aerated as it discharges from the subsurface, metals will be oxidised and hydrolysed, which generates acidity (protons), examples of which are shown in equations 3 to 5.

Ferrous iron oxidation: $Fe^{2+} + \frac{1}{4} O_2 + H^+ \leftrightarrow Fe^{3+} + \frac{1}{2} H_2O$ (3a)

Ferric iron hydrolysis: $Fe^{3+} + 2H_2O \leftrightarrow Fe(OH)_x + 3H^+$ (3b)

Results in a net generation of 2 protons.

Aluminium hydrolysis: $Al^{3+} + 3H_2O \leftrightarrow Al(OH)_3 + 3H^+$ (4)

Results in a net generation of 3 protons.

Manganese oxidation: $Mn^{2+} + \frac{1}{2} O_2 + 2H^+ \leftrightarrow Mn^{4+} + H_2O$ (5a)

Manganese hydrolysis: $Mn^{4+} + 2H_2O \leftrightarrow MnO_2 + 4H^+$ (5b)

Results in a net generation of 2 protons.

2.5 Implications for a passive treatment system

As discussed in section 2, it is essential to identify whether the mine water is net acidic, circum neutral or net alkaline. If the water is net acidic and/or circum neutral then the mine water will need some form of additional alkalinity, either by caustic dosing or via treatment with an alkaline material such as limestone.

With net alkaline water it is also essential to assess the ratio of alkalinity to metal loading and therefore the potential acidity in the mine water. The oxidation and hydrolysis of metals will result in acidity generation; if the potential mineral acidity loading is higher than the alkalinity concentration, then the oxidation and hydrolysis of these metals may result in the generation net acidic water (see equations 3 to 5). This may occur either within the treatment system or in the discharge from the treatment system.

3. Sampling Design and Methodology

3.1 Rationale

As detailed in Section 1, the total acidity measured by the laboratory in the mine water is substantially higher than that calculated from the concentration of dissolved metals and pH in the mine water. The acidity in the western wells is such that at times the acidity concentration exceeds the alkalinity concentration, thus rendering the mine water net acidic. Although it was initially hypothesised that the pumped water was predominantly surface water inflow to the mine, and that the pumps were removing this surface water from the mine workings, due to this large discrepancy between mineral acidity and total acidity, it was hypothesised that a major source of this acidity was generated from carbonic acid.

In order to establish if this was the case, a field sampling experiment was devised to assess the amount of acidity in the mine water both before and after degassing of the mine water.

3.2 Sampling Design

The sampling design was devised to assess the carbonic acidity in the mine water, and how the acidity changes after the water had equilibrated with the atmosphere. In order to do this, excess carbon dioxide must be removed from the mine water sample. This can be accomplished by one or all of the below:

1. Natural equilibration with the atmosphere, accelerated by agitation/aeration
2. Purging with nitrogen gas
3. Boiling for 1-3 minutes to drive off all gases

Natural equilibration with the atmosphere was decided against due to time limitations, and also that it is difficult to determine when an end point has been reached with out performing multiple assessments of the acidity until a steady state is reached. Purging the sample with nitrogen gas will also remove excess carbon dioxide (and therefore acidity), and does not require heating of the mine water and therefore loss of any of the mine water by evaporation, however practically it is difficult to transport a nitrogen gas cylinder to site.

Boiling the water sample is a quick and efficient method to ensure that all gases are driven off the sample. The carbonic acidity can be assessed on site by measuring the acidity before and after boiling; the difference between the acidity values will be due to the carbonic acidity; the acidity measured in the boiled water will be the permanent acidity from the oxidation and hydrolysis of metals and from the latent carbonic acidity.

3.3 Methodology

At each site a combination of analyses were conducted to provide a comprehensive model of the metal, alkalinity and acidity loading from each pump head and the combined discharge.

At each monitoring site, the works included:

- The collection of water samples for carrying out of on-site water quality characteristics.
- The collection of water samples for laboratory analyses.
- On-site visual observations, including weather conditions and appearance of water discharge.

At each pumping well, the pumps were turned on to allow purging of the water for at least one day prior to sampling if the pumps were not in use on the proposed sampling date. If the pumps were operational, then the water was purged from the pump tap at each well head for 10 to 20 seconds to allow any precipitate and build up to be flushed from the tap. Water was collected in a bucket (c. 20 litre or similar) via a hose pipe connected to the tap. The bucket was be located outside of the pumping chamber and the pipe submerged at the base of the bucket to minimise turbulence and aeration of the mine water as it entered the bucket.

The combined discharge was sampled directly from the discharge pipe.

The prevailing weather was noted on each sample date, and any changes throughout the day.

3.3.1 On-Site Water Analyses

Analyses that were conducted at each sample point were:

- Acidity (titration as $CaCO_3$, using HACH kit)
- Alkalinity (titration as $CaCO_3$, using HACH kit)
- pH (using multimeter)
- Conductivity (using multimeter)
- Temperature (using multimeter)
- Dissolved oxygen (using multimeter)

Field parameters such as dissolved oxygen, conductivity and pH were measured using an appropriately calibrated field multimeter. The multimeter instrument was calibrated with suitable pH, EC and dissolved oxygen standards prior to the water monitoring. The multimeter probes were allowed to stabilise in the bucket (directly in the outflow in the case of the combined discharge) and measurements and samples taken when values stabilise.

Acidity and alkalinity titrations were carried out according to the manufacturer's protocol. Acidity and alkalinity is assessed using mini pH titration kits. Bromophenol blue is a pH sensitive indicator used to assess a change in pH during the alkalinity titration, and phenolphthalein is the indicator used during the acidity titration. The number of drops of acid or alkali used to generate a colour change, hence an end point in the titration, are recorded and converted into mg/l $CaCO_3$.

All equipment used for water analysis was cleaned with distilled water between monitoring points and, in the case of analysis bottles in the Hach test kits, rinsed with the water to be analysed prior to refilling and carrying out the field test. All wash water and should be disposed of appropriately in accordance with duty of care.

Analysis for the acidity loading within the mine water was conducted on both raw and boiled mine water to give an indication of the temporary and permanent acidity within the mine water. Approx 500 ml of the mine water was boiled on a small portable stove for 2 to 5 minutes in a Teflon coated inert pan. The water was allowed to cool and the acidity assessed by titrations as for the raw mine water.

3.3.2 Laboratory Analyses

At each sample point, 9 bottles of discharge water were taken for each sample, for which different water quality parameters would later be measured by the testing laboratory. Bottles were filled to the top, with no headspace. The bottles used for the analyses are detailed in Table 1 below, and were provided pre-filled with reagent where possible by the laboratory. When possible, samples were taken to the lab on the sample day to ensure that they were maintained at a suitably low temperature (~ 40C). Details of the metals and non metals analysed are provided in Table 3.1 below.

Bottles were clearly labelled with sample well number, date, time and analysis required immediately after sampling. A record of samples taken were on a chain of custody sheet was filled in prior to dispatch of the samples to the laboratory. The chain of custody clearly stated the analysis requirements for each sample.

Analysis	Volume (ml)	Acid preservative	Bottle	Filtration
Total metals	50	Nitric acid	Plastic	No
Dissolved metals	50	Nitric acid	Plastic	Yes, 0.45µm filter
Minerals (non metals)	500	Non	Plastic	No
Acidity (Cold)	250	Non	Plastic	No
Acidity (Hot)	250	Non	Plastic	No
Alkalinity (Hot)	250	Non	Plastic	No
Mercury	100	K dichromate	Amber glass	No
TKN	100	Sulphuric acid	Amber glass	No
Ferrous Fe and Mn	40	Hydrochloric acid	Glass	No

Table 3.1 Details of bottles for analysis:

Physical parameters	Bicarbonate	Calculated values	TDS
	Carbonate		Cation Sum
	Colour		Anion Sum
	Turbidity		Ion Sum
	Conductivity		Ion Balance
	pH		
	Acidity		
Major Ions:	Sodium	Nutrients:	Ortho-Phosphorus (as P)
	Potassium		Phosphorus
	Calcium		Nitrite and Nitrate (as N)
	Magnesium		TKN
	Alkalinity (as $CaCO_3$)		Ammonia as (N)
	Sulphate		Total Organic Carbon
	Chloride		Total Inorganic Carbon
	Silica		
Metals (total and dissolved for each):	Iron	Bismuth	Selenium
	Ferrous Iron	Boron	Silver
	Manganese	Cadmium	Strontium
	Copper	Chromium	Sulphur
	Zinc	Cobalt	Thallium
	Aluminium	Lead	Tin
	Antimony	Lithium	Titanium
	Arsenic	Mercury	Uranium
	Barium	Molybdenum	Vanadium
	Beryllium	Nickel	Cadmium

Table 3.2 - Details of Metals and Non Metals Laboratory Analyses

Samples of boiled water from each location were analysed in the laboratory for a range of physical parameters including alkalinity.

Major Ions:	Alkalinity
Physical Parameters	Carbonate
	Colour
	Turbidity
	Conductivity
	pH
	Acidity
	Bicarbonate

Table 3.3 - Details of Laboratory Analyses on degassed samples

4. Findings and Interpretation

4.1 On site analyses

At each pumped well head, pH, electrical conductivity (EC; us/cm), temperature (T^0C) and dissolved oxygen (DO; %) were measured directly in the raw mine water. Field titrations for alkalinity and acidity and a colourimetric testing of iron were also conducted on the raw mine water.

Carbon dioxide was removed from the mine water by boiling, cooled in small aliquots and the pH, alkalinity and acidity measured on the degassed mine water.

Electrical conductivity, temperature and dissolved oxygen were not measured on the boiled mine water as water was lost by evaporation during the boiling, resulting an increase in the EC due to concentration of the ions rather than giving an indication of a chemical change. Dissolved oxygen was not measured as the boiling should have driven off any oxygen in the mine water.

4.1.1 pH

In all cases there was an increase in pH units of between 0.36 and 2.53 between the raw and degassed mine water, although it had been anticipated that oxidation and hydrolysis of metals in the water would result in a decrease in pH. This increase in pH can be attributed to a substantial loss of carbonic acidity which will result in an increase in pH.

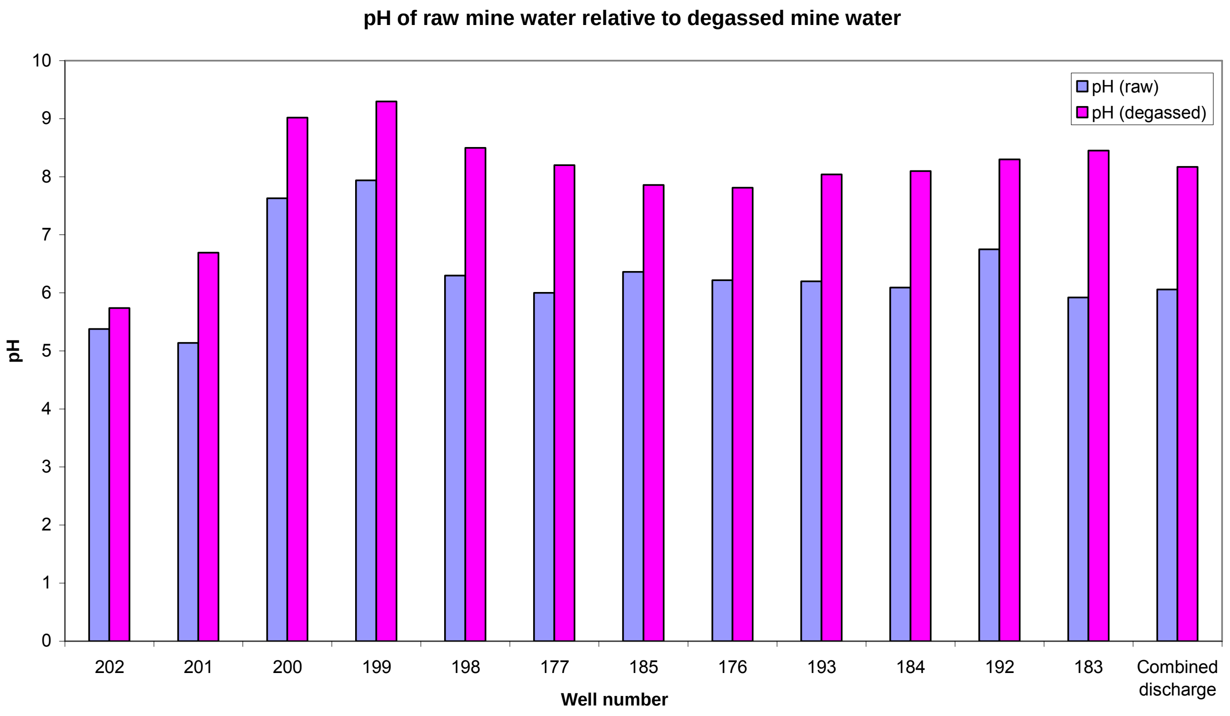


Figure 4.1 – Field pH of mine water before and after boiling. In general, there is an increase in pH between raw mine water and degassed mine water that may be attributable to removal of acidity from mine water. NOTE: Possible inaccuracy with the calibration of the pH meter may have resulted in the high pH measured in wells 198 to 200. Laboratory pH measurement suggests that the field pH for these well values is a factor of 1 unit too high for both raw and boiled mine water. However, the relative difference between the two pHs is still valid.

