LOWER MURRAY LAKES PROJECT

MANAGEMENT OPTIONS FOR ACID SULFATE SOILS IN THE LOWER MURRAY LAKES, SOUTH AUSTRALIA

Stage 1 - Preliminary Assessment of Treatment Options

Prepared by Earth Systems for

Primary Industries and Resources South Australia Rural Solutions SA

& The Department for Environment and Heritage, South Australia

EARTH SYSTEMS
Environment - Water - Sustainability

December 2008

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PRIMARY INDUSTRIES AND RESOURCES SOUTH AUSTRALIA

RURAL SOLUTIONS SA

&

THE DEPARTMENT FOR ENVIRONMENT AND HERITAGE, SOUTH AUSTRALIA

by

EARTH SYSTEMS

Environment – Water – Sustainability

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EARTH SYSTEMS

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CONTENTS

EXECUTIVE SUMMARY 5

1.0 INTRODUCTION 8

1.1 BACKGROUND 8
1.2 ACID GENERATION IN THE LOWER MURRAY LAKES 11
1.3 ESTABLISHED METHODS FOR LIMESTONE DOSING 12
1.3.1 Limestone distribution methodologies – Lakes 13
1.3.2 Limestone distribution methodologies – Waterways 13
1.3.3 Limestone distribution methodologies – Catchments 15
1.4 GUIDING PRINCIPLES FOR LIMESTONE DOSING 15

2.0 SCOPE OF WORKS 17

3.0 METHODOLOGY 17

3.1 SITE VISIT 17
3.2 REVIEW OF EXISTING INFORMATION 17
3.2.1 Acid Sulfate Soil / Acid and Metalliferous Drainage Management Guidelines 17
3.2.2 Reports on ASS and water quality issues in the Lower Murray Lakes 18
3.2.3 Environmental Monitoring Data for the Lower Murray Lakes 19
3.3 IDENTIFICATION AND PRELIMINARY ASSESSMENT OF TREATMENT OPTIONS 19
3.4 DETAILED ASSESSMENT OF PREFERRED TREATMENT OPTION(S) 20

4.0 RESULTS 20

4.1 IDENTIFICATION AND PRELIMINARY ASSESSMENT OF TREATMENT OPTIONS 20
4.1.1 Introduction 20
4.1.2 Option 1: Single point static dosing into flowing water 22
4.1.3 Option 2: Multi-point static dosing from access roads in lakes 23
4.1.4 Option 3: Mobile dosing via barges 23
4.1.5 Option 4: Erosional dispersion of limestone 24
4.1.6 Option 5: Alkalinity generating ponds 24
4.1.7 Option 6: Limestone addition to exposed sediments and shorelines 24
4.1.8 Option 7: Limestone addition by helicopter 25
4.1.9 Preliminary assessment of treatment options 25
4.2 PREFERRED TREATMENT OPTION(S) 26
4.2.1 Strategy 26
4.2.2 Limestone supply 27
4.2.3 Risks and mitigation measures 30
4.2.4 Monitoring and assessment of performance 31
4.2.5 Additional investigations and/or trials required 32
4.2.6 Preliminary cost estimates for preferred options 32

5.0 CONCLUSIONS 33

6.0 RECOMMENDATIONS 34

7.0 REFERENCES 35

ATTACHMENTS

ATTACHMENT A **PRELIMINARY COST ESTIMATE FOR PREFERRED TREATMENT OPTIONS AND TRIALS**

EXECUTIVE SUMMARY

Rural Solutions SA (RSSA) commissioned Earth Systems Pty Ltd (Earth Systems) to investigate and review management options for acid sulfate soils at Lake Alexandrina and Lake Albert (Lower Murray Lakes). This report provides a preliminary assessment of treatment options for the Lower Murray Lakes. The Lower Murray Lakes are located at the mouth of the Murray River, approximately 75 km south-east of Adelaide.

Water levels in the Lower Murray Lakes are declining as a result of the unprecedented drought currently affecting the area (Fitzpatrick et al., 2008), and over allocation of flows in the Murray-Darling river system. The lowering of lake water levels increases the volume of sulfidic material in acid sulfate soils (ASS) that is exposed to atmospheric oxygen. As this material is exposed to oxygen it generates acid and metalliferous drainage (AMD) which has the potential to result in ecological, health and water quality issues. The generation of acid and metalliferous water has the potential to be a significant environmental issue for the Lower Murray Lakes.

ASS management approaches for the lakes can be broadly categorised as follows:

1. Prevent AMD by managing lake water levels to ensure that ASS are permanently submerged and sulfide oxidation is therefore minimised.
2. Control AMD in-situ via neutralisation (addition of alkaline amendment to acid sulfate soils) and/or reduction (addition of organic matter to acid sulfate soils).
3. Treat AMD within the lake water bodies, either passively or actively, via neutralisation (alkalinity addition) and/or reduction (organic matter addition).

This preliminary report provides an assessment of the feasibility of implementing the third approach identified above, focussing on neutralisation methods using limestone (ie. calcium carbonate; $CaCO_3$).

The key objective of neutralisation using limestone would be to distribute and store alkalinity, as evenly and rapidly as possible, across the beds of both Lake Alexandrina and Lake Albert.

A number of treatment options were considered for the Lower Murray Lakes, involving the use of ultra fine grained limestone. A suitable reagent has been identified with superior characteristics to conventional fine grained (crushed) limestone. The dosing methods can be broadly classified as static, passive or mobile. Key options are itemised below:

1. Dose limestone from a single point in each lake and utilise flowing water to disperse the reagent.
2. Install short roads (constructed from limestone aggregate) at strategic locations within each lake to access standing water and utilise static pumping systems to mix and disperse reagent into the lakes.
3. Dose limestone from multiple points in each lake via mobile barges and utilise on-board pumping systems to mix and disperse reagent into the lakes.
4. Add limestone to the margins of key tributaries of Lake Alexandrina to provide passive limestone slurry addition to the lake during high flows.
5. Install alkalinity generating ponds adjacent to key tributaries of Lake Alexandrina (eg. Murray River).
6. Selectively add limestone slurry or dry powder to exposed sediments or lake shorelines in areas containing the highest risk acid sulfate soils.
7. Utilise helicopters equipped with 2-5 tonne controlled release hoppers to dispense limestone strategically around or within the lakes.

Limestone addition to the Lower Murray Lakes is a feasible option for storing alkalinity in the lake systems for the purposes of neutralising acid that may be generated from unsaturated sediments around the shoreline of the lakes. Limestone addition could be conducted pro-actively or be instigated at pre-arranged alkalinity / pH / carbonate saturation index trigger values.

Based on a preliminary assessment of the options listed above, the preferred treatment strategy for the Lower Murray Lakes involves a combination of Options 1 and 2. These options are considered relatively easy to implement and have the potential to provide maximum limestone addition to the lakes within reasonably short timeframes. The cost effectiveness of limestone dosing can be maximised if reagent is effectively dispersed into each lake from a single dosing point (or as few points as possible).

Option 1 has the potential to dose up to 10,000 tonnes of limestone into Lake Alexandrina over a 35 day period from a single stationary barge. This would be equivalent to 5% of the existing dissolved alkalinity in the Lower Murray Lakes (approximately 200,000 tonnes $CaCO_3$) and would be sufficient to neutralise approximately 10,000 tonnes of sulfuric acid. This is expected to cost approximately $2,000,000. Dose rates could be readily increased or decreased as required.

The effective dispersal of the limestone from a single point remains in question, and a 200 tonne trial to monitor and confirm performance of Option 1 is proposed. The trial is likely to cost approximately $115,000 and requires the cooperation of the ferry operators at Wellington.

If static dosing from single point sources demonstrates limited limestone dispersal, multi-point static dosing is proposed. The installation of short access roads (constructed from limestone aggregate) out into the lakes to provide supplementary dosing points (Option 2) would reduce the risk of incomplete limestone dispersion that may be associated with single point addition to the lakes. The dosing of 2,000 tonnes of limestone from the end of a 100 m long access road out into one of the lakes is estimated to cost $600,000 and take approximately 15 days.

Limestone slurry dosing from mobile (powered) barges (Option 3) is the next preferred strategy, and although more expensive than static dosing, success is very likely. Helicopter-based dosing (Option 7) remains a viable option that can be rapidly implemented, but will be the most expensive approach available.

A commitment to continue pumping water into Lake Albert to ensure that water levels maintain saturated shoreline sediments would be a simple way to quantitatively lower the AMD risk from the lake system. In this way, only mitigation measures for Lake Alexandrina need be considered.

Further work to quantify potential limestone dosing requirements would assist with selection of the most appropriate treatment options.

Mitigation options other than neutralisation with limestone are still available for controlling or preventing acidification of the Lower Murray Lakes. These will be examined in a Stage 2 report.

RECOMMENDATIONS

Key recommendations from this study include:

1. Conduct trial treatment of Lake Alexandrina from the Wellington ferry with 200 tonnes of limestone.
2. If this trial treatment is successful in its aim to substantially disperse limestone throughout Lake Alexandrina, then consider establishing dosing infrastructure and a limestone stockpile south of Wellington to have the option of continuing this dosing in the event that trigger alkalinity values in the lake are exceeded.
3. Conduct trial treatment of Lake Albert with 200 tonnes of limestone by dosing at the pump station between the two lakes.
4. If trial treatment demonstrates that fixed point dosing at Wellington and the Lake Albert pump station are only partially successful, one or more of the following options may be considered for Lake Alexandrina and/or Lake Albert:
   - Identify locations in either lake where limestone could be delivered and dosed from the shore due to good road access and onshore water levels of 0.5-1.0 m.
   - Conduct a geotechnical investigation of the potential to install limestone access roads directly onto lake sediments.
   - Install a limestone access road in a strategic location, extending from the lake shoreline toward the centre of the lake until a water depth of 0.5-1.0 m is attained.
   - Conduct trial treatment from the end of the limestone access road.
5. Depending on the results of the trials described above, consider dispensing limestone from multiple points in each lake from mobile barges.
6. Conduct three x 30 tonne trials of limestone addition to the margins of key tributaries of Lake Alexandrina.
7. Re-assess the need for implementing alkalinity addition options 5, 6 and 7 when sulfide oxidation rates have been determined and pollutant fluxes quantified.
8. Continue to control water levels in Lake Albert so that mitigation measures are only required in Lake Alexandrina.
9. Key data requirements to quantify the likely scale and timing of acidity fluxes from unsaturated lake sediments include:
   - Sulfide oxidation rates as a function of the moisture content of the unsaturated sediments;
   - Groundwater discharge rates (ie. as a function of rainfall recharge, lake water levels, wave action, geo-tides, etc) and hence acidity release rates into the lakes;
   - Stored organic matter content of unsaturated lake sediments, and the extent of sulfate reducing bacterial activity in unsaturated sediments.

