LOWER MURRAY LAKES PROJECT

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

Stage 2 - Preliminary Assessment of Prevention, Control and 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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RURAL SOLUTIONS SA
&
THE DEPARTMENT FOR ENVIRONMENT AND HERITAGE, SOUTH AUSTRALIA

by

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ATTACHMENTS

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 acid prevention, control and treatment options for the Lower Murray Lakes, incorporating the results of a recent assessment of limestone treatment options (Earth Systems, 2008). The Lower Murray Lakes are located at the mouth of the Murray River, approximately 75 km south-east of Adelaide (Figure 1).

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. This 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 and social 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 avoided or 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).

An acidity generation model was developed for the exposed sediments of the Lower Murray Lakes, to investigate likely acidity fluxes from the exposed sediments as a function of the volume of exposed sediment, the mass of pyrite present and the effective oxidation rate of the pyrite. Key conclusions derived from the acid balance model include:

- The total acidity generation potential for the Lower Murray Lakes (assuming a 1.0 m water drop) is around 680,000 tonnes H_2SO_4.
- Approximately 200,000 tonnes of soluble alkalinity ($CaCO_3$ equivalent) is currently available within the lakes to neutralise any acid generated from exposed shoreline sediments. A further 17,500 tonnes of alkalinity ($CaCO_3$ equivalent) enters the lake system each year via the Murray River.
- Effective oxidation rates of (i) less than 2 wt% FeS_2/year are not expected to result in any lake acidification, (ii) around 5 wt% FeS_2/year could result in a gradual decline in lake water alkalinity over approximately 10 years followed by progressive acidification of the lakes, (iii) greater than 50 wt% FeS_2/year could lead to rapid acidification of the lakes (over a period of months).
- If significant sulfate reduction is likely to occur or can be encouraged to occur within the exposed sediments, or is likely to occur or can be encouraged to occur in the basal lake sediments, then this model will be significantly overestimating the risk associated with acid generation.

A brief assessment of the water chemistry of the lakes suggests some natural remediation may be occurring in the deeper portion of the lakes. If this process is confirmed to be operating, it needs to be sustained. The process is expected to benefit from the maintenance of carbonate saturation in lake waters and sulfate reducing bacterial (SRB) activity in basal lake sediments. Maintaining carbonate saturation may require limestone addition to the lakes at some point in time, depending how much is currently stored in lake sediments. SRB activity may require significant organic carbon storage and ongoing organic carbon inputs to the basal lake sediments. The precipitation of pyrite via SRB activity may also be limited by the availability of iron, thereby requiring artificial iron oxide (eg. hematite) addition. The presence of excess iron could have the effect of accelerating sulfate removal from the water column and simultaneously speed up alkalinity addition (/acidity consumption).

A total of 30 potential management options for the Lower Murray Lakes have been identified in this report. These management options were assessed and scored in terms a) ease of implementation; b) expected (remedial) performance; c) timeframe for implementation and achievement of water quality objectives; d) cost, and e) overall risk.

The key preferred management options include maintaining limestone saturation and an excess of organic matter within the lakes to ensure ongoing natural remediation processes. This could primarily be achieved by:

- Limestone addition to lakes if necessary to maintain carbonate saturation; and/or
- Organic matter (± iron oxide) addition to lakes if necessary to maintain vigorous SRB activity in basal lake sediment.

In addition, one or more secondary management options are likely to be required, depending on their performance in a series of monitored field trials and outcomes of other proposed investigations.

Of the 30 potential management options considered in this report:

- Nine (9) limestone treatment options (that would assist with maintaining limestone saturation) were identified but not included in the detailed assessment as they were independently reviewed in Earth Systems (2008).
- Five (5) options involving addition of organic matter (± iron oxide) to the lakes were identified but not included in the detailed assessment, as initial indications from available water chemistry data indicate that sufficient organic matter may be naturally present in the lake sediments (to be confirmed).
- Six (6) "secondary management options" were selected for more detailed assessment.

The preferred (highest scoring) secondary management options largely fall into the category of "source control" rather than treatment. These involve approaches that attempt to limit acidity discharges from the exposed sediment banks by retarding sulfide oxidation or encouraging SRB activity within the exposed sediments. Such methods aim to reduce the dependence on natural remediation (or passive/active treatment).

The preferred secondary management options are listed below:

- Keep exposed sediments wet (install and fill trenches with limestone and water).
- Keep exposed sediments wet (install perforated pipes and irrigate banks).
- Keep exposed sediments wet (install and use irrigation systems).
- Cap exposed sediments.
- Add organic matter to lakes (revegetate upwind shores).
- Add organic matter to exposed sediments (revegetate exposed sediments).