4.1.2 Alkalinity and Acidity

There were significant changes in the alkalinity and acidity between the raw mine water and the degassed mine water. Before degassing, all the western wells were net acidic with the exception of well 198. The southern wells were all net alkaline, but this was borderline in some cases, for example 183, 184 and 192 that lie in the southern part of the southern well field. In general, the concentration of acidity and alkalinity reduced in the degassed mine water relative to the raw mine water after boiling.

It is anticipated that the reduction in acidity is attributable to the degassing of the mine water and hence the loss of carbonic acid(see equation 2), and protons being consumed as CO_2 is lost from the water. The loss of alkalinity may be related to the increase in pH (see section 4.1.1). As the pH of the mine water increases, the alkalinity is converted to carbonate and precipitates out, therefore being lost from the aqueous system.

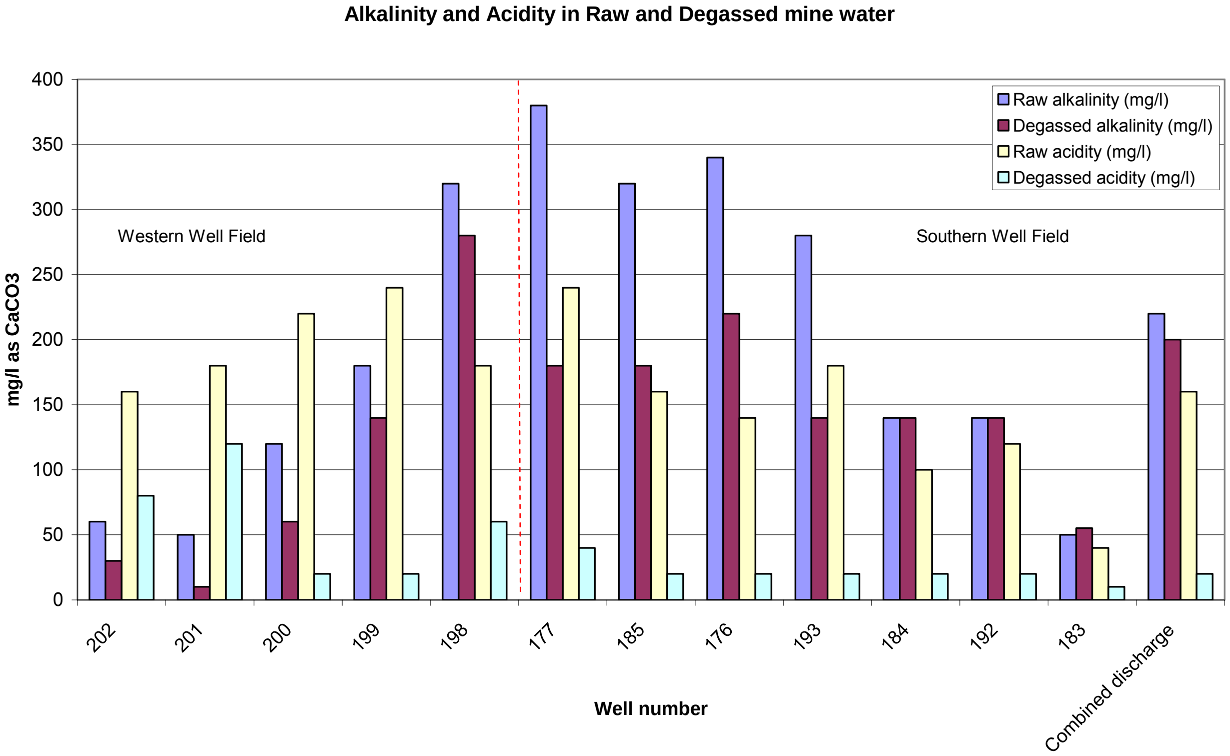


Figure 4.2 – Field assessment of alkalinity and acidity across the well field before and after boiling. Note the large loss of acidity

4.1.3 Iron

Iron was measured using a field colorimetric test in all the well samples and the combined discharge. In general, iron was highest in the western well fields relative to the southern well fields, and iron concentrations increased from east to west and from south to north.

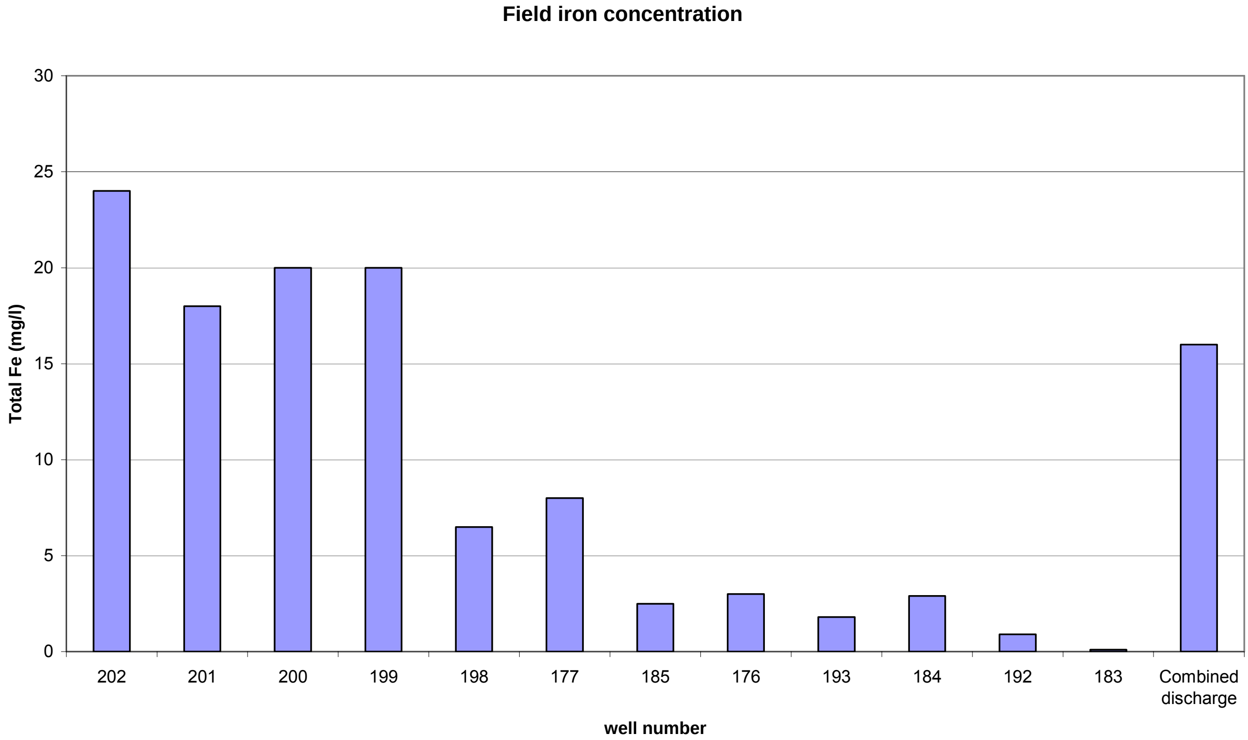


Figure 4.3 – Iron concentration is highest in the western wells relative to the southern wells with a decreasing trend west to east and north to south.

4.1.4 Electrical conductivity, Dissolved oxygen and temperature

Temperature in the western well field was an average of 3 °C higher than the southern well field (12 °C versus 9 °C). This suggests that the water being pumped from the western well field is originating from a different level as compares to the southern well field.

Dissolved oxygen is very low in all the wells (except well 183), which indicates that conditions are highly reducing in the well field (0.02 mg/l to 1.97 mg/l DO). Dissolved oxygen is higher in well 183 (4.83 mg/l) which suggest that the origin of water in this well is different to the other wells; possibly the water is sourced from surface water infiltration.

Electrical conductivity, which is an indicator of the total dissolved ions in water and therefore can be used as a proxy for metal loading, varies substantially across the site. In general electrical conductivity is highest in the centre of the well field at the intersection of the line of the southern and western well fields, with values decreasing from east to west and north to south.

4.2 Laboratory Analyses

A full laboratory analysis of all the samples was conducted to assess how the acidity, alkalinity and metal loading varied over the well field, and in the case of the degassed samples, how the alkalinity, acidity and TIC varied for each sample.

4.3 Metal loading

The main metal loading in the samples comes from iron, manganese, aluminium and zinc. In general the concentration of the dissolved fraction of the metals in the mine water is very similar to the concentration of total metals, which indicates that the predominant metal loading is in the dissolved form.

Iron is present in all the wells, however the highest concentrations are found at the west end of the western wells, notably wells 202 to 199. Iron loading is low in the southern wells at approximately 1.5 mg/l, with concentrations reducing from north to south.

Aluminium is present at significant concentration in wells 202 and 201 in the western wellfield and at lower concentrations in wells 183, 184 and 192 of the southern wells.

Manganese loading is the highest in the centre of the western well field and lowest in the south of the southern wellfield. Manganese is present in all the mine water samples, with the highest loading of 34 mg/l Mn in well 200. In the southern wells manganese is the dominant metal contaminant in the mine water.

Zinc, as for aluminium is highest in wells 202 and 201 in the western well field and at lower concentrations in wells 183, 184 and 192 of the southern wells.