1.0 INTRODUCTION

1.1 BACKGROUND

Rural Solutions SA (RSSA) commissioned Earth Systems Pty Ltd (Earth Systems) to investigate and review management options for acid sulfate soils at Lake Alexandrina and Lake Albert (Lower Murray Lakes). This report provides a preliminary assessment of treatment options for the Lower Murray Lakes. The Lower Murray Lakes are located at the mouth of the Murray River, approximately 75 km south-east of Adelaide.

The majority of soils around the Lower Murray Lakes contain sulfuric acid (sulfuric material) and/or have the potential to form sulfuric acid upon exposure of sulfidic material to atmospheric oxygen. Sulfuric soils are defined as soils that generate a pH of less than 4 when mixed in a 1:1 ratio with water. Sulfidic soils, on the other hand, generate a pH greater than 4 upon mixing with water (1:1 ratio) but have the potential to produce acidic drainage (pH < 4) following oxidation. In the Lower Murray Lakes soils, sulfides are generally present in the form of pyrite (FeS_2) and iron monosulfide (FeS). The latter commonly occurs as a "monosulfidic black ooze" (MBO).

Water levels in the Lower Murray Lakes are declining as a result of the unprecedented drought currently affecting the area (Fitzpatrick et al., 2008), and over allocation of river flows. The lowering of lake water levels increases the volume of sulfidic material that is exposed to atmospheric oxygen. As this material is exposed to oxygen it generates acid and metalliferous drainage (AMD) which has the potential to result in ecological, health and water quality issues. Generation of AMD due to the oxidation of sulfidic material has the potential to be a significant environmental issue for the Lower Murray Lakes.

Four sites around the Lower Murray Lakes, in particular, have been prioritised for development of ASS management strategies, as they are believed to contain the highest risk ASS materials. These sites are generally characterised by drained, unsaturated and aerobic sulfuric hydrosols. The four sites of particular concern are shown in Figure 1.1 and their characteristics are summarised in Table 1.

Table 1. Sites containing highest risk ASS materials around the Lower Murray Lakes.

Site ID	Site Name	Location	Soil type	Area (km^2)	Length (km)	Width (km)
1	Point Sturt	Lake Alexandrina, on the western side of the lake, south of Milang.	Sulfuric hydrosols	1.112	7.7	0.3
2	Poltalloch	Lake Alexandrina, on the eastern side of Albert Passage, which connects the two lakes.	Sulfidic hydrosols	3.244	13.0	0.7
3	Meningie	Lake Albert, eastern shoreline, extending in a northerly direction from the town of Meningie.	Sulfuric hydrosols	2.895	8.7	0.5
4	Campbell Park	Lake Albert, on the western side of the lake, near Campbell Park.	Sulfuric hydrosols	1.755	4.3	0.6

Earth Systems is currently investigating a range of management options for ASS in the Lower Murray Lakes. The investigation will assist with the identification of effective acid sulfate soil remediation strategies that could achieve short-term minimisation / suppression of the acid and metalliferous drainage (AMD) discharging from ASS into the lakes.

ASS management approaches for the lakes can be broadly categorised as follows:

1. Prevent AMD by managing lake water levels to ensure that ASS are permanently submerged and sulfide oxidation is therefore minimised.
2. Control AMD in-situ via neutralisation (addition of alkaline amendment to acid sulfate soils) and/or reduction (addition of organic matter to acid sulfate soils).
3. Treat AMD within the lake water bodies, either passively or actively, via neutralisation (alkalinity addition) and/or reduction (organic matter addition).

This preliminary report provides an assessment of the feasibility of implementing item 3 above, focussing on neutralisation methods using limestone (calcium carbonate; $CaCO_3$).

The key objective of neutralisation using limestone would be to distribute stored alkalinity, as evenly and rapidly as possible, across the beds of both Lake Alexandrina and Lake Albert. This approach could be equally effective as a “passive”, pro-active treatment option or an “active” (emergency response) treatment option for the Lower Murray Lakes. As a passive treatment option, deposits of ultra fine grained limestone on the lake beds would progressively dissolve into the water column in response to acid generation from exposed shoreline sediments and subsequent influx to the lakes.

Due to time limitations, this report does not investigate the likelihood, scale or timing of acidification of the Lower Murray Lakes. For the purposes of this report, it has been assumed, conservatively, that:

- Lake acidification could be a significant issue in both Lake Alexandrina and Lake Albert.
- The scale of lake acidification could potentially require the addition of up to 10,000 tonnes $CaCO_3$ equivalent per month (this assumption is arbitrary and will primarily depend upon future lake water levels and sulfide oxidation rates, which are currently unknown).
- The onset of lake acidification could potentially occur within the next 6-12 months.

Neutralisation options that could be applied under this scenario for the Lower Murray Lakes are identified and assessed in this report.

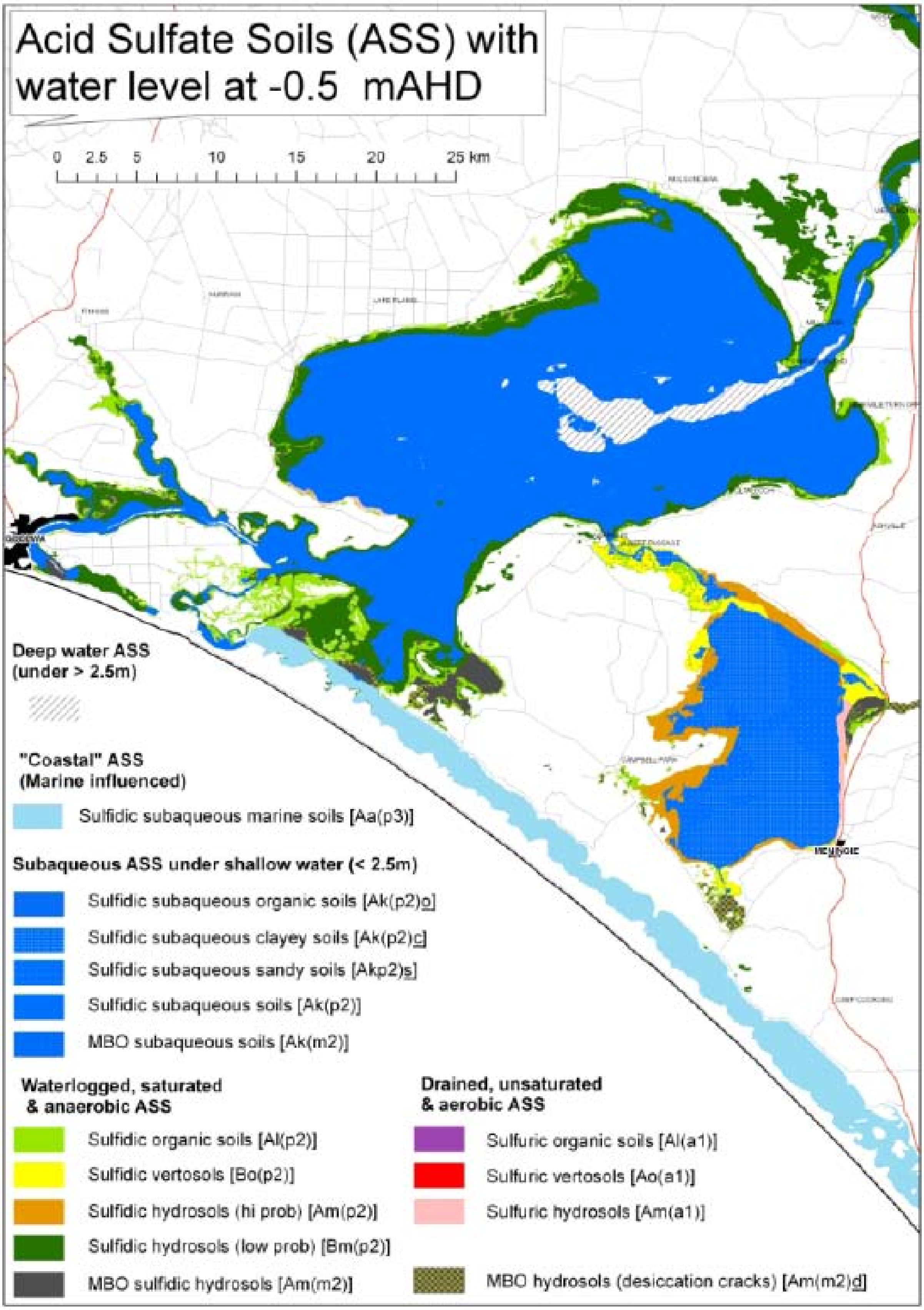

Figure 1.1. Predicted distribution of acid sulfate soils (ASS) of the Lower Murray Lakes at drought water levels (-0.5 m AHD). Taken from Fitzpatrick et al (2008). See Fitzpatrick et al (2008) for description of soil categories.

1.2 ACID GENERATION IN THE LOWER MURRAY LAKES

Acid sulfate soils have the potential to adversely affect water quality in the Lower Murray Lakes. When sulfidic material is exposed to oxidising conditions, sulfides begin to oxidise and water subsequently transports reaction products including acidity, sulfate, iron and other metals into surface water and groundwater. Acid and metal production associated with pyrite oxidation is shown in Reactions 1 to 4.

An initial oxidation reaction involves the oxidation of pyrite to produce ferrous iron (Fe2+), sulfate and acid, as shown in Reaction 1.

FeS_2 + 7/2 O_2	+ H_2O →	Fe^{2+} +	2 SO_4^{2-}	+ 2 H^+		***[Reaction 1]***
Pyrite oxygen	water	ferrous iron	sulfate	acid		

The ferrous iron (Fe2+) released by pyrite oxidation may be further oxidised to ferric iron (Fe3+) consuming some acid (Reaction 2). Notice that this reaction does not involve pyrite.

Fe^{2+}	+ 1/4 O_2 +	H^+ →	Fe^{3+}	+ ½ H_2O	***[Reaction 2]***
Ferrous iron	oxygen	acid	ferric iron	water	

The ferric iron then reacts with water to form ferric hydroxide ($Fe(OH)_3$), which precipitates out of solution, producing additional acid (Reaction 3).

Fe^{3+} +	3 H_2O →	$Fe(OH)_3$ +	3 H^+	***[Reaction 3]***
Ferric iron	water	ferric hydroxide (orange precipitate)	acid	

As shown in Reaction 3, the precipitation of ferric hydroxide is a key acid producing stage. Once sulfide minerals have oxidised and released Fe^{2+}, it is extremely difficult to prevent ferrous iron oxidising to ferric iron with concomitant iron hydroxide precipitation and further acid generation.

A summary reaction of the complete oxidation of pyrite (by oxygen) in sulfidic shoreline materials may be expressed as follows (Reactions 1-3 combined):

FeS_2	+ 15/4 O_2	+ 7/2 H_2O →	2 SO_4^{2-}	+ 4 H^+	+ $Fe(OH)_3$	***[Reaction 4]***
Pyrite	oxygen	water	sulfate	acid	ferric hydroxide	

Furthermore, the presence of soluble ferric iron (Fe3+) can accelerate the oxidation of pyrite, generating additional sulfate and acid, as shown in Reaction 5.