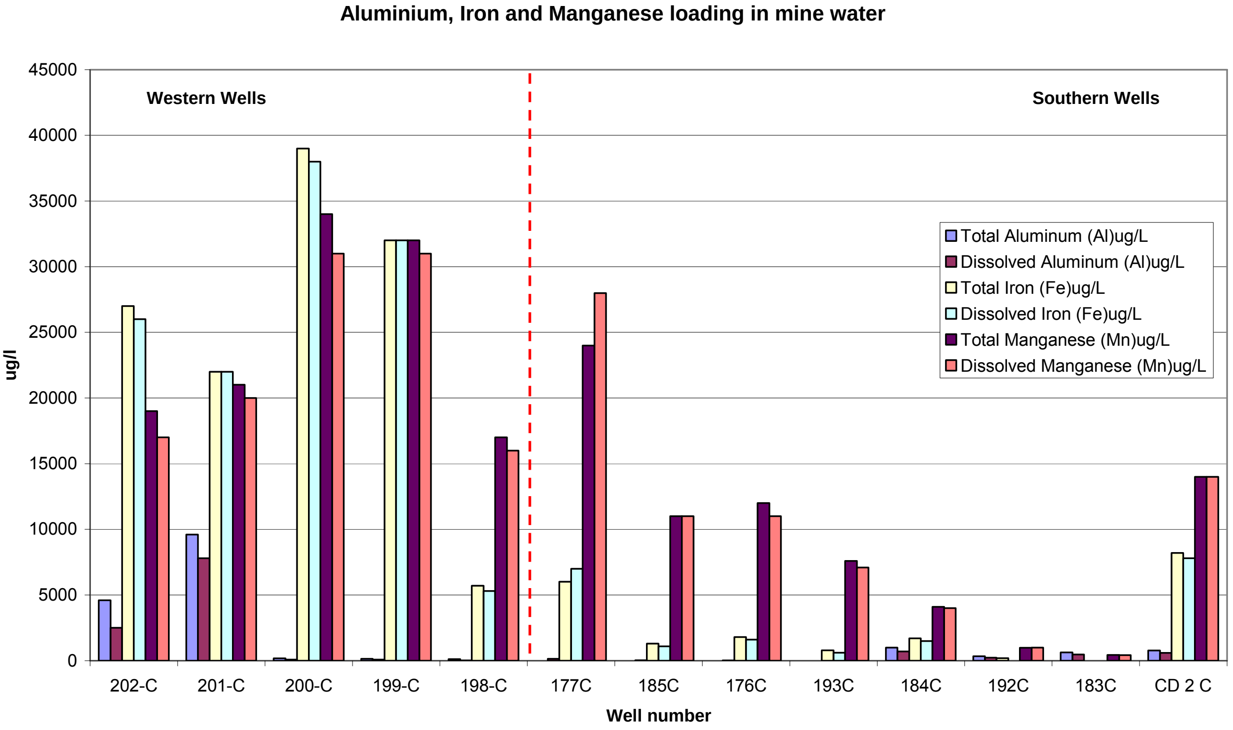


Figure 4.4 – Laboratory analysis of total and dissolved Al, Fe & Mn in the raw mine water. Note the decreasing trend in Mn from the north to south and high concentrations of Al in the western wells

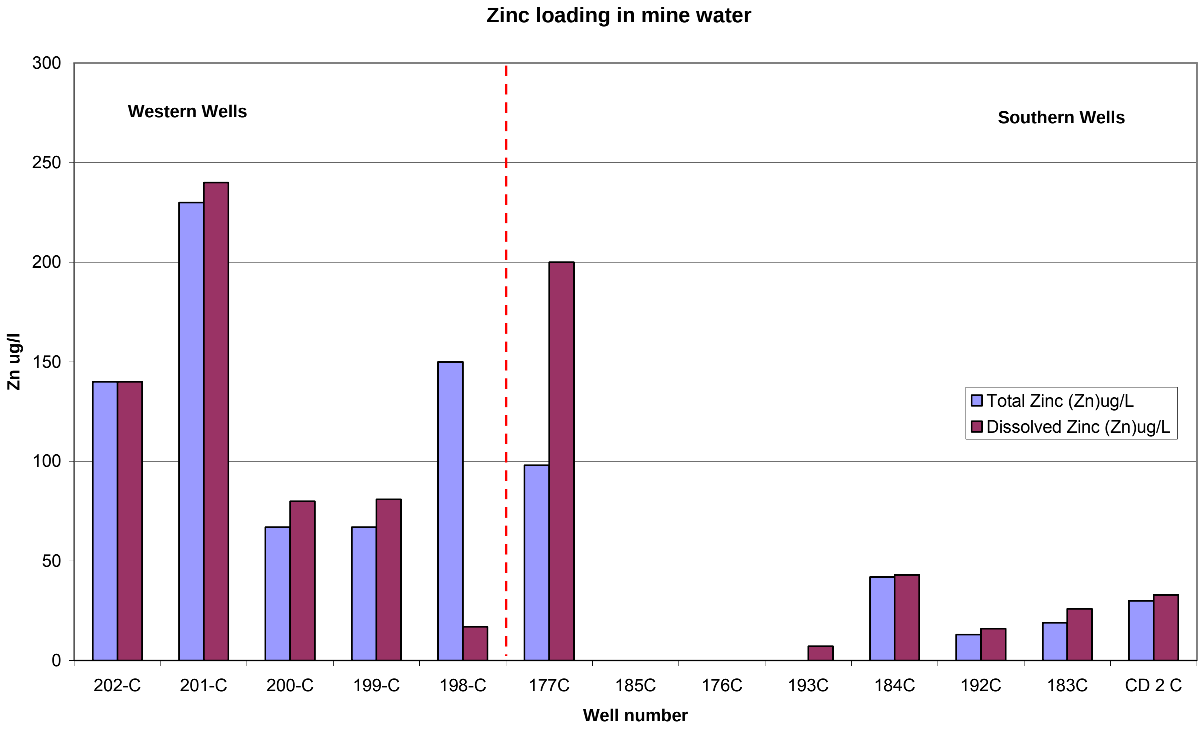


Figure 4.5 - – Laboratory analysis of total and dissolved Zn in the raw mine water.

4.4 Carbonate chemistry and acidity

In order to assess the effect that the degassing would have upon the carbonate chemistry within the mine water, specifically in terms of the carbonic acidity, the alkalinity, acidity and total inorganic carbon were measured in the mine water before and after boiling. The results of which are presented in Figure 4.6.

An average of 77% of the acidity and 30% of the alkalinity was lost due to boiling and degassing of the mine water from the 12 wells sampled. In the western wells, the water was strongly net acidic prior to degassing, however after degassing, the water only remains net acidic in the two most western of the western wells (wells 202 and 201). This correlates with a high aluminium and zinc loading, both of which will impart permanent acidity to the water (following oxidation and hydrolysis) after the carbonic acidity is removed via degassing. The remaining wells predominately contain Fe and Mn, which may not be at a sufficiently high concentration to maintain the acidity loading of the mine water.

In the southern wells, the water is on balance circum neutral prior to degassing, as some wells are net alkaline and some net acidic. However, after degassing all mine water from the southern wells was net alkaline.

Total Inorganic Carbon (TIC) in all the wells reduced by between 23% (well 183; the southern most well from the southern wells) and 95% (in well 201; one of the western most wells in the western wells). Loss of inorganic carbon indicates that carbon is being lost from the solution. It is presumed that this is the gaseous loss of carbon dioxide which occurs during the degassing of the mine water.

The results therefore suggest that a large proportion of the acidity loading in the Neville street mine waters are a result of carbonic acid due to an elevated concentration of dissolved carbon dioxide in the mine water. It is hypothesised that the ratio of carbonic acid loading relative to mineral acidity in the mine water will have historically been of a similar order of magnitude.

In order to assess the remaining acidity in the mine water after equilibration with atmospheric CO2 and O2, and therefore to predict the acidity loading trend with time, the measured laboratory acidity was altered to reflect degassing and compared with the mineral acidity. This is depicted in figure 4.7. It should be noted that the loss of alkalinity was also taken into account when presenting the alkalinity: acidity balance for the mine water. This is because the pH rise caused by the degassing and subsequent loss of acidity may have also resulted in the natural loss of alkalinity in the treatment system.With reference to Figure 4.7, it can be seen that the mine water should remain net alkaline for a longer time period than that predicted using the laboratory acidity value alone. This reduction in mine water acidity, as calculated from the relative loss of carbonic acidity, has altered the projected mine water alkalinity:acidity balance trend, resulting in an anticipated circum neutral water between June 2014 and Dec 2015 rather than July 2010. This is based upon complete de-gassing of the mine water and therefore near complete removal of the carbonic acidity.

It was anticipated that the mineral acidity trend would closely mirror the hot acidity trend. Although it is similar, the calculated alkalinity: acidity ratio predicts that the mine water will become net acidic earlier than that calculated for the mineral acidity. This may be due to several factors, but one of the most likely is that carbonic acid acidity will never be entirely removed from the mine water, with a residual acidity remaining in the mine water. In addition, the calculated mineral alkalinity: acidity ratio does not take into account the loss of alkalinity as a result of the natural degassing of the mine water. Furthermore, the calculated hot alkalinity: acidity ratio has been extrapolated backwards, and assumes that the carbonic acid balance within the mine workings has remained the same over time. All these must be taken into account when interpreting the potential time period upon which the mine water may be net acidic more often than net alkaline.

It should be noted that these trends and hypotheses are based on chemical data and do not take into account other factors of the system such as the hydrogeology, which is outside the scope of this study. These factors could have significant impact as to how the system chemistry will develop in the future.

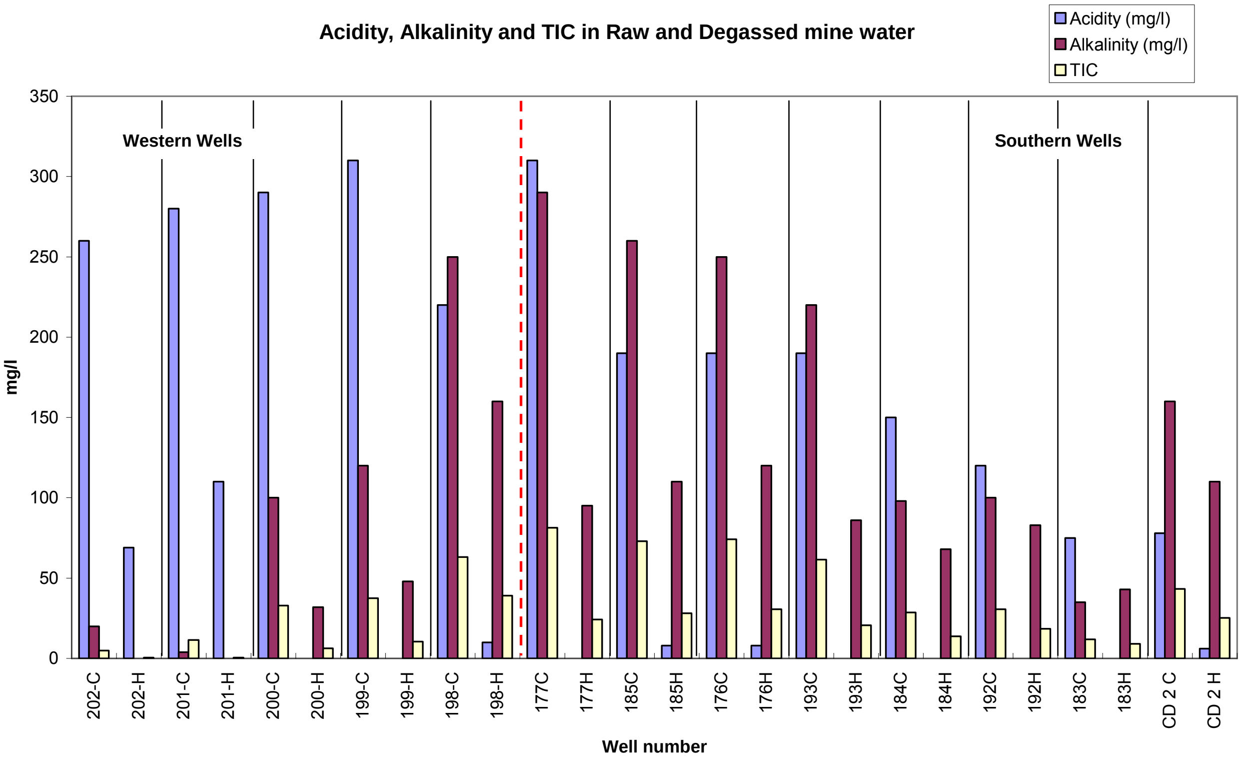


Figure 4.6 – Laboratory measured total acidity, alkalinity and Total Inorganic Carbon in the raw and degassed (boiled) min water. Note the large loss in acidity, alkalinity and TIC between the raw and degassed mine waters.

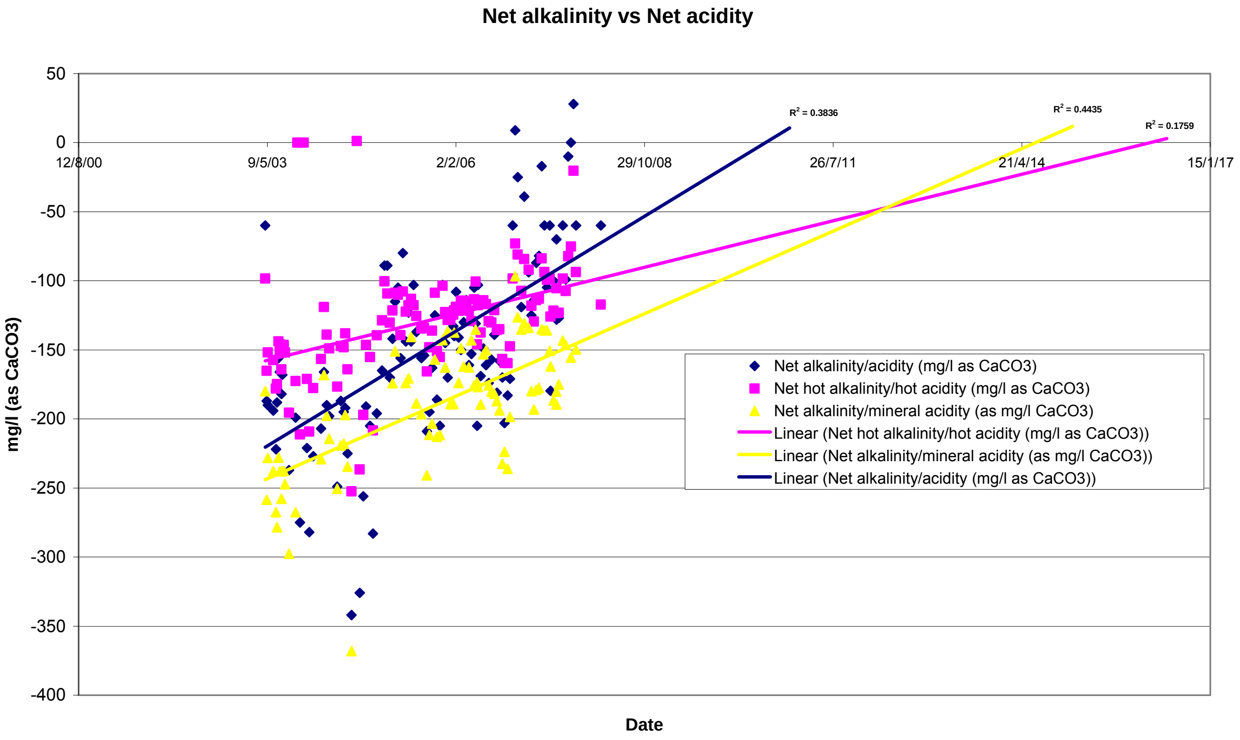


Figure 4.7 – Projected trend of net alkalinity: acidity ratio with time. A negative mg/l $CaCO_3$ indicates that the water is net alkaline. The trend suggests that the water is becoming more acidic with time, with projected circum neutral water expected between June 2014 and Dec 2015

4.5 Interpretation

Both field and laboratory results from the sampling round carried out in March 2008 has suggested that the mine water from the Neville Street well field is a mixture of deep mine water and surface waters. It is believed that the quality of the mine water is indicative of the degree of mixing of the two mine waters, and is relative to the residence time of the water within the system.

The western well field and southern well field water qualities are largely very different; the differences are summarised below, and the implications to the mine water quality trends highlighted.

4.5.1 Temperature

The temperature of the western well field is an average of 3 degC higher than the southern well field, with the western well field approximately 12 degC and the southern well field approximately 9 deg C. This difference in temperature is indicative of water from different depths; a higher temperature is indicative of deeper ground water. As the pumps are assumed to be at the same depth throughout the well field, these differences are thought to be as a result of the western well field pumps drawing water from a deeper depth, whereas the southern well pumps may draw water from the surface water inflows from the southern inflows.

4.5.2 Dissolved Oxygen

The dissolved oxygen concentration is very low across the well field, with exception of one pump (well 183). This indicates that the water has had sufficient residence time within the mine workings to become depleted in oxygen, again indicating that the water originates from deeper mine workings. Pump 183 is higher in oxygen than the rest of the well field; this is the most southern well and it is anticipated that the higher oxygen is the influence of surface water infiltration from the shallow mine workings to the south of the site.

4.5.3 Elevated Aluminium

Aluminium has been detected in all wells except well 193. High concentrations of aluminium were measured in the most western wells of the western well field. Aluminium can, in some circumstances be used as an indicator of water sourced from deeper mine workings. This is because Al can be generated from the dissolution of clay minerals; the coal seams in the Sydney coal field are interlaid with sandstones, shales and conglomerates which under highly acidic and reducing environments may dissolve, therefore liberating aluminium.

Therefore, it is thought that the mine water in the Neville Street well field is a mixture of surface water and deep mine water, with a higher proportion of deep water in the north west of the well field, with a gradual move towards surface water in the south east of the well field.

5. Implications

5.1 Treatment sizing for Current Water regime

Based on the most recent chemical data obtained in March 2008, iron concentrations are significantly higher in the western well field as compared to the southern well field, and in addition the average iron concentration in each well field has increased from the February 2008 sampling round.

Treatment options are discussed for the southern well field and the western well fields separately, with the options for the co-treatment of the mine waters also discussed.

An assessment of the pumping rates and volumes over the last 5 years for both the southern and western wells has been made and is summarised in Table 5.1. The assessment uses historical flow data to determine pump utilisation under the current pump operating sequence and management regime. The table summarises the utilisation of each well in terms of annualised percentage pump operation to maintain the mine water at the required level in the workings.

Well Number	193	192	185	183	176	184	198	177	201	202	200	199
Operational sequence	1	2	3	4	5	6	7	8	9	10	11	12
Flow cumulative (l/sec)	27.8	60	96	126	153	186	215	245	275	295	325	354
Sum days operational	1601	1588	1300	914	664	486	290	189	133	90	75	29
Percentage time operational	100%	99.2%	81.2%	57.1%	41.5%	30.4%	18.1%	11.8%	8.3%	5.6%	4.7%	1.8%

Note: - Southern well field are highlighted

Table 5.1 –Pumping Well Utilisation

5.1.1 Southern well field

The cumulative iron concentration in the mine water is 1.74 mg/l and the maximum concentration was measured in well 177 at 6 mg/l Fe. The cumulative manganese concentration in the mine water is 7.9 mg/l and the maximum concentration was measured in well 177 at 24 mg/l Mn. Based on these concentrations the discharge from the southern well field could be treated by wetland only. However, due to the increasing trend in concentration of total metals in the well field and the amount of dissolved carbon dioxide it would be preferable to have some degree of settlement, degassing lagoon prior to discharge into a wetland. This is discussed further in the preferred option put forward in Section 7.

Sizing of wetland
The wetland should be sized according to guidelines of Hedin and colleagues:

$A = (Q_d(\text{Inf}-\text{Ef}))/R_A$

A = wetland area (m^2)
Q_d = flow (m^3/day)
Inf = Input concentration (mg/l)
Ef = Effluent concentration (mg/l)
R_A = Area-adjusted contaminant removal rate ($g/m^2/d$) (in this case we approximate the R_A to 10 $g/m^2/d$ as recommended by the Pyramid guidelines)

Based on the current worst case input of 6 mg/l Fe and a flow rate of 220.2 l/s, a minimum treatment area of **11,415m^2** would be required to reduce the metal concentration in the mine water to <1 mg/l. This could be in one or more wetlands, dependant on site constraints. Given the high flow rates it is recommended that the water be introduced to the wetland via 4 or more aeration cascades to prevent short-circuiting within the wetland. This will allow additional oxygen to enter the water to completely oxidise the metals in the mine water. This is the minimum size based on current worst iron concentration for the southern well field. However, it allows for no redundancy or deterioration in water quality.

Summary of the treatment of the southern wells

For the purposes of outline design sizing, it is anticipated that the pumped mine water will be continuously delivered at a reasonably constant flow and metal concentration. It is known that the system is dynamic and may continue to be variable with respect to metal loading; therefore some excess capacity and flexibility in the design will be required to allow for this. The wetland could be used solely to treat this discharge but there are significant risks relating to degassing, changes in quality and other metal loads which would be best achieved by the use of initial settlement. This is discussed further in our preferred design option presented in Section 7.

5.1.2 Western well field

The cumulative iron concentration in the mine water is 25.02 mg/l and the maximum concentration was measured in well 200 at 39 mg/l Fe. The cumulative manganese concentration in the mine water is 25 mg/l and the maximum concentration was measured in well 200 at 34 mg/l Mn. In addition to iron and manganese, aluminium was also measured in wells 202 and 201 at a maximum concentration of 9.6 mg/l in well 201. The cumulative aluminium concentration in the mine water was calculated as 2.81 mg/l Al.

Due to the increasing trend in concentration of total metals in the well field, we have based our initial treatment scheme sizing on the conservative iron concentration of 50 mg/l Fe (c.39 mg/l + 25% contingency). Additional redundancy will be needed in the system because it is anticipated that manganese and aluminium should be co-removed and therefore the system needs to be robust enough to accommodate these extra metals.

Based on total acidity and alkalinity data, the combined flow from the western well field is net acidic, however following complete degassing to remove carbonic acidity, sufficient acidity is lost form the water to generate a net alkaline water. However, this is based on total degassing, which might not be practicable, and also takes no account of any deterioration in quality over time.

Based upon sufficient acidity removal to generate net alkaline water, the use of a settlement lagoon and reed bed wetland to treat the discharge from the western wells should be adequate. However, the settlement lagoon will need to have the option to be dosed with caustic should the water become net acidic over time.

Sizing of settlement lagoon

The sizing of the settlement lagoon is based upon the pumping rates and the sludge accumulation rates. Assuming an iron concentration of 50 mg/l and a maximum flow rate of 139.1 l/sec, a minimum four separate aeration cascades are required. These are to introduce sufficient oxygen to the mine water to allow maximum CO_2 removal to reduce the carbonic acidity concentration, and to oxidise all the iron in the mine water to oxides and oxyhydroxides.

The size of the settlement lagoons is based upon a linear relationship between the percentage reduction in influent iron concentration required and the hydraulic retention time (Pyramid Guidelines[1]).

The relationship used is –

Minimum residence time = (0.5 x % lowering of Fe required)

Based upon an influent of 50 mg/l iron and a required reduction in metal loading to less than 10 mg/l in the settlement lagoons;

- The % lowering of Fe required is 40/50 = 80%
- The residence time in the settlement lagoons is 0.5 x 80 = 40 hours.

At a flow rate of 139.1 l/sec and an iron concentration of 50 mg/l then the *minimum void space required* for 80% metal removal is 20 030m^3. This is calculated by:

Void space = 139.1 l/sec x 60 x 60 /1000 = 500.76m^3/hr x 40hrs = 20,030 m^3

Iron will accumulate as iron oxyhydroxides. At a conservative influent iron concentration of 50 mg/l and assuming that 40 mg/l will be removed in the settlement lagoon then the total mass of metal removal in the settlement lagoon will be 480.7 kg/day. This can be calculated using the following expression:

$(40 \times 139.1 \times 60 \times 60 \times 24)/10^6 =$ 480.7 kg/day Fe

This will be removed as Fe oxides and oxyhydroxides.

This is calculated as:
480.7 kg/day x (106/56) = 909.95 kg/day $Fe(OOH)_x$

Given a sludge volume of between 5% and 3%, the settlement lagoon 1 will collect between 18.2 m^3 and 30 m^3/day as $Fe(OOH)_x$.