FeS_2 +	14 Fe^{3+} +	8 H_2O →	15 Fe^{2+}	+ 2 SO_4^{2-}	+ 16 H^+	***[Reaction 5]***
Pyrite	ferric iron	water	ferrous iron	sulfate	acid	

Note that in Reaction 5, 16 moles of acid are produced per mole of pyrite oxidised, as compared with 4 moles of acid generated when pyrite is oxidised by molecular oxygen (Reaction 4). Whether pyrite oxidation proceeds through Reaction 4 or 5 depends on the chemical conditions in solution at the pyrite surface. Reaction 5 suggests that iron plays a significant role in promoting sulfide oxidising reactions that result in AMD.

Similar oxidation reactions occur for MBO. MBO oxidation is shown in Reaction 6:

FeS +	$2\,O_2$	$\rightarrow$	Fe^{2+}	+ SO_4^{2-}		***[Reaction 6]***
Monosulfide	oxygen		ferrous iron	sulfate		

The oxidation of MBO is not acid generating but is acidity generating. The ferrous iron (Fe^{2+}) produced in Reaction 6 may oxidise to ferric iron, as shown in Reaction 2 and eventually precipitate as ferric hydroxide as in Reaction 3.

Two distinct processes, both promoted by oxidation of sulfide minerals, are responsible for decreasing the pH of an aqueous solution:

1. Acid (H^+) is directly generated by the oxidation of sulfur (Reaction 1).
2. Acid (H^+) is generated by the precipitation of metal hydroxides (eg. $Fe(OH)_3$, $Mn(OH)_4$: Reaction 3) during oxidation / neutralisation / dilution reactions.

While process 1 is controlled only by the availability of oxygen and water, process 2 depends on the solubility of the metal aqueous species, which in turn is controlled by the factors such as pH of the solution and oxidation state of the metal. In other words, the generation of acid through process 1 is limited by the sulfide oxidation rate, while the generation of acid through process 2 is delayed until metals can precipitate from solution (thus the term “latent acidity” or “mineral acidity”).

The term “acid” quantifies only the actual amount of H^+ present in solution and is generally expressed as pH. The term “acidity”, on the other hand, accounts for both the actual H^+ concentration of the aqueous solution and the potential for acid generation due to mineral or latent acidity (ie. H^+ produced by process 2).

1.3 ESTABLISHED METHODS FOR LIMESTONE DOSING

The two main drivers for developing techniques for dosing limestone in various waterways and water bodies are a) acid rain, produced by the aqueous dissolution of SO_2 (sulfur dioxide) gas from fossil fuel combustion, and b) acid and metalliferous drainage (AMD), generated by the oxidation of sulfide minerals during mining activities. Several European countries, most noticeably Sweden and Norway, as well as Canada have experienced significant acid rain issues. Several approaches to acid neutralisation using limestone have also been developed in the Eastern US (Appalachian region) in an effort to mitigate the impacts of AMD associated with coal mining.

All of these methods permit the dispersion of small to moderate quantities of limestone to catchments, waterways and water bodies. While these are not all applicable to the situation faced in the Lower Murray Lakes, they are summarised below for background purposes.

The mass of limestone potentially required to treat acidity generation in the Lower Murray Lakes may be significantly greater in term of tonnes per ML or tonnes per unit time than many other world applications. Hence, new limestone dosing methodologies have been developed for this study and are outlined in Section 4.

1.3.1 Limestone distribution methodologies – Lakes

Limestone can be applied to lakes and ponds by:

- Dispersing by boat or barge;
- Spreading on winter (lake) ice by tractor, or
- Aerial broadcasting by helicopter.

These techniques are described in Helfrich et al., 2001 and Donnelly et al., 2003. Dispersing limestone from a boat or barge is the most popular way to treat lakes and ponds (Helfrich et al., 2001). Use of tractors to disperse limestone over frozen lakes is common in colder climates. Application by aircraft allows access to remote areas but is significantly more costly; sometimes up to four times the cost of boat delivery (Helfrich et al., 2001).

An example of a barge distribution system is provided by Sweetwater Inc., located in the US. Limestone is delivered to a site as a dry powder in pneumatic tanker trucks and blown through hoses into the barge's hold. Once the barge is on the water the limestone is mixed with lake water to form a 50-70 wt.% uniform slurry which is applied to the lake.

1.3.2 Limestone distribution methodologies – Waterways

Typical limestone addition techniques for waterways include:

- Direct limestone addition;
- Limestone gravel bars or barriers;
- Autogenous mills (rotating drums);
- Automated limestone dosers;
- Limestone diversion wells.

When dosing into acid water, limestone addition should ideally be conducted throughout the year to avoid significant pH fluctuations (White, 2000).

Direct limestone addition

The direct addition of coarsely ground limestone to watercourses has been tested in the UK, Sweden, the US and Canada with mixed success (Donnelly et al., 2003). The effectiveness of this method is generally inversely proportional to the flow of the stream. A successful example of direct addition occurred in the Appalachian Mountains, Virginia, in the US. The streams were "not yet acidic but at the threshold of acidification" (Downey et al. 1994 in Donnelly et al. 2003). The limestone was formed as a pile in the stream that was gradually eroded. It was deemed unlikely that this method would be successful in streams with higher flow rates. Spreading limestone gravel in the base of rivers has been effective in low flow rivers in Nova Scotia but is much less effective in rivers with a high flow (White, 2000).

Limestone gravel bars or barriers

Limestone gravel bars and barriers ensure that water either passes over a bed of limestone or flows through a limestone filter (Donnelly et al., 2004). A limestone filter is held in place by larger boulders or wire but allows the water to flow through (Donnelly et al., 2003).

Limestone gravel bars have been shown to be most effective in low flow streams (White 2000) where water-rock interaction is optimised. This method was unsuccessful in Pennsylvania, as particles and leaves filled the gaps between the stones.

An experiment in Nova Scotia found that pH increased by an average of 0.05-0.1 log units for each barrier encountered. The experiment also found that gravel bars in straight shallow sections of the river are more physically stable than those in areas where the river is deep and winding or the bottom is uneven (White, 2000).

Pearson and McDonnell (in White 2000) suggest that creating a head of water behind a limestone barrier would prevent deactivation of the limestone by creating a current through the limestone to keep it clear of silt. While this may minimise blocking, it will also lower water-rock interaction times. In addition, it may prevent fish migration (White, 2000, Donnelly 2003).

The simplicity of this approach can make it very cost effective, but limited to neutralising flow-through acidity or at best add soluble alkalinity to water. The total mass of alkalinity added in this fashion is relatively small.

Autogenous mills

Revolving or rotating drums are autogenous mills containing limestone aggregate. Limestone is automatically fed into one or more perforated autogenous mills that rotate in response to river flow. No external power source is required, however the hydraulic head driving the systems needs to be at least equal to the diameter of the drum (White, 2000). These systems use the energy of moving water to facilitate autogenous grinding of limestone aggregate into smaller particles that are automatically dispensed into a river (White, 2000). The river flow rate determines the rotation speed of the drum and thereby regulates the mass of limestone dispensed into the stream (Donnelly et al., 2003). Revolving drums were developed to overcome the problem of limestone inactivation by neutralisation precipitates (White, 2000), the difficulty of providing power to remote sites and the high cost of finely ground limestone. The high capital and operating cost and relatively low dose rates of these systems has meant that their uptake has been limited.

Automated limestone dosers (silos)

Limestone dosers are stationary, automated devices that dispense finely ground, powdered limestone or limestone slurry into a river at a controlled rate from a silo (White, 2000). The rate can be controlled by pH feedback from the water. Donnelly et al. (2003) claimed that the "*Flow and pH are monitored both upstream and downstream of the doser, and the amount of lime required to neutralise the acidity is dispensed. It is the most accurate and precise method of limestone dosing, as the dose is controlled to coincide with times when it is needed most*". However White (2000) indicated that this method is often unreliable as pH probes are subject to drift. According to White (2000), water level can also be used to indicate both the flow rate and the pH and is more reliable. According to White (2000), these devices are more prone to breakdown than rotating drums and diversion wells (see below).

Limestone dosers have been successfully used in Sweden, the UK and the US. Dosers have also been recommended for use in Canada (Donnelly et al., 2003) and have successfully neutralised acid pulses in streams during major rainfall events (Donnelly 2003).

Limestone may be dispensed either as a dry powder or as a slurry. Dosers may be permanent structures or portable. These devices generally use electricity but some have been developed to operate using hydropower (White, 2000).

Diversion wells

Diversion wells operate by directing part of the flow from a watercourse through a pipe to the base of a vertical well. The well is filled with limestone aggregate which is kept in motion by the upward flowing water. The water flows through the limestone aggregate and out of the well into the watercourse (Donnelly et al. 2003; White, 2000). Diversion wells use the energy of the up welling water to abrade and grind the limestone into smaller particles. When the particles are small enough, they are mobilised from the well and directed back into the waterway. Much of the neutralisation does not occur in the well, but in the waterway as the limestone particle travels downstream. White (2000) claims that efficiencies of limestone use can be as high as 90%.

Limestone diversion wells can be effective when used in hilly terrain. They require a hydraulic head of at least 1.5m over relatively short distances (eg. 10-100m), and are more efficient in even steeper country. A well in Sweden is reported to deliver 150 tonne of limestone per year, but the designers claim that this could be doubled (White, 2000). This approach remains limited to relatively small dosing tasks, and does not work efficiently in high or low flows scenarios (Donnelly et al., 2003).

1.3.3 Limestone distribution methodologies – Catchments

Limestone applied by helicopter, truck or hand within the catchment of a lake will eventually carry soluble alkalinity into a lake (Helfrich et al., 2001). Catchment treatment is generally more expensive than direct lake or stream application, and is unlikely to be as efficient. International experience suggests that the average cost of direct lake application is only about 20% of the cost of one average watershed treatment. However, catchment treatment has the capacity to provide more sustained neutralisation and has been effective on small lakes with small tributaries (Helfrich et al., 2001).

In south-west Scotland, 20% of the Loch Fleet catchment was amended with limestone in an initial project in 1986. The pH and alkalinity of the system was successfully restored. A limestone addition project conducted in the Woods Lake catchment in New York was less successful, as the low rainfall and thin soils meant that the limestone did not dissolve as efficiently as in Scotland. While 96% of the applied limestone did not dissolve after twenty months, the project was considered successful (Donnelly et al., 2003).

While some believe that limestone addition to an entire catchment is the best long-term solution to acidification, the method is rarely a practical solution due to the high cost and slow system response time (Connelly et al., 2003).

1.4 GUIDING PRINCIPLES FOR LIMESTONE DOSING

Some of the most important guiding principles for limestone dosing in any situation include the following:

- Dosing limestone slurry into water tends to be far more efficient that dosing a dry powder and produces minimal fugitive dust emissions. Applying limestone as a slurry can reportedly increases its dissolution efficiency by 25-50% compared to applying a dry powder (White, 2000, Helfrich et al., 2001).
- Limestone saturation in near neutral water can theoretically take several days to achieve (eg. 14 days) under ideal conditions. In practice, dissolution can take several years, even in limestone under-saturated water. Optimising limestone-water interaction can enhance dissolution rates.