Therefore after 1 year of operation, the settlement pond will contain between 6,643m^3 and 10,950m^3 of sludge. However, this is based upon all 5 of the western wells operating for 365 days per year. Clearly, historical data suggests that the pumps will not be required to be in operation to this extent, therefore this sludge calculation is highly conservative.

This is based upon the settlement pond removing 80% of the iron loading. It is possible that a higher percentage of iron may be removed and in addition, other metals such as manganese and aluminium will be removed. This will create additional sludge volume. Assuming that the lagoons will be de-sludged every year to ensure that the minimum residence time is maintained, it is recommended that the total area required for the settlement lagoon is a minimum 30,980 m^3. This is calculated from;

10,950 m^3 (sludge volume/yr) x 1 (years accumulated sludge) + 20,030 m^3 (min. void space) = **30,980m^3**.

This volume is based on the worst case scenario of a 3% sludge volume.

Sizing of wetland

The wetland should be sized according to guidelines of Hedin and colleagues:

$A = (Q_d(Inf-Ef))/R_A$

A = wetland area (m^2)
Q_d = flow (m^3/day)
Inf = Input concentration (mg/l)
Ef = Effluent concentration (mg/l)
R_A = Area-adjusted contaminant removal rate (g/m^2/d) (in this case we approximate the R_A to 10 g/m^2/d as recommended by the Pyramid guidelines)

Based on an input of approximately 10 mg/l Fe and a flow rate of 139.1 l/sec, a minimum treatment area of **10,816 m^2** would be required to reduce the metal concentration in the mine water to <1 mg/l. This could be in one or more wetlands, dependant on site constraints. Given the high flow rates it is recommended that the water be introduced to the wetland via 4 or more aeration cascades to prevent short-circuiting within the wetland. This will allow additional oxygen to enter the water to completely oxidise the metals in the mine water.

6. Outline Design

6.1 Rationale

The concept for the outline design for the treatment scheme to treat the current water chemistry to an acceptable discharge of <1.0mg/L of Iron is set out below.

In terms of general design criteria it is recommended that the settlement lagoons and wetlands have a length to width ratio of no less than 2:1 and no more than 5:1. Due to the potentially large volume of the settlement lagoons required, in order to minimise the required land area and maximise volume these could be up to 3 m deep. However, this depth is best not exceeded in order to limit the formation and size of any reducing environment near the lagoon bed. The depth will also be subject to geotechnical and groundwater conditions at the site.

Western Wellfield	Treatment Process	Southern Wellfield
AERATION	Aerate to oxidise metals and remove dissolved CO_2 to reduce carbonic acidity.	AERATION
CHEMICAL DOSING	IF NECESSARY: Add alkali to increase pH and generate net-alkaline mine water	
SETTLEMENT	Reduce Iron loading via settlement of Fe oxyhydroxides	SETTLEMENT
AERATION	Aerate to further oxidise metals and remove any latent CO_2	AERATION
WETLAND	Reduce iron loading to <1.0 mg/L	WETLAND

Figure 6.1 – Outline Design Process

In determining the optimum outline design for the scheme the requirement for the continued flexibility of the system to manage future changes in mine water condition need to be considered. The following table outlines the potential changes in mine water condition which may be anticipated and identifies how this may be managed.

Western Well Field		
Potential Future Condition	Treatment Response	Comment
Increase in acidity	Commence/increase chemical dosing rate	Dosing may be required when western wells are pumped shortly after commissioning
	Mix settlement pond effluent with southern well field water to utilise additional alkalinity from southern wellfield.	Incorporate into Preferred Scheme Arrangement
Aeration is Insufficient to fully degas the mine water and remove carbonic acidity	Retrofit mechanical aeration	
	Provide additional aeration cascade at start of the scheme	
	Commence/increase chemical dosing rate	
Increase in dissolved metal loading	Additional settlement pond required to increase residence time and reduce settlement pond effluent to <10 mg/L	Design based on up to 50mg/l from west wells
	Add additional chemical/flocculent	
	Mix settlement pond effluent with southern well field water to dilute iron concentration prior to a secondary settlement pond	Incorporate into Preferred Scheme Arrangement
	Mix settlement pond effluent with southern well field water to dilute iron concentration to <10 mg/L prior to wetland	Incorporate into Preferred Scheme Arrangement
Mine water quality deteriorates in individual wells	Alter pumping sequence to maintain pumping from better quality wells	
	Consider abandoning pumping from worst quality wells and actively managing pumping prior to rainfall event to reduce water levels, by pumping more from better quality wells, new wells located closer to outcrop/recharge area.	
pH is not correctly adjusted after settlement pond	Mix Settlement pond effluent with southern wellfield water (either prior to settlement pond or prior to wetland) to blend the chemistry of the waters	
De-sludging requirements for settlement pond	Western well field may be managed such that it remains dormant during a dry weather period in summer for sludge to dry out and supernatant water to be over-pumped.	
Maintaining wetland water level and avoid growth of grasses in wetland when western well field not operational.	Provide adhoc pumping of the western well field pumps to maintain a base flow of water	
	Provide option for southern well field water to discharge to the western wetland.	Incorporate into Preferred

		Scheme Arrangement

Table 6.1 – Western Well Field Risks and Flexibility Requirements

South Well Field		
Potential Future Condition	Treatment Response	Comments
Increase in Acidity	Provide provision for a future chemical dosing to southern well field water. This would be a secondary dosing location for the scheme	Incorporate into Preferred Scheme Arrangement
	Mix water with western wellfield water (which may have benefited from the addition of chemical dosing) to provide a net alkali water. Mixing could take place prior to settlement pond or prior to wetlands.	Incorporate into Preferred Scheme Arrangement
	Provide additional dosing to western well field water to provide additional alkalinity to the water to remain net alkali when mixed with southern well field water	
Aeration is Insufficient to fully degas carbonate Acidity	Retrofit mechanical aeration	
	Provide additional aeration cascade at start of the scheme	
	Provide provision for future chemical dosing or ability to mix with partially treated water from the western well field settlement pond.	Incorporate into Preferred Scheme Arrangement
Increase in dissolved metal loading	The settlement pond would need to be increased in size to increase residence time and reduce iron loading to <10 mg/L prior to wetland	Incorporate into Preferred Scheme Arrangement
	Add additional chemical/flocculent	
	Mix settlement pond effluent with western well field water to dilute iron concentration prior to settlement pond	
	Mix sediment pond effluent with western well field water to dilute iron concentration to <10 mg/L prior to wetland	
pH is not correctly adjusted after settlement pond	Mix settlement pond effluent with southern well field water (either prior to settlement pond or prior to wetland) to blend the chemistry of the waters	
De-sludging requirements for sediment/settlement pond at frequency of up to every 2 years	Bypass channel system required for southern well water during de-sludging works	
	Over pumping system required during de-sludging operation.	Incorporate into Preferred Scheme Arrangement

Table 6.2 - Southern Well Field Risks and Flexibility Requirements

7. Preferred Option

7.1 General

The key risk and therefore flexibility required in the design of the preferred option is the changes in mine water quality; both acidity and metal loading.

This is a major unknown and a certain amount of contingency needs to be incorporated into the preferred option whilst avoiding over-engineering.

In addition to risks, there are also areas of opportunity to maximise efficiency and reduce costs. The key area of operational cost for the proposed scheme is the chemical dosing requirements. This could be achieved by blending poor and good quality waters to provide a net alkaline mixture. However the fluctuations in the chemistry within the well field do not provide a steady condition to determine when dosing may be required to commence. Although dosing may not be required immediately, it is considered inevitable that acidity will need to be addressed when pumping from some of the western wells. In the short term this may be accommodated within the treatment scheme by short term exceedances in the effluent quality from the western wells, without causing detriment to either the wetland or the Cadegan Brook. However if the deterioration in mine water quality continues, some form of dosing will be required for the western wells within a short period of operation.

The elements for managing the risks and potential for efficiency improvements are identified in the Table in Section 6 and have been incorporated onto the following preferred option.

7.2 Preferred Option

7.2.1 Southern Well field

Given the rapidly increasing trend in concentration of total metals in the well field and the large amount of dissolved carbon dioxide in the Neville Street well field mine waters, it is recommended that provision is made for a settlement lagoon for treatment of the southern Well field mine waters. This will allow substantial degassing of the mine water and the removal of some of the metals prior to the water discharging into the wetland system.

Based on historical pump rate data from the last five years (see Table 5.1) the western well field is only operational for 18% of the time. However, owing to well 198 in the western well field being activated prior to well 177 in the southern well field, the percentage time when more than one well from the western well field is operational is only 8.3%, i.e. for c. 30 days a year. This period is during the winter/spring months (generally October to April) when river flows, and therefore any dilution from receiving waters, should also be relatively high. The time during which more than two wells from the western well field are pumping is even less, approximately 5.6% (i.e. c. 20 days per year).

Given the low frequency of operation of the western well pumps, a western well field settlement lagoon and wetland system would be little used for much of the year. Therefore it is recommended that when up to two of the most frequently operated western wells (well 198 and 201) are active in the western well field, then water from these pumps is treated directly in the southern well field treatment system only. Water from these wells is currently of a better quality than the remaining western wells, and therefore would not require any dosing before treatment in a settlement lagoon. In addition, blending and dilution of these waters by the southern well waters would aid in the amelioration of the water from the western wells.

Currently, given the combined chemistry of the southern well field water and two western well field waters it would not be necessary to treat the water using pre-settlement, and a wetland-only system should be sufficient to treat this water. However, as it is anticipated that the metal loading will increase in the southern and the western well field over time and that manganese will be co-removed and need extra void space for accumulation in the treatment system, it is recommended that a settlement pond be used.

Based on the most recent chemical data, the cumulative iron from the southern wells and two western wells is 4.31 mg/l Fe, with a maximum iron concentration of 22 mg/l (from well 201). The cumulative manganese concentration from the southern wells and two western wells is 10.94 mg/l Fe, with a maximum Mn concentration of 24 mg/l (from well 177). However, given the high variability in this system, it is recommended that the treatment scheme sizing is based on the conservative cumulative iron concentration of 15 mg/l Fe. The design is therefore based on the condition of treating the maximum flow with the coexistent maximum iron concentration to ensure that the discharge quality is met for all pumping scenarios.

This value of 15 mg/l is based on a worst case scenario of the iron concentration in the western wells increasing to 50 mg/l (see western well sizing – Section 5.1.2) and the iron in the southern wells increasing to 5 mg/l. This calculation is tabulated and summarised in Table 7.1. By sizing the treatment system on this conservative iron concentration a degree of redundancy will be added to the system, and will allow for changes in the pumping regime and/or mine water chemistry in the future.

The sizing of the system should also be based on the maximum cumulative flow rate from the southern and two western wells of 279.5 l/sec.

Pumping sequence	1	2	3	4	5	6	7	8	9	10	11	12	South Fe loading (mg/s))	West Fe loading (mg/s)	Fe Comb conc mg/l
Well number	193	192	185	183	176	184	198	177	201	202	200	199			
Flow from well (l/sec)	27.8	32.2	36.6	29.9	26.9	32.8	29.6	29.7	29.5	20	30	29			
Cumulative flow (l/sec)	27.8	60	96.6	126.5	153.4	186.2	215.8	245.5	275	295	325	354			
Worst case Quality Fe (mg/l)	5	5	5	5	5	5	50	5	50	50	50	50			
Loading Fe (mg/s)	139	300	483	632.5	767	931	10790	1227.5	13750	14750	16250	17700			
	1	1	1	1	1	1	1	1	1	1	1	1	1080	6905	22.6
	1	1	1	1	1	1	1	1	1	1	1	0	1080	5455	20.1
	1	1	1	1	1	1	1	1	1	1	0	0	1080	3955	17.1
	1	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**1080**	**2955**	**14.7**
	1	1	1	1	1	1	1	1	0	0	0	0	1080	1480	10.4
	1	1	1	1	1	1	1	0	0	0	0	0	931	1480	11.2
	1	1	1	1	1	1	0	0	0	0	0	0	931	0	5
	1	1	1	1	1	0	0	0	0	0	0	0	767	0	5
	1	1	1	1	0	0	0	0	0	0	0	0	633	0	5
	1	1	1	0	0	0	0	0	0	0	0	0	483	0	5
	1	1	0	0	0	0	0	0	0	0	0	0	300	0	5
	1	0	0	0	0	0	0	0	0	0	0	0	139	0	5

Table 7.1 – Cumulative Iron Predictor table based on 5 mg/l Fe mine water quality from the southern wells, and 50 mg/l Fe mine water quality from the western wells.

Note 1. When 9 pumps are in operation, the predicted cumulative iron is 14.7 mg/l.

Note 2. The quality in well 198 is considerably better than that in the remaining western wells with the chemistry being more similar to the southern wells. CBDC have indicated that a mine collapse has severed the hydrogeological connection between well 198 and the remaining western wells; however this has not been investigated by Atkins as part of this report. Therefore, for the purpose of this iron predictor, we have used the conservative approach of classifying the chemistry of well 198 as a western well, for the situation where this well will deteriorate to the same quality as the remaining western wells.

Sizing of settlement lagoon

The sizing of the southern wells settlement lagoon is based upon the pumping rates and the sludge accumulation rates. Assuming an iron concentration of 15 mg/l and a flow rate of 279.5 l/sec the system would require a minimum of four separate aeration cascades to introduce sufficient oxygen to the mine water to oxidise all the iron in the mine water to oxides and oxyhydroxides.

The size of the settlement lagoons is based upon a linear relationship between the percentage reduction in influent iron concentration required and the hydraulic retention time (Pyramid Guidelines[1]).

The relationship used is –

Minimum residence time = (0.5 x % lowering of Fe required)

Based upon an influent of 15 mg/l iron and a required reduction in metal loading to less than 10 mg/l in the settlement lagoons;

- The % lowering of Fe required is 5/15 = 33%
- The residence time in the settlement lagoons is 0.5 x 33 = 16 hours.

At a flow rate of 279.5 l/sec and an iron concentration of 15 mg/l then the minimum void space required for 33% metal removal is 16,099m^3. This is calculated by:

Void space = 279.5 x 60 x 60 / 1000= 1006.2 m^3/hr x 16hrs = 16,099m^3

Iron will accumulate as iron oxyhydroxides. At an influent iron concentration of 15 mg/l and assuming that 5 mg/l will be removed in the settlement lagoon then the total mass of metal removal in the settlement lagoon will be 120.7 kg/day. This can be calculated using the following expression:

(5 x 279.5 x 60 x 60 x 24)/10^6 = 120.7 kg/day Fe

This will be removed as Fe oxides and oxyhydroxides.

This is calculated as:
120.7 kg/day x (106/56) = 228.5 kg/day $Fe(OOH)_x$

Given a sludge volume of between 5% and 3%, the settlement lagoon 1 will collect between **4.6 m^3** and **7.5 m^3/day** as $Fe(OOH)_x$.

Therefore after 1 year of operation, the settlement pond will contain between **1,668 m^3** and **2,753 m^3** of sludge. This is based upon the settlement pond removing only 33% of the total metals. However, it is possible that a higher percentage of metals may be removed in the settlement lagoon including metals such as manganese and aluminium.

It is anticipated that manganese will be removed as manganese oxides and oxyhydroxides in the settlement lagoon; therefore it is advised that additional void space will be required for a combination of iron and manganese sludge deposition. Given the similar atomic weight of iron and manganese (56 and 55 respectively), it is anticipated that the density of the iron and manganese sludges (as metal oxides and oxyhydroxides) will be very similar. However, given the slower kinetics of manganese oxidation, and therefore manganese removal relative to iron removal, it is likely that a lower percentage of manganese will be removed in the settlement lagoon relative to iron.

To account for the potential Mn removal, extra void space for accumulation should be incorporated into the scheme and/or more frequent de-sludging will be required. This void space can be calculated based on the influent concentration and the kinetics of Mn removal. Currently, the Mn loading is 2.5 times higher than the Fe loading in the influent combined water; however it is anticipated that the slower kinetics of Mn removal will limit the volume of Mn sludge produced in any settlement lagoon. This is based on no dosing of the mine water and minimal increase in pH of the mine water in the settlement lagoon. Based on these assumptions, it would be recommended to account for the precipitation of Mn with an additional 50% sludge capacity in the design.

However, based upon the fact that dosed mine water may enter the scheme in the future, via western well field water and / or dosing of the southern well field, it would be recommended to add additional sludge capacity for the entire metal loading in the mine water. This would add an additional 250% sludge capacity to the design.

Assuming that the lagoons will be de-sludged every 2 years to ensure that the minimum residence time is maintained, it is recommended that the total volume required for the settlement lagoon be based on the void space required based on flow and residence time plus 2.5 times the estimated iron sludge accumulation rate.

This is calculated by;

2,753m^3 (sludge volume/yr) x 2.5 times redundancy (to allow for additional metal sludge accumulation) x 2 (years accumulated sludge) + 16,099m^3 (min. void space) = 29,864m^3.

However, this is based upon all nine wells operating for 365 days per year. Historical data suggests that the pumps will not be required to be in operation to this extent, therefore this sludge calculation is highly conservative. Based on historical pumping data, it is calculated that the mean yearly flow rate from the nine wells that will be treated in the southern well field is 140 l/sec. Based on this flow rate, the sludge volume that will be produced a year will be less than that calculated for the maximum cumulative flow rate of 279.5l/sec. This can be calculated using the following expression:

$(5 \times 140 \times 60 \times 60 \times 24)/10^6 =$ 60.5 kg/day Fe

This will be removed as Fe oxides and oxyhydroxides.

This is calculated as:
60.5 kg/day x (106/56) = 114.5 kg/day $Fe(OOH)_x$

Given a sludge volume of between 5% and 3%, the settlement lagoon 1 will collect between **2.3 m^3** and **3.8 m^3/day** as $Fe(OOH)_x$.

Therefore after 1 year of operation, the settlement pond will contain between **839.5 m^3** and **1387 m^3** of sludge. Assuming that the lagoons will be de-sludged every 2 years to ensure that the minimum residence time is maintained, it is recommended that the total volume required for the settlement lagoon be based on the void space required based on flow and residence time plus 2.5 times the estimated iron sludge accumulation rate.

This is calculated by;

1387m^3 (sludge volume/yr) x 2.5 times redundancy (to allow for additional metal sludge accumulation) x 2 (years accumulated sludge) + 16,099m^3 (min. void space) = 23,034 m^3.

Therefore:

- Settlement lagoon sizing based on maximum cumulative flows and maximum loading and 2.5 times contingency for additional metal sludge accumulation = 29,864 m^3

This is based on the worst case scenario and mixing will occur during the whole year rather than only for a small percentage (no western wells on for 70% of the time). This figure should provide additional flexibility and time between de-sludging.

- Settlement lagoon sizing based on mean calculated cumulative flows and maximum loading and 2.5 times contingency for additional metal sludge accumulation = 23,034 m^3

This is based on the anticipated scenario where the southern pumps will be operated without the additional western well pumps for 70% of time.

It should be noted that additional capacity could be added in order to limit the time between desludging.

Wetland Sizing

The wetland for the southern wells plus the two additional western wells has been re-sized based on the assumption that the initial settlement lagoon will reduce the iron concentration to less than 10 mg/l.

Based on an input of approximately 10 mg/l Fe and a flow rate of 279.5 l/s, a minimum treatment area of **21,734m^2** would be required to reduce the metal concentration in the mine water to <1 mg/l. This could be in one or more wetlands, dependant on site constraints. Given the high flow rates it is recommended that the water be introduced to the wetland via 4 or more aeration cascades to prevent short-circuiting within the wetland. This will allow additional oxygen to enter the water to completely oxidise the metals in the mine water.

7.2.2 Western Well field

The initial treatment design, as laid out in Section 5.1.2, for the western well fields is based upon the treatment of 5 wells pumping 100% of the time at a conservative iron concentration of 50 mg/l Fe. Given that the preferred option design for the southern well field (see 7.1.1) has the capacity to treat the two most frequently pumped western wells and that it is anticipated that the remaining western wells will operate for a maximum of 5.6% of the year (corresponding to c. 20.5 days/yr), the proposed preferred option is for a reduced scheme.

It is proposed that the revised scheme for the western wells should have the capacity to treat the three remaining western wells only, however, with a contingency to treat the entire western wells (5 wells) should a change in the mine water quality necessitate it.

The contingency should include the potential to dose the mine water from the western wells, and also should include an area of land in which a secondary settlement lagoon can be built if and when required, although it is not anticipated that this will be required in the short term.

Recent metal loading data from the three western wells 202, 200 and 199 only had a cumulative iron concentration in the mine water of 33.3 mg/l with the maximum concentration measured in well 200 at 39 mg/l Fe. The cumulative manganese concentration in the mine water was 29.4 mg/l and the maximum concentration was measured in well 200 at 34 mg/l Mn. In addition to iron and manganese, aluminium was measured in well 202 at a concentration of 4.6 mg/l. The cumulative aluminium concentration in the mine water was calculated as 1.3 mg/l Al.

Due to the increasing trend in concentration of total metals in the well field, and the potential that treatment of wells 198 and 201 may be required, the initial treatment scheme sizing design has been based on the iron concentration of 50 mg/l Fe (c. 39 mg/l + 25% contingency).

Based on total acidity and alkalinity data, the combined flow from the western well field is strongly net acidic, however following complete degassing to remove carbonic acidity, the water is circum neutral. This is based on total degassing, which might not be practicable, and takes no account of any deterioration in quality over time. In addition, the water will have limited to no buffering capacity for acidity that will be produced during the oxidation and hydrolysis of the metals in the mine water.

Therefore it is proposed that thorough aeration is required followed by the potential for alkali dosing to treat this mine water before settlement. Based upon sufficient carbonic acidity removal and alkali dosing to generate net alkaline water, the use of a settlement lagoon and reed bed wetland to treat the discharge from the western wells should be adequate.

Alternatively and additionally the waters from these three wells could be blended with those from the southern well field. For such a scheme initial degassing and settlement would be appropriated to remove some metals prior to mixing with the influent water to the southern well field settlement lagoon. This would then be settled in the southern well field lagoon prior to polishing in a wetland.

<u>Sizing of settlement lagoon</u>

The sizing of the settlement lagoon is based upon the pumping rates and the sludge accumulation rates. Assuming an iron concentration of 50 mg/l and a maximum cumulative flow rate of 79.8 l/sec, two separate aeration cascades are required. These are to introduce sufficient oxygen to allow maximum CO_2 removal from the mine water to reduce the carbonic acidity concentration, and to oxidise all the iron in the mine water to oxides and oxyhydroxides.

The size of the settlement lagoons is based upon a linear relationship between the percentage reduction in influent iron concentration required and the hydraulic retention time (Pyramid Guidelines[1]).

The relationship used is –

Minimum residence time = (0.5 x % lowering of Fe required)

Based upon an influent of 50 mg/l iron and a required reduction in metal loading to less than 10 mg/l in the settlement lagoons;

- The % lowering of Fe required is 40/50 = 80%
- The residence time in the settlement lagoons is 0.5 x 80 = 40 hours.

At a flow rate of 79.8 l/sec and an iron concentration of 50 mg/l then the *minimum* void space required for 80% metal removal is 11,491m^3. This is calculated by:

Void space = 79.8 l/sec x 60 x 60 /1000 = 287.3m^3/hr x 40hrs = 11,491 m^3

Iron will accumulate as iron oxyhydroxides. At a conservative influent iron concentration of 50 mg/l and assuming that all 50 mg/l will be removed in the settlement lagoon should the water be dosed then the total mass of metal removal in the settlement lagoon will be kg/day. This can be calculated using the following expression:

(50 x 139.1 x 60 x 60 x 24)/10^6 = 600.9 kg/day Fe

This will be removed as Fe oxides and oxyhydroxides.