- The finer grained the limestone, the faster the dissolution rate, and hence the more effective the dosing activity. Generally, limestone particle size needs to be less than 500 µm, with at least 50 wt. % being less than 50 µm. Finer grain sizes will dissolve even faster and will tend to be even more uniformly dispersed.
- Limestone has a reverse aqueous solubility relationship with temperature relative to most minerals. This means that the solubility of limestone increases with decreasing water temperature.
- Aragonite ($CaCO_3$) and vaterite ($CaCO_3$) can dissolve significantly faster than calcite ($CaCO_3$) or dolomite ($[Ca\ Mg]CO_3$), and while calcite dissolves faster than dolomite, magnesian calcite in some circumstances dissolved faster than calcite.
- Limestone dissolution rates increase with decreasing pH, but passivation of the surfaces of limestone grains with neutralisation precipitates (eg. metal hydroxides and gypsum) tends to dramatically lower the efficiency of limestone use under low pH conditions. Aluminium hydroxide hydrate is most strongly implicated in the blinding of limestone surfaces and the diminution of stoichiometric limestone neutralisation.
- Remobilisation of limestone particles during water movement (eg. river flow) will tend to increase the efficiency of limestone use due to the abrasion / erosion of coatings of neutralisation precipitates around limestone grains.
- The quantity of limestone addition to a water body or waterway is a function of the contained or anticipated acidity load, the dosing method and the energy of the receiving environment. Some dosing methods require a greater mass of limestone than others, for an equivalent acidity load, due to the inherent inefficiency associated with limestone use.
- Indications of whether limestone grains will be mobilised from their site of initial deposition can be gained from knowledge of the grainsize of the sediment onto which they were deposited. For example, if fine grained limestone (eg. 100 µm particle size) is deposited onto a medium-grained sand bed with an average grainsize of 500-1,000 µm, it is highly likely that the limestone will eventually be transported to a lower energy setting by wind, wave or river flow action.
- Limestone that is not remobilised by wind, wave or flow action (eg. in a lake setting) can be covered by more recent sediment over time and rendered effectively inert. This is not uncommon in lake settings.

2.0 SCOPE OF WORKS

The objective of this report (Stage 1) is to assess the feasibility of options for passive and/or active treatment of the Lower Murray Lakes, using ultra fine grained limestone.

The scope of the assessment includes:

1. Identification of available treatment options.
2. Development of methodologies for implementing preferred treatment option(s).
3. Timeframe for implementing the preferred treatment option(s).
4. Timeframe for achieving effective mitigation following implementation of the preferred treatment option(s).
5. Identification of risks associated with the preferred treatment option(s), and measures available to mitigate those risks.
6. Identification of monitoring requirements to assess the performance of the preferred treatment option(s).
7. Preliminary costing of the preferred treatment option(s).
8. Identification of additional investigations and/or trials required prior to implementation of the preferred treatment option(s).

3.0 METHODOLOGY

The methodology for assessing the feasibility of treatment options for the Lower Murray Lakes included the following key steps:

- Site visit (Section 3.1).
- Review of existing information (Section 3.2).
- Identification and preliminary assessment of treatment options for the Lower Murray Lakes (Section 3.3).
- Detailed assessment of preferred treatment option(s) for the Lower Murray Lakes (Section 3.4).

3.1 SITE VISIT

A site visit was conducted by Earth Systems, with representatives of Rural Solutions SA and the Department for Environment and Heritage (DEH), on 23 September 2008.

3.2 REVIEW OF EXISTING INFORMATION

3.2.1 Acid Sulfate Soil / Acid and Metalliferous Drainage Management Guidelines

The management guidelines for acid sulfate soils (ASS) and acid and metalliferous drainage (AMD) presented in Table 2 were reviewed in the context of the ASS issue in the Lower Murray Lakes.

Table 2. ASS and AMD management guidelines relevant to the Lower Murray Lakes.

Title	Author	Date
National Strategy for the Management of Coastal Acid Sulfate Soils	National Working Party on Acid Sulfate Soils	2000
EPA Guidelines: Site Contamination – Acid Sulfate Soil Materials	EPA South Australia	2007
Queensland Acid Sulfate Soil Technical Manual – Soil Management Guidelines	Queensland Government Department of Natural Resources and Mines	2002
Coastal Acid Sulfate Soil Management Guidelines, Barker Inlet, SA	CSIRO and Natural Heritage Trust	2003
Managing Acid and Metalliferous Drainage	Department of Industry, Tourism and Resources	2007

3.2.2 Reports on ASS and water quality issues in the Lower Murray Lakes

A number of reports on the ASS issue and associated water quality concerns in the Lower Murray Lakes were reviewed, as summarised in Table 3.

Table 3. Reports on ASS and water quality issues in the Lower Murray Lakes.

Title	Author	Publisher	Date
Water Quality Screening Risk Assessment of Acid Sulfate Soil Impacts in the Lower Murray, SA	Stauber, Chariton, Binet, Simpson Bateley, Durr, Fitzpatrick and Shand	CSIRO Land and Water Science	April 2008
Acid Sulfate Soils in Subaqueous, Waterlogged and Drained Soil Environments in Lake Albert, Lake Alexandrina and River Murray below Blanchtown (Lock 1): Properties, Distribution, Genesis, Risks and Management	Fitzpatrick, Shand, Marvanek, Merry, Thomas, Raven, Simpson and McClure	CSIRO Land and Water Science	August 2008
Numerical Assessment of Acid-Sulfate Soil Impact on the River Murray Lower Lakes During Water Level Decline	Hipsey and Salmon	University of Western Australia Centre for Water Research	August 2008
Acid, Metal and Nutrient Mobilisations Dynamics in Response to Suspension of MBOs in Freshwater and to Freshwater Inundations of Dried MBO and Sulfuric Soil Materials	Sullivan, Burton, Bush, Watling and Bush	Southern Cross Geoscience	August 2008
Literature Review: Seawater Incursion Lake Alexandrina	Maunsell Australia	Unpublished report	June 2008
Literature Review: Acid Sulfate Soil Mitigation Using Organic Mulch	Maunsell Australia	Unpublished report	June 2008

3.2.3 Environmental Monitoring Data for the Lower Murray Lakes

A range of environmental monitoring datasets for the Lower Murray Lakes were reviewed, as outlined below:

- Bathymetry and contour data for the Lower Murray Lakes and surrounding region (DEH, 2008).
- Geology map of the Lower Murray Lakes and surrounding region (SARIG, 2008).
- Rainfall and evapotranspiration data for the region surrounding the Lower Murray Lakes (SA Murray Darling Basin Natural Resources Management Board, 2008).
- Meteorological data (including wind speed and direction data) from Hindmarsh Island (BOM, 2008).
- River hydrology, groundwater flows and lake water level data.
- Water quality data for the Lower Murray Lakes and key tributaries including the Murray River, Finniss River, Bremer River and Angas River (Luke Mosley, EPA SA, 2008).

Relevant data from the above sources were utilised in the estimation of potential treatment requirements for the Lower Murray Lakes.

A geochemical / water quality modelling tool, PHREEQC, developed by the U.S. Geological Survey, was used to estimate saturation indices for various minerals, based on existing water chemistry data for Lake Alexandrina (Milang) and Lake Albert (Meningie). The carbonate saturation indices are of particular relevance to the potential acidification of the Lower Murray Lakes, and assist with assessment of the effect of limestone dosing on lake water quality.

3.3 IDENTIFICATION AND PRELIMINARY ASSESSMENT OF TREATMENT OPTIONS

A number of treatment options were considered for the Lower Murray Lakes, focussing on neutralisation methods using ultra fine grained calcium carbonate (limestone; $CaCO_3$).

A preliminary assessment of these options was then conducted, with the preferred option(s) selected on the basis of:

- Ease of implementation.
- Expected performance (ability to achieve water quality objectives).
- Capital and operating costs of implementation.
- Timeframes for implementation and achievement of water quality objectives.
- Risk.

Detailed assessment of the preferred treatment option(s) was then conducted, as described in Section 3.4.

3.4 DETAILED ASSESSMENT OF PREFERRED TREATMENT OPTION(S)

A detailed assessment of the preferred treatment option(s) for the Lower Murray Lakes was conducted. This involved the following key stages:

- Development of methodology for implementing preferred treatment option(s).
- Timeframe for implementing the preferred treatment option(s) and achieving effective mitigation.
- Identification of risks associated with the preferred treatment option(s), and measures available to mitigate those risks.
- Monitoring and performance assessment for the preferred treatment option(s).
- Preliminary costing of the preferred treatment option(s).
- Additional investigations and/or trials required.

4.0 RESULTS

4.1 IDENTIFICATION AND PRELIMINARY ASSESSMENT OF TREATMENT OPTIONS

4.1.1 Introduction

The limestone proposed for addition to the Lower Murray Lakes comes from a specific source near Robe. It represents an ultra-fine grained limestone product that requires no crushing. Without local access to such material, many of the proposed dosing strategies identified below would not be considered feasible.

Recent water chemistry data supplied by the EPA indicates that the lake waters are already marginally saturated with respect to carbonate minerals. This includes calcite, dolomite and aragonite (based on from PHREEQC modelling). Saturation index data for waters from Milang in Lake Alexandrina and Meningie in Lake Albert are shown in Figures 4.1 and 4.2.

The data in Figures 4.1 and 4.2 suggests that dosing with limestone will do little to change the chemistry of the lake water, but will simply provide additional, stored buffering capacity to the lakes. Depending on how the limestone is added to the lakes, this is expected to take the form of a thin layer of limestone over the base of lake sediments. Based on grainsize considerations, much of the limestone is expected to ultimately settle in the deeper, lower energy portions of the lakes following most but not all of the proposed alkalinity addition strategies.

Consideration has been given to the following treatment options for the Lower Murray Lakes, focussing on neutralisation methods using ultra fine grained calcium carbonate (limestone; $CaCO_3$) as the neutralisation reagent:

- Option1: Dose limestone from a single point into each lake and utilise flowing water to disperse reagent into the lakes (Section 4.1.2).
- Option 2: Install access roads (constructed from limestone aggregate) at strategic locations within each lake and utilise pumping systems from the end of these roads to mix and disperse reagent into the lakes (Section 4.1.3).