This is calculated as:
600.9 kg/day x (106/56) = 1,137 kg/day $Fe(OOH)_x$

Given a sludge volume of between 5% and 3%, the settlement lagoon will collect between 22.7 m^3 and 37.5 m^3/day as $Fe(OOH)_x$.

Therefore after 1 year of operation (approximately 20.5 days per year based on current pump operational sequence), the settlement pond will contain between 409m^3 and 675m^3 of sludge.

This is based upon the settlement pond removing 100% of the iron loading. However, when dosed other metals such as manganese and aluminium will be removed. This is due to the fact that caustic dosing will accelerate and promote metal removal and create additional sludge volume. It is essential that these metals are allowed for in the sizing of the settlement lagoon.

To account for the potential additional metal removal, extra void space for accumulation must be incorporated into the scheme and/or more frequent de-sludging will be required. This void space can be calculated based on the influent concentration of Fe and Mn. The Fe loading is currently approximately equal to the Mn loading in the influent combined water, and it is anticipated that caustic dosing will allow an equal volume of Mn and Fe sludge to form. Therefore it is recommended that in order to account for the precipitation of metals other than iron an additional 100% sludge capacity is allowed in the design.

The size of the settlement pond is calculated by

675 m^3 (sludge volume/yr) x 2 contingency (for other metal accumulation) x 2 (years accumulated sludge) + 11,491m^3 (min. void space) = **14, 191 m^3**.

This volume is based on the worst case scenario of a 3% sludge volume.

Sizing of wetland

A wetland is preferred to polish final effluent, even after dosing when metal concentrations are generally very low. However, initially, it might be possible to treat the three western wells passively, and therefore a wetland would be required. In addition, should the western wells be diverted after initial settlement through the lagoon for the southern wells, then additional wetland capacity will be required to account for the slightly reduced efficiency of the southern well system.

The wetland has been sized according to guidelines of Hedin and colleagues:

$A = (Q_d(\text{Inf-Ef}))/R_A$

A = wetland area (m^2)
Q_d = flow (m^3/day)
Inf = Input concentration (mg/l)
Ef = Effluent concentration (mg/l)
R_A = Area-adjusted contaminant removal rate (g/m^2/d) (in this case we approximate the R_A to 10 g/m^2/d as recommended by the Pyramid guidelines)

Based on an input of approximately 10 mg/l Fe and a flow rate of 79.8 l/sec, a minimum treatment area of **6,205 m^2** would be required to reduce the metal concentration in the mine water to <1 mg/l. This could be in one or more wetlands, dependant on site constraints. Given the high flow rates it is recommended that the water be introduced to the wetland via 2 aeration cascades to prevent short-circuiting within the wetland. This will allow additional oxygen to enter the water to completely oxidise the metals in the mine water.

7.2.3 Summary

The preferred option as set out above allows flexibility and redundancy in order to maximise the extent of passive treatment and therefore limit the amount of dosing required by having the capability to blend different waters for the current pumping well layout and the mine water chemistry. The design parameters are conservative to allow for changes in quality, however not so as to be prohibitive.

Maximising the efficiency of the initial aeration of the mine water will maximise the effectiveness of the mine water scheme, however careful monitoring of the acidity and alkalinity of the mine water will ensure that the treatment remains optimised.

The overall quality of the mine water, in terms of acidity and metal loading, is shown to be degrading over time. If this trend continues it should be anticipated that the water will become net acidic and therefore will require addition of a chemical to improve the pH and allow the remaining treatment to perform passively.

8. Scheme Performance

8.1 Introduction

The proposals within the preferred option described in Section 7 need to be aligned with CBDC's initial and long term requirements for the treatment of the mine water at Neville Street. These need to balance conflicting constraints including land availability, treatability, budget availability and alternative options for the long term management of the well field. On guidance received from CBDC, the variables being considered include

- A reduced size initial scheme consisting of;
    - An initial cascade to maximise the aeration of the mine water
    - The construction of a single settlement pond to contain a volume of 23,000m^3 located between the old rail bed and the Cadegan Brook
    - A single wetland of 14,000m^2 located between the old rail bed and the Cadegan Brook,
- Abandonment of 4 pumping wells from the western well field and the construction of 4 new pumping wells targeting better quality water.
- The likely performance of the reduced size of treatment scheme for specific scenarios identified by CBDC ahs been assessed,

The following sections consider the likely performance of the reduced treatment scheme to treat the water under two scenarios:

- A maximum flow rate and Fe concentration of between 5 and 10 mg/l Fe (as advised by CBDC).
- A maximum flow rate and metal loading based on the recent recorded water quality data (March 2008).

8.2 Treatment performance of 12 wells based on anticipated mine water chemistry

This section presents an assessment of the likely performance of the reduced treatment scheme to treat the water from all 12 wells, with sludge accumulation based upon the annualised average of flow and iron concentration from historical pump rates. The initial 9 wells would deliver a flow of 279.6 l/sec. However, based on all 12 wells being in operation would deliver a flow of 359.3 l/sec.

As advised by CBDC, it is proposed that the mine water quality for treatment from these wells will range in concentration from between 5 and 10 mg/l Fe. This quality is understood to be derived from a combination of the current mine water chemistry from the southern well field, and the anticipated chemistry that will be encountered in water from additional wells that are to be drilled in the vicinity of the southern wells (the eastern wells). Therefore, based on this predicted mine water quality, the anticipated functioning of the scheme has been assessed and is tabulated in Table 8.1 and detailed below.

Treatment system performance based upon flow from 12 wells and 5 and 10 mg/l Fe										
	Year 0		**Year 1**		**Year 2**		**Year 3**		**Year 4**	
Settlement lagoon	**Fe Concentration (mg/l)**		**Fe Concentration (mg/l)**		**Fe Concentration (mg/l)**		**Fe Concentration (mg/l)**		**Fe Concentration (mg/l)**	
	5	**10**	**5**	**10**	**5**	**10**	**5**	**10**	**5**	**10**
Flow max (l/sec)	359.3		359.3		359.3		359.3		359.3	
Flow based on annual average (l/sec)	142.6		142.6		142.6		142.6		142.6	
Residence time (hrs)	17.8		17.4	17.0	17.0	16.3	16.6	15.5	16.3	14.9
Fe removal (%)	35.6		34.8	34.0	34.0	32.5	33.3	31.1	32.6	29.7
Fe removal (mg/l)	1.8	3.6	1.7	3.5	1.7	3.3	1.7	3.1	1.6	3.0
Fe in settlement pond effluent (mg/l)	3.2	6.4	3.3	6.5	3.3	6.7	3.3	6.9	3.4	7.0
Sludge accumulation (at 5%) m3/yr	0.0	0.0	302.8	605.6	599.0	1198.0	888.8	1751.6	1172.3	2281.1
Sludge accumulation (at 3%) m3/yr	0.0	0.0	499.6	999.2	988.4	1976.8	1466.5	2890.1	1934.3	3763.8
Wetland										
Fe in effluent (mg/l)	**<1.0**	**1.9**	**<1.0**	**2.0**	**<1.0**	**2.2**	**<1.0**	**2.4**	**<1.0**	**2.5**

Table 8.1 - Treatment system performance based upon flow from all 12 wells with sludge accumulation rates based upon the annualised flow for a predicted Fe concentration of 5 and 10 mg/l Fe.

Based upon the maximum flow rate, the system should remove 100% of the iron with a maximum input of 5 mg/l Fe. This will continue to operate successfully (to less than 1 mg/l Fe) for over 4 years. However, should the Fe in the mine water increase to a maximum concentration of 10 mg/l, then at these flows the system should remove up to 80% of the Fe from the mine water, and the effluent Fe concentration will increase from 1.9 mg/l to 2.5 mg/l over this period. This is based upon maximum flow rates, however does not take into account any loss of void space that may occur due to sludge accumulation from other metals such as Mn and Al.

Should a provision be made for the accumulation of Mn and Al rich sludge, then the functioning efficiency of the treatment system will be reduced, as detailed in Table 8.2. As for the scenario demonstrated in Table 8.1, with an influent concentration of 5 mg/l Fe, and a maximum flow rate, all the Fe will be removed from the mine water, even when taking into account additional void space that will be lost from the possible accumulation of additional metal sludge. However, based on a 10 mg/l input of Fe, the effluent Fe concentration should range from 1.9 mg/l to 3.3 mg/l. Given the high concentration of metals other than Fe in the mine water, it is advised that the scenario presented in Table 8.2 is more representative than that presented in Table 8.1.

Therefore, based upon a discharge consent of <1 mg/l Fe, the proposed system should function for over 4 years at maximum flow rates with an input concentration of 5 mg/l Fe. However, based on an input concentration of 10 mg/l Fe, the system is insufficiently sized to reduce the iron concentration to less than 1 mg/l Fe.

Based upon a discharge consent of < 3 mg/l, and influent concentration of both 5 and 10 mg/l Fe, the proposed system will function for up to 3 years at maximum flow rates before de-sludging of the settlement pond may be required. This is based upon the accumulation of both Fe and Mn rich sludge.

8.3 Treatment performance of 12 wells based on recent mine water chemistry data

This section presents an assessment of the likely performance of the reduced treatment scheme to treat the water from the initial 9 wells based on the recorded water quality data from March 2008 and based on historical pump rate data. Based on recent data (March 2008), the cumulative flow quality from the nine wells was 4.31 mg/l Fe. However, all 12 wells being in operation should deliver a flow of 359.3 l/sec and a cumulative iron concentration of 10.75 mg/l. Based on the last 5 years of pumping data, all 12 wells are operational at the same time for 6.5 days/yr on average.

Based on the measured mine water quality; the anticipated functioning of the scheme is summarised in Table 8.3 and detailed below.

Based upon the maximum flow rates from the seven wells from the southern well field and two wells from the western well field (cum. 5 mg/l), the system should remove 100% of the iron for over 4 years of continuous operation. However, during the 20 days/year when the three remaining western wells will be in operation, it is calculated that the effluent iron from the wetland should be between 2.6 and 3.6 mg/l. This removal rate is based upon maximum flow rates and accounts for loss of void space that may occur due to sludge accumulation from other metals such as Mn and Al.

Therefore, based upon a discharge consent of <1 mg/l Fe, the proposed system should function for over 4 years at maximum flow rates when only the initial 9 wells are in operation. However, based on the 20 days a year when the remaining 3 wells may be in operation, the system is insufficiently sized to reduce the iron concentration to less than 1 mg/l Fe.

Assuming a discharge consent of < 3 mg/l, the proposed system should not breach the discharge consent for up to 2 years. After

8.4 Treatment scheme performance.

The functioning of the proposed treatment scheme as detailed in sections 8.1 and 8.2 is based upon recently available data and data advised to be used by CBDC. No account has been given for the changes in the chemistry of the mine water over time. Given the dynamics of the system, it is possible that the mine water quality will deteriorate in the well field, thus reducing the functioning efficiency of the system, resulting in the requirement of more frequent de-sludging and / or a breach of the discharge consent.