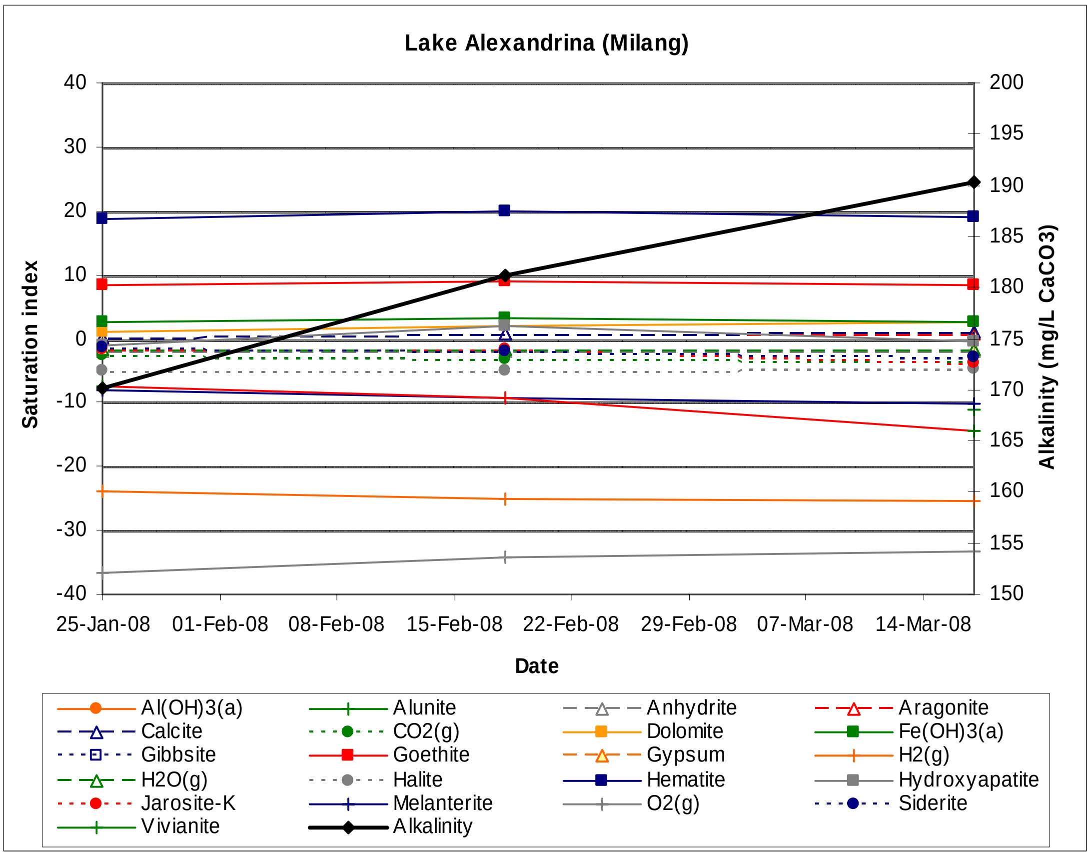

Figure 4.1. Saturation indices from water chemistry data in Lake Alexandrina at Milang.

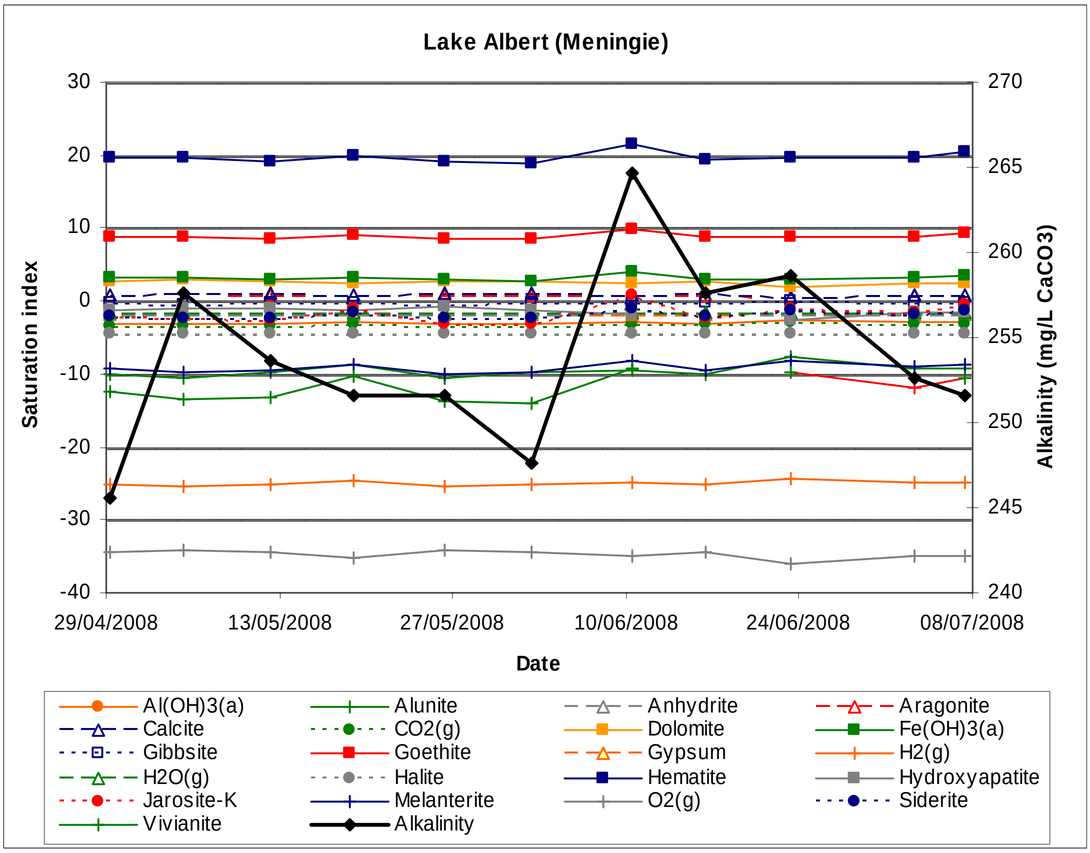

Figure 4.2. Saturation indices from water chemistry data in Lake Albert at Meningie.

- Option 3: Dose limestone from multiple points in each lake via moving barges and utilise on-board pumping systems to disperse the limestone as a slurry into the lakes (Section 4.1.4).
- Option 4: Add reagent to the margins of key tributaries of Lake Alexandrina to provide passive limestone addition to the lake during high flows (Section 4.1.5).
- Option 5: Install alkalinity generating limestone ponds adjacent to key tributaries of Lake Alexandrina (Section 4.1.6), and (passively or actively) direct some flow through these ponds to carry soluble alkalinity into the lakes.
- Option 6: Selectively add limestone to the lake shorelines in areas containing the highest risk acid sulfate soils (Section 4.1.7).
- Option 7: Subaerial addition of limestone via helicopter (Section 4.1.8).

A preliminary assessment of these options is provided in Section 4.1.9.

The following working hypothesis has been developed to assist with assessment of the proposed treatment options. Acid and metalliferous drainage will be generated from the unsaturated margins of the lakes, and is predicted to migrate through shallow groundwater pathways and discharge into lake water near the (migrating) shoreline. Since little particulate limestone is expected to settle in this high energy setting, the acidity is expected to be neutralised by the soluble bicarbonate alkalinity in the lake water. As the alkalinity of lake water locally decreases around the shoreline, chemical potential gradients will work to restore the chemical equilibrium by lowering the overall bicarbonate concentration of the lake water. If the bicarbonate concentrations are lowered to sub-calcite saturation levels, then limestone dosed into the lake will begin dissolving until saturation has been restored. Hence, adding limestone and maintaining calcite saturation within the lake system would appear to be a reasonable treatment strategy.

4.1.2 Option 1: Single point static dosing into flowing water

Dosing ultra fine grained limestone into calcite under-saturated water downstream of Wellington during enhanced (controlled) flows from the Murray River should provide a good opportunity to add and store alkalinity in Lake Alexandrina.

Limestone could be dosed from a 100 tonne capacity barge, setup on a tow line across the Murray River, a few kilometres downstream of Wellington. Controlled release of water from Lock 1 will be necessary to enhance river flow. 30 tonne or smaller capacity trucks could deliver and dump limestone onto a purpose built tray lying on the barge. The barge will need to be drawn out into the middle of the river, where pumps will be activated to draw water from the river and spray the margins of the limestone stockpile. The resulting limestone slurry will be released from the holding tray at a controlled rate into the river. The engineered river flow should carry the ultra-fine grained slurry some distance into Lake Alexandrina where it will slowly settle.

It may also be feasible to add limestone at the pump station between the two lakes to disperse limestone to Lake Albert. This could be achieved by controlled dumping of limestone close to the suction lines of the existing pump set. A portable pump could be used to mobilise the limestone powder, form a slurry and direct it into the suction lines of the Lake Albert pumps.

River flow, wind and wave-action will all be useful for dispersing the limestone slurry. Pump-derived flow could be used to further assist limestone dispersion throughout each lake.

Further detail on this option is provided in Section 4.2.

4.1.3 Option 2: Multi-point static dosing from access roads in lakes

This option would involve the installation of 2-3 limestone roads from the shoreline towards the centre of each lake. The roads are needed to provide access to approximately 0.5-0.75 m depth of water. Ultra fine grained limestone could then be trucked-dumped at the end-point of each road and subsequently dosed into the lakes via a twin pump system. One pump is used for generating a slurry and the other for dispersing the slurry far out into the lake. The coarse limestone road aggregate (eg. 20 mm) could provide an additional (secondary) alkalinity to the lakes over the long term, or alternatively the roads could be deconstructed following successful dosing if necessary.

The length of the road will be controlled by the depth of the water, but may be up to 100 metres long and almost 10 metres wide. They would be strategically positioned such that:

- Dosing of ultra fine grained limestone into the lakes could be achieved from the end-point of each road into key central locations (relatively deep water) that would facilitate dispersion of the reagent throughout each lake.
- Advantage would be taken of bathymetric data to minimise the cost of the road construction.
- Road construction and later traffic could be accommodated on the lake sediments.

The end-point of each limestone road would require sufficient surface area for stockpiling limestone and mixing and dosing equipment. Regular re-fuelling of the pumps will also be necessary.

The option of installing limestone roads, and subsequently dosing limestone from the end-point of these roads into the centre of lakes Alexandrina and Albert, could potentially be combined with limestone dosing into flowing water, as described in Option 1.

Alternatively, it may be possible to conduct multi-point static dosing from the shore if good road access is available and onshore water levels are in the range 0.5-1.0 m.

Further detail on this option is provided in Section 4.2.

4.1.4 Option 3: Mobile dosing via barges

In the event that dispersion of the ultra-fine grained limestone from a fixed location (ie. Options 1 and 2) is insufficient to generate adequate limestone coverage of the lakes, dosing from mobile platforms (barges) will be necessary.

This option would require the identification or creation of approximately 3-6 locations around the perimeter of each lake where barges could be loaded with 20-80 tonnes of limestone. This is expected to require the installation of short access roads (constructed from limestone) out into the lakes to facilitate the delivery of ultra fine grained limestone, and the mooring, loading and movement of barges.

Excavators located at the end of the limestone roads could transfer stockpiles of limestone onto the barges. Water depth at the end of the roads needs to be sufficient to ensure that the loaded barges remain afloat. Diesel powered pumps located on the barges would be used to produce and disperse a limestone slurry throughout the lakes. GPS tracking of barge routes could be coordinated to ensure uniform coverage of the bed of the lakes.

It is possible that Option 3 could be combined with Options 1 and/or 2.

4.1.5 Option 4: Erosional dispersion of limestone

Stockpiles of ultra-fine grained limestone could be deposited close to or within the courses of the Murray, Bremer, Finniss and Angas rivers (close to their mouths) to permit passive limestone slurry addition to Lake Alexandrina from these waterways during flow events.

Strategically located stockpiles of limestone will be progressively eroded by stream flow during high flow events, carrying a limestone slurry (and soluble alkalinity) into Lake Alexandrina. Dose rates are unlikely to exceed several tonnes per day (maximum) during high flow events, even form the Murray, indicating that this approach will probably need to be supplemented by other methods. The low cost and ease with which this option could be implemented suggests that it should proceed as a supplementary approach to the final preferred option.

Option 4 will not be applicable to Lake Albert, due to the lack of significant river discharges directly into this water body.

4.1.6 Option 5: Alkalinity generating ponds

This option will ensure that soluble alkalinity is continuously and passively added to water in Lake Alexandrina during river flow. This can be achieved by installing alkalinity generating ponds adjacent to (or possibly within) the courses of key tributaries to Lake Alexandrina (ie. Murray, Bremer, Finniss and Angas rivers). Such ponds contain reactive limestone aggregate distributed in a fashion that optimises the dissolution of limestone in the water. Water could be passively diverted from the river into the alkalinity producing ponds or potentially it could be pumped, and then eventually overflow back into the river channel. Water discharging from the ponds could ideally be saturated with respect to limestone, and thereby carry soluble alkalinity into the lake.

Achieving limestone saturation for large flows (eg. 1000 L/s) is predicted to be prohibitively expensive, and hence the effective mass of limestone addition via this option is expected to be relatively small. For example, if 200 L/s of Murray River water was directed into a large alkalinity producing pond that permitted saturation with respect to limestone, the maximum daily alkalinity addition to Lake Alexandrina would be approximately 3.5 to 4.0 tonnes of $CaCO_3$.

The dissolution rate of limestone in near neutral water is very slow, and hence achieving or approaching saturation with respect to limestone will require long residence times for water in the alkaline ponds. Longer residence times mean larger ponds and higher construction costs, but they can deliver higher alkalinity outputs.

If acidity generation rates from ASS marginal to the lakes are identified as being in the order of a few tonnes of sulfuric acid (H_2SO_4) per day, then this option needs to be more closely considered.

4.1.7 Option 6: Limestone addition to exposed sediments and shorelines

Rather than adding limestone to the lakes in the form of a slurry that will eventually overlie sediments in the lower energy, deeper portions of the lake, it is possible to dispense limestone over exposed sediments along the shoreline. While this could be achieved for the entire shoreline of both lakes, the cost will be high and the rate of regent addition relatively slow. Hence, it is considered more appropriate to target limestone addition to the shoreline in the high risk areas, as defined by soil types (sulfide content) and extent of oxidation.

Rainfall events, which will generate the key periods of acidity discharge, will also wash some ultra fine grained limestone and soluble alkalinity down into the unsaturated sediments. In addition, runoff from the sediments will wash some limestone slurry and soluble alkalinity down into the lake waters. It is not clear at this stage whether this approach could match the acidity generation with the alkalinity addition.

Limestone could be added to the exposed sediments and shoreline using the following approaches:

- Limestone slurry batches could be prepared in 4WD mixer tankers and pumped onto exposed shoreline sediments from the nearest access point. The tankers could be supplied with water and limestone from nearby all weather 2WD roads. Slurry hose lines from the tankers could be up to 500m long to ensure that most locations could be reached. A 10,000 litre tanker has the potential to prepare and dispense a batch of limestone slurry (comprising 2-3 dry tonnes of limestone) every 1-2 hours. Typically a single tanker could disperse approximately 15-20 tonnes of dry limestone equivalent per day.
- Limestone could be dispensed as a dry powder along the exposed sediments (or shorelines) utilising swamp dozers fitted with suitable dry powder dispensing systems. It is unlikely that the dozers will be able to carry more than 1-2 tonnes at a time. Strategically located stockpiles of limestone could speed up dispersal times, but rates are likely to be approximately 30-50 tonnes per day per dozer.

4.1.8 Option 7: Limestone addition by helicopter

Significant dispensing flexibility could be provided with the use of helicopters. They could be used to place dry limestone powder directly into the lakes, specifically along the shoreline, or across the exposed sediments. This will be an expensive option that carries the risk of generating dust issues, but with some planning has the potential to be applied in an emergency response scenario.

It is estimated that a flying crane could lift approximately 2-5 tonne dry powder batches per flight. Such a batch could potentially be dispensed in 10-15 minutes. With planning, turn-around times for batches could be reduced to 15-20 minutes. Hence, it may be possible to dose an average of about 10 tonnes of dry powdered limestone per hour, or 100 tonne per 10 hour day.

4.1.9 Preliminary assessment of treatment options

Table 4 provides a preliminary assessment of the treatment options described in Sections 4.1.2 to 4.1.8. The assessment is based on ease of implementation, expected performance, capital and operating costs, timeframes for implementation, achievement of water quality objectives and associated risks.

Based on the results of the preliminary assessment in Table 4 the preferred treatment strategy for the Lower Murray Lakes, at this stage, involves a combination of the following options:

- Dose limestone from a single point into each lake and utilise flowing water to disperse reagent into the lakes.
- Install (limestone) access roads at strategic locations within each lake to reach deeper water, stockpile ultra fine grained limestone at the end and utilise pumping systems to mix and disperse limestone into the lakes.

These options are considered relatively easy to implement and have the potential to provide maximum alkalinity addition to the lakes within reasonably short timeframes. The cost effectiveness of limestone dosing can be maximised if it is efficiently dispersed into each lake from static dosing points (ie. as few points as possible). The installation of access roads to provide supplementary dosing points would reduce the risk of incomplete reagent dispersion that may be associated with single point addition into the lakes.

A more detailed methodology for implementation of the two preferred options is provided in Section 4.2.

Table 4: Preliminary assessment of treatment options for the Lower Murray Lakes.

Option		**Preliminary Assessment Criteria (optimum score 5)**					**OVERALL (optimum score 25) *#**
No.	Description	Ease of implementation	Expected performance	Capital / operating costs	Timeframes for implementation / achievement of water quality objectives	Risk	
1	Single point static dosing into flowing water	4	4	4	5	4	**21**
2	Multi-point static dosing from access roads in lakes^	3	3	3	4	4	**17**
3	Mobile dosing via barges	2	5	3	3	4	**17**
4	Erosional dispersion of limestone	5	2	5	2	1	**15**
5	Alkalinity generating ponds	3	2	2	3	1	**11**
6	Limestone addition to exposed sediments and shorelines	3	3	3	3	4	**16**
7	Limestone addition by helicopter	3	4	1	5	1	**14**

* Further investigation and/or trials would assist to confirm preliminary assessment results.

Assessment assumes independent implementation of each option, although there is potential to combine options.

^ Assume geotechnical stability of lake sediments would be sufficient for limestone road construction.

4.2 PREFERRED TREATMENT OPTION(S)

4.2.1 Strategy

The preferred treatment strategy for the Lower Murray Lakes involves a combination of Options 1 and 2.

- Dose limestone from a single point into each lake and utilise flowing water to disperse reagent into the lakes (refer to primary dosing locations in Figure 4.3).
- Install limestone aggregate roads at strategic locations within each lake and utilise pumping systems to disperse reagent into the lakes. Potential secondary dosing locations are indicated in Figure 4.3.

In the case of Lake Alexandrina, the preferred strategy would involve dosing limestone into the Murray River, downstream of Wellington (refer to Figure 4.3). Controlled release of Murray River flows from Lock 1 during limestone dosing would facilitate dispersion of limestone throughout the lake.

In the case of Lake Albert, the preferred strategy would involve dosing limestone via the existing pump station between the two lakes, and operating the pumps at full capacity to maximise reagent dispersion into Lake Albert (refer to Figure 4.3).

In addition to limestone dosing into the Murray River near Wellington and into Lake Albert via the existing pump station, dosing of ultra fine grained limestone at 2-3 central locations within each lake via limestone access roads may be required to enable better distribution of reagent across both lakes.

Single point dosing trials could be conducted to confirm the requirement, if any, for installing limestone access roads and dosing limestone from additional (central) locations within each lake, as previously described.

The strategy described above could either be considered a passive prevention strategy that is proactively implemented prior to detectable lake acidification, or an emergency response strategy that is activated in the event of achieving specific trigger levels of one or more parameters (eg. pH, alkalinity, carbonate saturation index).

The ease of implementation and low cost associated with Option 4 suggest that this approach should be trialled to quantify its performance.

4.2.2 Limestone supply

A specific ultra fine grained limestone is proposed for dosing into Lakes Alexandrina and Albert. Key specifications for the preferred reagent are provided in Table 5. The ultra fine grain size (average 8 μm), reasonable purity (85% carbonates), low capital cost and relatively low transport cost (within 200 km from Lower Murray Lakes) were key factors in the reagent selection process. Furthermore, the selected limestone has previously been used by Earth Systems successfully for other lake dosing, water quality applications.

Table 5: Specifications of ultra fine grained limestone proposed for dosing into Lakes Alexandrina and Albert.

Parameter	Unit	Value
Physical and chemical properties		
Average particle size	μm	8
Chemical composition		
Calcium carbonate ($CaCO_3$)	%	65.1
Magnesium carbonate ($MgCO_3$)	%	17.0
Alumina (Al_2O_3)	%	1.4
Ferric oxide (Fe_2O_3)	%	0.6
Sodium chloride (NaCl)	%	0.7
Quartz (SiO_2)	%	4.4

The actual mass of limestone required for addition to the lakes is unknown. Routinely the supplier only stockpiles approximately 5,000 tonne per year. Limestone addition requirements need to be determined and the supplier informed to ensure that this source of material can provide all of the lakes needs.