Treatment system performance based upon 12 well flow rates and 5 and 10 mg/l Fe with provision for Mn removal										
	Year 0		**Year 1**		**Year 2**		**Year 3**		**Year 4**	
Settlement lagoon	**Fe Concentration (mg/l)**		**Fe Concentration (mg/l)**		**Fe Concentration (mg/l)**		**Fe Concentration (mg/l)**		**Fe Concentration (mg/l)**	
	5	**10**	**5**	**10**	**5**	**10**	**5**	**10**	**5**	**10**
Flow max (l/sec)	359.3		359.3		359.3		359.3		359.3	
Flow based on annual average (l/sec)	142.6		142.6		142.6		142.6		142.6	
Residence time (hrs)	17.8		16.8	15.9	15.9	14.0	15.0	12.5	14.2	11.1
Fe removal (%)	35.6		33.6	31.7	31.8	28.0	30.1	25.0	28.4	22.3
Fe removal (mg/l)	1.8	3.6	1.7	3.4	1.6	2.8	1.5	2.5	1.4	2.2
Fe in effluent (mg/l)	3.2	6.4	3.3	6.6	3.4	7.2	3.5	7.5	3.6	7.8
Sludge accumulation (at 5%) m3/yr	0.0	0.0	757.0	1514.0	1514.0	3028.0	2271.0	4542.0	3028.0	6056.0
Sludge accumulation (at 3%) m3/yr	0.0	0.0	1249.0	2498.1	2430.3	4860.5	3547.3	6830.7	4603.7	8586.9
Wetland										
Fe in effluent (mg/l)	**<1.0**	**1.9**	**<1.0**	**2.1**	**<1.0**	**2.7**	**<1.0**	**3.0**	**<1.0**	**3.3**

Table 8.2 - Treatment system performance based upon flow from all 12 wells with sludge accumulation rates based upon the annualised flow for a predicted Fe concentration of 5 and 10 mg/l Fe. Provision has also been allowed for accumulation of Mn and Al sludge, by adding a 2.5 times contingency factor.

Treatment system performance based upon 9 well flow rates with 20 days operation of all 12 wells with cumulative concentrations of 5 and 11 mg/l Fe used.										
Settlement lagoon	**Year 0**		**Year 1**		**Year 2**		**Year 3**		**Year 4**	
	Fe Concentration (mg/l)		**Fe Concentration (mg/l)**		**Fe Concentration (mg/l)**		**Fe Concentration (mg/l)**		**Fe Concentration (mg/l)**	
	5	**11**	**5**	**11**	**5**	**11**	**5**	**11**	**5**	**11**
Flow 9 wells (l/sec)	279.6		279.6		279.6		279.6		279.6	
Flow from additional 3 wells (l/sec)	79.7		79.7		79.7		79.7		79.7	
Flow based on annual average from 9 wells (l/sec)	139.6		139.6		139.6		139.6		139.6	
Flow based on annual average from 3 additional wells (l/sec)	3.1		3.1		3.1		3.1		3.1	
Residence time 9 wells (hrs)	22.9		21.2	16.5	19.7	15.4	18.3	14.3	17.0	13.3
Fe removal (%)	45.7		42.5	33.0	39.5	30.7	36.7	28.5	34.1	26.5
Fe removal (mg/l)	2.3	3.9	2.1	3.6	2.0	3.4	1.8	3.1	1.7	2.9
Fe in effluent (mg/l)	2.7	7.1	2.9	7.4	3.0	7.6	3.2	7.9	3.3	8.1
Sludge accumulation (at 3%) m3/yr	0.0	0.0	1570.5	59.2	3029.7	114.2	4385.6	165.3	5645.3	212.7
Combined sludge accumulation at 3%/yr	0.0		1629.7		3143.9		4550.8		5858.1	
Wetland										
Fe in effluent (mg/l)	**<1.0**	**2.6**	**<1.0**	**2.9**	**<1.0**	**3.1**	**<1.0**	**3.4**	**<1.0**	**3.6**

Table 8.3 - Treatment system performance based upon 9 well flow rates with 20 days operation of all 12 wells with cumulative concentrations of 5 and 11 mg/l Fe used. This data is based upon data collected in March 2008. Provision has also been allowed for accumulation of Mn and Al sludge, by adding a 2.5 times contingency factor.

NOTE – the influent concentration of 11 mg/l Fe is the combined discharge concentration that will occur approx. 20 days/yr.

9. Aeration

9.1 General Requirements for Aeration

This section considers the options for increasing the aeration of the mine water. The mine water requires aeration for two purposes. These are to:

- Equilibrate the CO_2 within the water to atmospheric temperature and pressure

This effectively de-gasses the mine water of excess CO_2 and allows the system to reach equilibrium (see Section 2). This decreases the acidity and increases the pH of the raw mine water thus promoting the oxidation of ferrous iron

- Maximise the oxidisation of the mine water in order to allow for the oxidation and hydrolysis of iron and manganese and their consequential removal

9.2 Design Criteria for Aeration Cascades

The primary purpose of an aeration feature is to expose the mine water to atmospheric oxygen. Available guidance from the PYRAMID guidelines (reference 1) and guidance proposed by Hedin and colleagues (reference 2) provide empirical guidelines for the use of aeration cascades where sufficient hydraulic head and land availability exists. The main design criteria for the design of the aeration cascades are summarised in the following points.

- Water should cascade over steps in a shallow film of between 10 and 20 mm to maximise the contact with atmospheric oxygen. Guidelines indicate that the cascade should be sized such that 1 l/sec passes across a 100 mm width of cascade.
- Cascade steps are suggested to be 50-70cm in height, with 3 to 6 steps forming each cascade.
- The water should pass over the cascade and fall into a plunge pool where entrained air bubbles can dissipate in the water column. This is described in the PYRAMID as being as deep as the preceding fall of water, however such area feature will encourage the accretion of ochre.
- The lip of the cascade should overhang the pool of water encouraging the passage of air to both sides of the cascade. It has been suggested that symmetrical dissipation within the plunge pool would enhance performance.
- Maintenance of the cascade should be considered. It may be appropriate to provide a hard standing area between the foot of the cascade and the settlement pond.
- Mine water should be distributed across the full width of the settlement pond to maximise its effectiveness.

In addition to the guidelines above, we would also recommend that the cascade is partially castellated to allow air to access beneath the flow of water, thus maximising the exposure to air.

An estimate of the efficiency of the cascade is difficult as it relies on a number of variable factors including temperature, and may vary seasonally and with flow and quality characteristics of the mine water discharge.

The design of the aeration cascade should consider the empirical guidelines and apply these as far as practicably is possible. However, it is recommended that the performance of the overall mine water treatment system is monitored to ensure that the treatment is optimised. Where sufficient oxidisation is not being achieved through the aeration cascade, a retrofit solution may need to be considered to provide additional oxidation, such as an additional aeration cascade, mechanical aeration within the settlement pond and / or chemical oxidation using hydrogen peroxide.

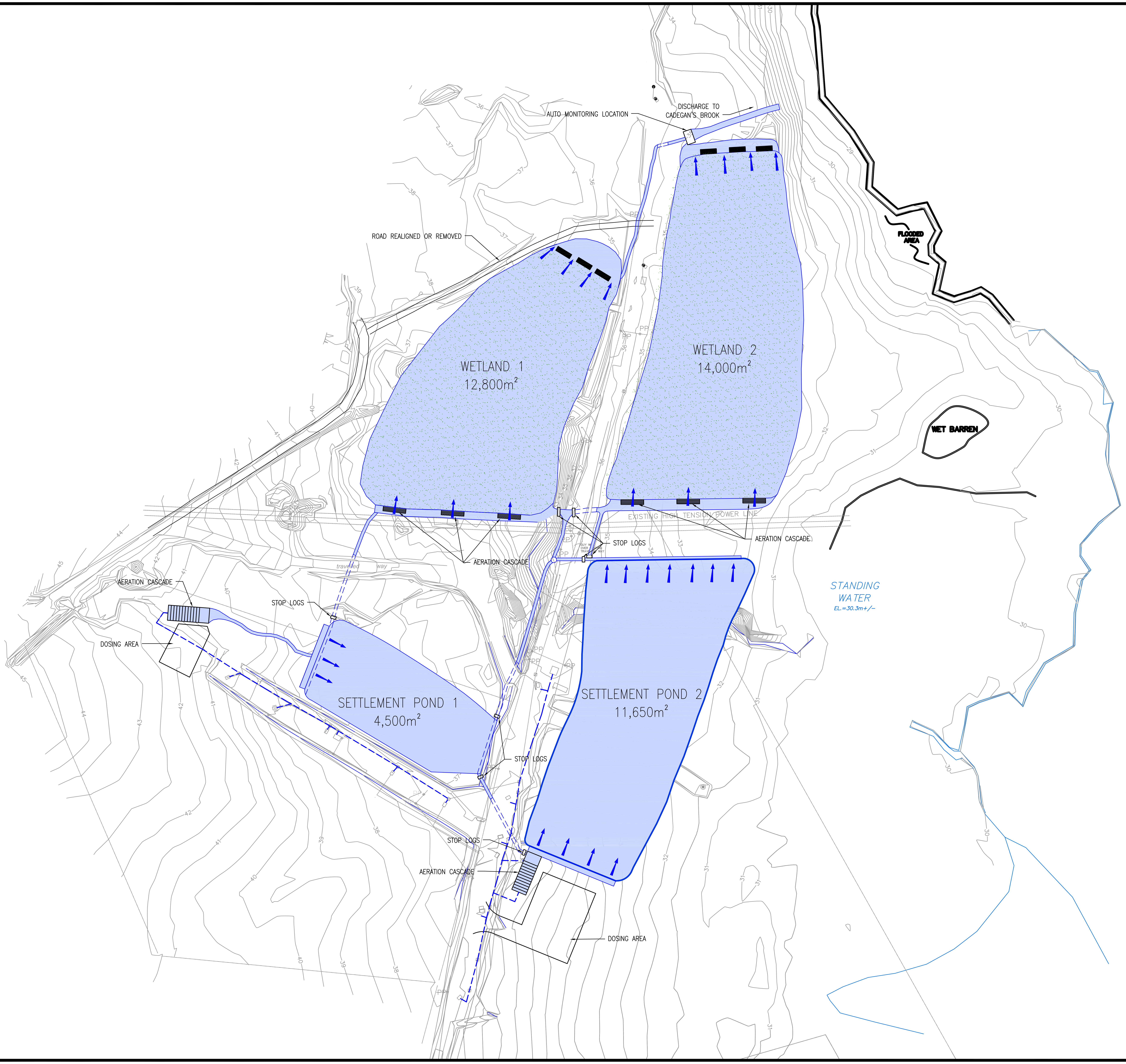
An indicative drawing of a suitable cascade for the maximum design flow of 360 l/sec is attached. This should be developed to fit within the constraints of the preferred scheme. At flows less than this, the flow of water across the cascade may be below that optimal for maximum aeration. This will be compensated for by additional residence time for lower flows within the settlement pond and wetland.

References:

[1] PIRAMID Consortium (2003), *Engineering guidelines for the passive remediation of acidic and/or metalliferous mine drainage and similar wastewaters.* European Commission 5th Framework RTD Project no. EVK1-CT-1999-000021 "Passive *in-situ* remediation of acidic mine/industrial drainage" (PIRAMID). University of Newcastle upon Tyne, Newcastle upon Tyne, UK. 166pp.

[2] Hedin, R.S., Nairn, R.W. and Kleinmann, R.L.P. (1994*) Passive Treatment of Polluted Coal Mine Drainage*. Bureau of Mines Information Circular 9389. United States Department of Interior, Washington DC. 35 pp.

ATKINS
5063247/001



N

REVISIONS	Drawn By	Checked By	Date

PURPOSE OF ISSUE	Rev.	Authorised for issue	Date

Atkins Ltd
Consulting Engineers
The Axis, 10 Holliday Street
Birmingham West Midlands B1
Tel 0121 483 5000
Fax 0121 483 5252
©

THIS DRAWING IS NOT TO BE SCALED

CLIENT

PROJECT
CAPE BRETON

DRAWING TITLE
PROPOSED GENERAL ARRANGEMENT

Scales	DRAWN	CHECKED	CO-ORD CHECK
1 : 1000	MJ	AMF	
	DATE 10/04/08	DATE 10/04/08	DATE

0

SHEET
A1

PLOT DATE
10/04/08

DRAWING NO
5063247/001

REV
-