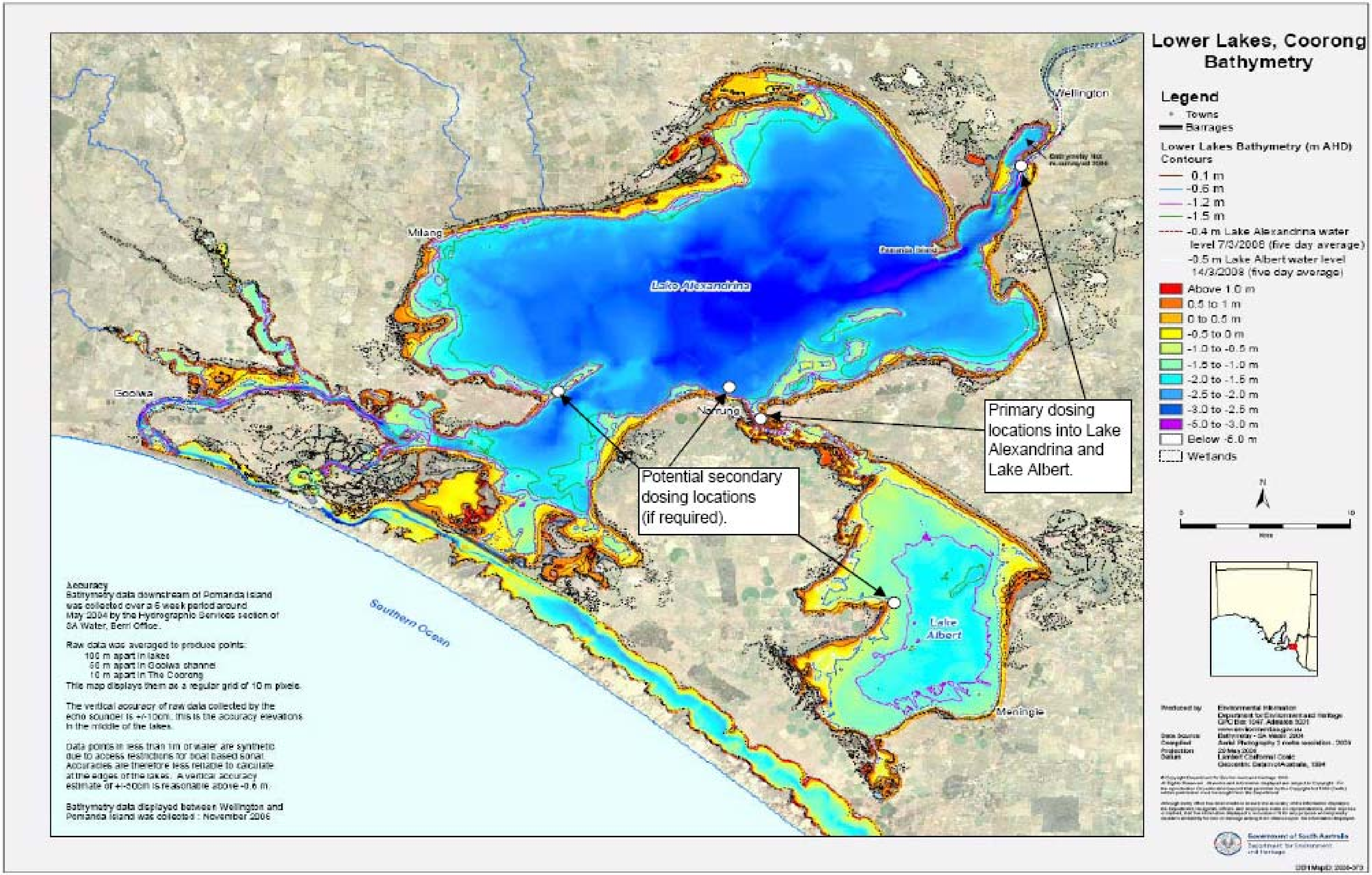

Figure 4.3. Potential locations for limestone dosing into Lakes Alexandrina and Albert. Base map taken from DEH (2008).

4.2.3 Risks and mitigation measures

A number of hazards associated with implementation of ultra fine grained limestone dosing into the Lower Murray Lakes have been identified, as shown in Table 6. The likelihood and potential consequences associated with each hazard were used as a basis for allocating a "risk classification" to each hazard (very low / low / moderate / high / very high). Various mitigation measures are provided in Table 6 to minimise the residual risk and therefore maximise the potential for successful implementation of the proposed treatment strategy.

Table 6: Risks associated with preferred treatment option(s) and risk mitigation measures.

Hazard	Likelihood	Consequence	Risk*	Risk mitigation measures
Inefficient mixing of limestone throughout Lake Alexandrina and/or Lake Albert	Conceivable in conditions of low flow and/or low wind velocities (limited wave action).	Rapid settling of limestone proximal to dosing locations. This will prevent uniform distribution of the limestone throughout the lake.	Moderate	Limestone dosing during high flow conditions in the Murray River (eg. 600 ML/day) and maximum pump flow rates into Lake Albert. Limestone can be dosed from multiple locations in both lakes, utilising "limestone access roads" in strategic locations. Limestone has been specifically selected with properties (ultra fine grained particle size) known to facilitate reagent dispersion. Pumping systems could be installed at strategic locations to facilitate water movement and limestone dispersion. Add on-shore limestone stockpiles proximal to or within the courses of the Bremer, Finniss and Angas rivers to permit passive limestone slurry addition to Lake Alexandrina from these waterways during high flow events. Consider other treatment options such as dosing from mobile barges.
Adverse effect on water quality (pH) associated with overdosing.	Water is already saturated with respect calcite, aragonite and dolomite. Overdosing does not appear to be possible.	Settling of limestone on the lake beds will provide stored alkalinity.	Very low	Not required.

Hazard	Likelihood	Consequence	Risk*	Risk mitigation measures
Adverse effect on water quality (turbidity) associated with ultra fine grained limestone.	Likely to be a short-term issue only. Success of the dosing method is dependent on maintaining ultra fine grained particles in suspension for a sufficient time to maximise dispersion of limestone throughout the lakes.	Potential adverse impacts on aquatic fauna in both lakes.	Moderate	Limestone dosing into lakes can be staged to enable movement of aquatic fauna to low-turbidity zones, away from reagent plumes. Monitor turbidity during limestone dosing and dispersion in the lakes and control dosing methods/rates accordingly.
Adverse effect on water quality associated with limestone impurities	The key impurity in the ultra-fine grained limestone is NaCl (up to 0.7 wt.%). Lake salinity could increase marginally due to NaCl addition.	Potential adverse impacts on aquatic fauna in both lakes.	Very low	Limestone with minimal impurities has been chosen. Monitor parameters of concern (or indicator parameters) during limestone dosing and dispersion in the lakes and control dosing methods/rates accordingly.

* Very low / low / moderate / high / very high.

4.2.4 Monitoring and assessment of performance

Detailed strategies need to be developed to monitor the progress and potential impacts of limestone addition. These will include:

- Plume dispersion (eg. aerial photography, turbidity measurements, subaqueous sediment traps).
- Water quality (turbidity, pH, electrical conductivity, major and trace elements, alkalinity, acidity, etc).
- Aquatic fauna and flora.
- Potential social impacts (eg. irrigation water quality, dust, general amenity, fishing).

The following additional monitoring data would assist in the interpretation of water quality results during and following limestone dosing activities:

- Water level and flow rates in the Murray River at Wellington.
- Water levels and volumes in Lake Alexandrina and Lake Albert
- Wind speed and direction.

4.2.5 Additional investigations and/or trials required

Prior to implementation of the preferred treatment option(s), the following additional investigations/trials are recommended:

- Conduct a small scale trial involving dosing of ultra fine grained limestone into the Murray River at Wellington. Limestone could be dosed from the existing ferry at Wellington, utilising a pumping system to control the dose rate. It is proposed that 200 dry tonnes of limestone be dosed into the river over 3 days. Short-term water release from Lock 1 would be required to maximise Murray River flows at Wellington during at least 1-2 days to maximise dispersion of limestone in Lake Alexandrina. Visual monitoring of the extent of the limestone plume and/or water quality monitoring would be required throughout the trial.
- Consider conducting a similar small scale trial involving dosing of 200 tonnes of ultra fine grained limestone into Lake Albert over 3 days, via the existing pumping station between the two lakes.
- Depending on the results of the trials described above, the following options may be considered for Lake Alexandrina and/or Lake Albert:
  - Identify locations in either lake where limestone could be delivered and dosed from the shore due to good road access and onshore water levels of 0.5-1.0 m.
  - Conduct a geotechnical investigation of the potential to install limestone aggregate roads directly onto lake sediments.
  - Install a limestone road in a strategic location, extending from the lake shoreline toward the centre of the lake until a water depth of 0.5-1.0 m is attained. Deliver and dose ultra fine grained limestone from the end of the limestone road via mixing and dosing pumps.

Depending on the results of the trials described above, dispensing limestone from multiple points in each lake via mobile barges may need to be considered.

Small scale trials of limestone addition to the margins of key tributaries of Lake Alexandrina would provide valuable information on the efficacy of this passive alkalinity addition approach. Significant limestone addition is only likely during high flow events.

Alkalinity addition options 5, 6 and 7 should be re-assessed when sulfide oxidation rates have been determined and pollutant fluxes quantified.

4.2.6 Preliminary cost estimates for preferred options

Preliminary cost estimates (±30%) have been determined for the following preferred treatment options:

1. Dosing of 10,000 tonne of limestone into the Murray River south of Wellington over a period of 35 days. This is estimated to cost close to $2,000,000. A more detailed breakdown of costs and assumptions is provided in Attachment A.
2. Dosing of 2,000 tonnes of limestone from a 100 m long limestone access road at a single location in one of the lakes over a period of 15 days. This is expected to cost slightly in excess of $600,000. A more detailed breakdown of costs and assumptions is provided in Attachment A.

In order to clarify the likely effectiveness of static limestone dosing from a single point, a trial dosing program has also been costed. It is proposed to use the ferry at Wellington to trial static limestone dosing in the Murray River by adding 200 tonnes over 2 days. It is estimated (±30%) that this trial will cost just over $115,000. A more detailed breakdown of costs and assumptions is provided in Attachment A.

5.0 CONCLUSIONS

Key conclusions from this study include:

- The addition of substantial quantities of limestone to the Lower Murray Lakes for the purposes of neutralising AMD from Acid Sulfate Soils is a feasible option, from both a technical and economic perspective.
- The mass of sulfuric acid likely to be generated in response to dewatering of the sediments around the shoreline of the Lower Murray Lakes has yet to be accurately quantified. Hence, the mass of limestone that may be required for neutralisation is also unknown.
- Estimates of the potential tonnages of limestone required for neutralisation indicate that the ability to dose at least 10,000 tonnes per 35 days would be useful under a worst case scenario. This would be equivalent to 5% of the existing dissolved alkalinity in the Lower Murray Lakes (approximately 200,000 tonnes $CaCO_3$) and would be sufficient to neutralise approximately 10,000 tonnes of sulfuric acid.
- Limestone addition could be instigated pro-actively or in response to pre-arranged trigger values.
- A range of potential dosing methodologies have been identified. They are consistent with the “guiding principles for limestone dosing” documented in Section 1.4. Only some of the methodologies have the ability to deliver large tonnages of limestone over a short time period.
- Preferred dosing methodologies include a) single point, static dosing into flowing water for each lake, and b) multi-point static dosing from short access roads in one or both lakes.
- Once acidity flux rates into the lakes have been quantified, it may be worthwhile re-assessing the value of alkalinity producing ponds if fluxes are relatively low.
- Alkalinity addition to the lakes can be expected to have the additional benefit of lowering filterable reactive phosphorous (FRP) concentrations in the lakes. Low FRP values could generate lower incidences of some algal blooms. Hence, low level, passive calcium addition to the lakes may have other water management benefits.
- A commitment to continue pumping water into Lake Albert to ensure that water levels maintain saturated shoreline sediments would be a simple way to quantitatively lower the AMD risk from the lake system. In this way, only mitigation measures for Lake Alexandrina need be considered.
- Further work to quantify potential limestone dosing requirements would assist with selection of the most appropriate treatment options.
- Mitigation options other than neutralisation with limestone are still available for controlling or preventing acidification of the Lower Murray Lakes. These will be examined in a Stage 2 report.

6.0 RECOMMENDATIONS

Key recommendations from this study include:

1. Conduct trial treatment of Lake Alexandrina from the Wellington ferry with 200 tonnes of limestone.
2. If this trial treatment is successful in its aim to substantially disperse limestone throughout Lake Alexandrina, then consider establishing dosing infrastructure and a limestone stockpile south of Wellington to have the option of continuing this dosing in the event that trigger alkalinity values in the lake are exceeded.
3. Conduct trial treatment of Lake Albert with 200 tonnes of limestone by dosing at the pump station between the two lakes.
4. If trial treatment demonstrates that fixed point dosing at Wellington and the Lake Albert pump station are only partially successful, one or more of the following options may be considered for Lake Alexandrina and/or Lake Albert:
   - Identify locations in either lake where limestone could be delivered and dosed from the shore due to good road access and onshore water levels of 0.5-1.0 m.
   - Conduct a geotechnical investigation of the potential to install limestone access roads directly onto lake sediments.
   - Install a limestone access road in a strategic location, extending from the lake shoreline toward the centre of the lake until a water depth of 0.5-1.0 m is attained.
   - Conduct trial treatment from the end of the access road.
5. Depending on the results of the trials described above, consider dispensing limestone from multiple points in each lake from mobile barges.
6. Conduct three x 30 tonne trials of limestone addition to the margins of key tributaries of Lake Alexandrina.
7. Re-assess the need for implementing alkalinity addition options 5, 6 and 7 when sulfide oxidation rates have been determined and pollutant fluxes quantified.
8. Continue to control water levels in Lake Albert so that mitigation measures are only required in Lake Alexandrina.
9. Key data requirements to quantify the likely scale and timing of acidity fluxes from unsaturated lake sediments include:
   - Sulfide oxidation rates as a function of the moisture content of the unsaturated sediments;
   - Groundwater discharge rates (ie. as a function of rainfall recharge, lake water levels, wave action, geo-tides, etc) and hence acidity release rates into the lakes;
   - Stored organic matter content of unsaturated lake sediments, and the extent of sulfate reducing bacterial activity in unsaturated sediments.

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Attachment A:

Preliminary Cost Estimate for Preferred Treatment Options and Trials

ATTACHMENT A - COST ESTIMATES FOR ADDITION OF LIMESTONE TO LOWER LAKES

OPTION 1: Addition of 10,000 tonnes of Limestone south of Wellington (Costings ± 30%)

Items		Quantity	Unit Rate	Unit	Number of Days	Cost Subtotal
Personnel	Project Director	2	$ 3,360	per day	17	$ 114,240
	Project Manager	2	$ 2,160	per day	35	$ 151,200
	Barge Operators	2	$ 840	per day	35	$ 58,800
	Pump Operator	2	$ 840	per day	35	$ 58,800
	Monitoring Personnel	2	$ 1,920	per day	40	$ 153,600
	Reporting Personnel	3	$ 1,653	per day	5	$ 24,800
Equipment	Barge (Lease)	1	$ 2,800	per day	35	$ 98,000
	Barge Mobilisation / Demobilisation	2	$ 90,000	per event	1	$ 180,000
	Tow wire infrastructure Installation	1	$ 95,000	installation	1	$ 95,000
	Pump @ 200L/s	2	$ 450	per day	35	$ 31,500
	Portable Lighting	4	$ 285	per day	35	$ 39,900
	Pump / Lighting Mobilisation / Demobilisation	2	$ 1,100	per event		$ 2,200
	Crane hire	1	$ 1,400	per day	5	$ 1,400
	Hire Vehicles	2	$ 120	per day	45	$ 10,800
	Limestone containment and slurry structure	1	$ 35,000	installation	1	$ 35,000
	Boat Hire	1	$ 750	per day	10	$ 7,500
Reagent	Fine grained limestone (incl. delivery)	300	$ 45	per tonne	33	$ 445,500
Civil Works	Road construction / improvement	1	$ 10,000	upgrade		$ 10,000
	Ramp to barge	1	$ 15,000	installation		$ 15,000
Monitoring	Light Aircraft	2	$ 1,500	per flight		$ 3,000
	Multi-Parameter Water Quality Meters	2	$ 3,500	per Meter		$ 7,000
	Water Depth Monitoring	1	$ 250	per day	10	$ 2,500
	Limestone Dispersion Monitoring	5	$ 350			$ 1,750
	Analytical Expenses	5	$ 250	per analysis	10	$ 12,500
Miscellaneous	Travel	4	$ 600	per return flight	1	$ 2,400
	Communications	1	$ 30		35	$ 1,050
	Food & Accommodation	5	$ 160	per day	35	$ 28,000
Consumables	Diesel for Pump	480	$ 2	/litre	35	$ 33,600
	Diesel for Drive Motor on Barge	100	$ 2	/litre	35	$ 7,000
	Diesel for Lighting	240	$ 2	/litre	35	$ 16,800
	Monitoring Consumables					$ 1,500
Reporting	Expenses	1	$ 1,500			$ 1,500
Contingency @ 20%						$ 330,368
				TOTAL (Ex-GST)		$ 1,982,208

Assumptions:
15 tonnes of limestone per hour (ie. 250 kg/minute or 4 kg/second)
2 x 12 hour shifts per day
10,000 tonnes of limestone dispended in 35 days
Refuelling from tanker truck
Total duration of 35 days

ATTACHMENT A - COST ESTIMATES FOR ADDITION OF LIMESTONE TO LOWER LAKES

Option 2: Addition of 2,000 tonnes of Limestone from a selected location within the Lakes (Costings ± 30%)

Items		Quantity	Unit Rate	Unit	Number of Days	Cost Subtotal
Personnel	Project Director	1	$ 2,800	per day	5	$ 14,000
	Project Manager	1	$ 1,800	per day	25	$ 45,000
	Pump Operator	2	$ 700	per day	15	$ 21,000
	Monitoring Personnel	1	$ 1,600	per day	15	$ 24,000
	Reporting Personnel	3	$ 1,653	per day	5	$ 24,800
Equipment	Dozer with Operator	1	$ 1,800	per day	20	$ 36,000
	Excavator with Operator	1	$ 1,800	per day	15	$ 27,000
	Pump @ 200L/s + 300L/s	1	$ 1,150	per day	14	$ 16,100
	Pump mobilisation / demobilisation	2	$ 600	per event	1	$ 1,200
	Hire Vehicles	2	$ 120	per day	15	$ 3,600
	Limestone containment and slurry structure	1	$ 35,000	installation	1	$ 35,000
	Boat Hire	1	$ 750	per day	5	$ 3,750
Reagent	Fine grained limestone for dosing	150	$ 45	per tonne	14	$ 94,500
Civil Works	Onshore road construction / improvement	1	$ 10,000	upgrade		$ 10,000
	Offshore limestone road to deep water (100m x 10m x 1.5m)	1	$ 101,250	installation		$ 101,250
Monitoring	Light Aircraft	1	$ 1,500	per flight	2	$ 3,000
	Multi-Parameter Water Quality Meters	1	$ 3,500	per Meter		$ 3,500
	Water Depth Monitoring	1	$ 250	per day	5	$ 1,250
	Limestone Dispersion Monitoring	5	$ 350			$ 1,750
	Analytical Expenses	5	$ 250	per analysis	10	$ 12,500
Miscellaneous	Travel	2	$ 600	per return flight	1	$ 2,400
	Communications	1	$ 30		15	$ 450
	Food & Accommodation	5	$ 160	per day	15	$ 12,000
Consumables	Diesel for Pump	300	$ 2	/litre	15	$ 9,000
	Monitoring Consumables					$ 800
Reporting	Expenses	1	$ 950			$ 950
Contingency @ 20%						$ 100,960
				TOTAL (Ex-GST)		$ 605,760

Assumptions:
15 tonnes of limestone per hour (ie. 250 kg/minute or 4 kg/second)
1 x 10 hour shift per day
2,000 tonnes of limestone dispended in 15 days from a single location

ATTACHMENT A - COST ESTIMATES FOR ADDITION OF LIMESTONE TO LOWER LAKES

Trial of Option 1: Addition of 200 tonnes of Limestone at Wellington from existing Ferry (Costings ± 30%)

Items		Quantity	Unit Rate	Unit	Number of Days	Cost Subtotal
Personnel	Project Director	1	$ 2,800	per day	4	$ 11,200
	Project Manager	1	$ 2,200	per day	15	$ 33,000
	Pump Operator	1	$ 1,100	per day	3	$ 3,300
	Monitoring Personnel	1	$ 1,600	per day	5	$ 8,000
	Reporting Personnel	1	$ 1,280	per day	4	$ 5,120
	Ferry Operator	1	$ 700	per day	3	$ 2,100
Equipment	Ferry (Lease)	1	$ 1,500	per day	3	$ 4,500
	Pump @ 200L/s	2	$ 450	per day	3	$ 2,700
	Pump Mobilisation / Demobilisation	2	$ 600	per event		$ 1,200
	Hire Vehicles	1	$ 120	per day	5	$ 600
	Boat Hire	1	$ 400	per day	3	$ 1,200
	HDPE Limestone containment structure	1	$ 7,500			$ 7,500
Reagent	Fine grained limestone (incl. delivery)	100	$ 45	per tonne	2	$ 9,000
Monitoring	Light Aircraft	1	$ 1,500	per flight		$ 1,500
	Multi-Parameter Water Quality Meters	1	$ 150	per Meter	2	$ 300
	Limestone Dispersion Monitoring	5	$ 350			$ 1,750
	Analytical Expenses	5	$ 250	per analysis	2	$ 2,500
Miscellaneous	Travel	3	$ 600	per return flight	1	$ 2,400
	Communications	1	$ 30		3	$ 90
	Food & Accommodation	2	$ 160	per day	5	$ 1,600
Consumables	Diesel for Pump	240	$ 2	/litre	2	$ 960
	Monitoring Consumables					$ 250
Reporting	Expenses	1	$ 300			$ 300
Contingency @ 15%						$ 15,161
				TOTAL (Ex-GST)		$ 116,231

Assumptions:
8.5 tonnes of limestone per hour (ie. 140 kg/minute or 2.3 kg/second)
1 x 12 hour shift per day
200 tonnes of limestone dispended in 2 days
Approval to utilise ferry at Wellington