A preliminary assessment of the expected capital and operating costs associated with each of the preferred secondary management options is provided in this report. Since the exposed sediment banks represent a very substantial area, it is proposed that the preferred secondary management options be only applied to high-risk segments of the lake sediments.

Hence, the estimates provided indicate costs per unit shore length or exposed sediment area.

The relative merit of the preferred management options is difficult to quantify as there are critical data gaps in our understanding of the lake acidification processes. Initial indications are that some acid production (sulfate addition) and acid neutralisation (including sulfate reduction) is occurring in the lakes. The scale and speed of the lake acidification as a function of declining lake water levels remains poorly understood. To develop further understanding of these issues and guide the selection of appropriate ASS management options, the following work program is recommended:

1. Investigation of lake sediment geochemistry.
2. Investigation of the proportion of sulfate contributed by recent sulfide oxidation processes based on sulfur and oxygen isotope geochemistry.
3. Establishment of a field monitoring and laboratory test work program to develop further understanding of the processes of acid generation, transport, and in-situ neutralisation / reduction within sediments and lake waters.
4. Field trials of secondary ASS management options (utilising the monitoring network proposed above).

Detail on the proposed work program is provided in this report.

RECOMMENDATIONS

Key recommendations arising from this study are outlined below:

- Conduct a more rigorous assessment of the available lake and river water chemistry to develop a better understanding of the processes influencing chemical changes. Provide this detailed assessment to all stakeholders every time new data is available.
- Undertake to monitor and maintain carbonate saturation in water within the lakes. This will involve routine assessment of saturation indices from water chemistry.
- Quantify the mass of available organic and inorganic carbon, iron and iron sulfide within the basal lake sediments and redress potential shortfalls or imbalances if necessary.
- Assess the potential to use sulfur (S) and oxygen (O) isotope analysis to quantify the bulk sulfide oxidation rates for the lake system, and assist with quantification of suitable management strategies.
- Implement the future work program detailed in Attachment C in order to fill critical data gaps.
- Utilise 3-5 of the proposed instrumented sediment banks (refer to Attachment C) to trial some of the preferred management options for the exposed sediments.
- Use the results of the future work program and stable isotope analytical program to refine the acidity generation, lake water quality and remediation models.

1.0 INTRODUCTION

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 acid prevention, control and treatment options for the Lower Murray Lakes, incorporating the results of a recent assessment of limestone treatment options (Earth Systems, 2008). The Lower Murray Lakes are located at the mouth of the Murray River, approximately 75 km south-east of Adelaide (Figure 1).

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 sulfide oxidation. In the Lower Murray Lakes soils, sulfides are generally present in the form of pyrite minerals (FeS_2) and iron monosulfide (FeS). The latter commonly occurs as a "monosulfidic black ooze" (MBO). "Sulfuric" and "sulfidic" soils are often referred to as Acid Sulfate Soils (ASS) and Potential Acid Sulfate Soils (PASS), respectively. For simplicity, the term "ASS" is used more generally in this report to describe both sulfuric (ASS) and sulfidic (PASS) soils. Refer to Attachment A for further information, including reactions, involved in acid generation due to sulfide oxidation.

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. This 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 issue for the Lower Murray Lakes.

The environmental significance of the Lower Murray Lakes was formally acknowledged in 1985, with their inclusion on the Ramsar List of Wetlands of International Importance (Haese et al, 2008). The lakes are also used extensively for agriculture, fishing, recreation, etc.

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 and their characteristics are summarised in Table 1.

This report investigates management options that could achieve long-term minimisation / suppression of acid and metalliferous drainage discharging from ASS into the lakes. The management options are focussed on the four sites identified in Table 1, but are potentially applicable to other affected sites around the perimeter of both lakes.

Plate 1. Aerial view of Lake Albert just north of Meningie. Sediments along this shoreline are considered to be among the highest risk ASS in 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).

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

Site ID	Site Name	Location	Soil type	Dimensions*		
				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

* Based on GIS data for lake water levels of -0.5 m AHD, provided by Marvanek (2008).

Plate 2. Lake water levels have decreased by around 1 metre over the last 2 years. The receding shoreline near Meningie is evident in the image above.

Figure 1. Location map.

2.0 SCOPE OF WORKS

The objective of this report is to assess the feasibility of potential options for management of acid sulfate soils (ASS) on the Lower Murray Lakes, South Australia.

The scope of the assessment includes:

1. Review of existing strategies for managing ASS (prevention, control and treatment) including any examples of the success or failure of these approaches at other sites.
2. Review of existing water chemistry and other environmental datasets for the Lower Murray Lakes.
3. Development of an acidity generation model to investigate the likelihood, timing and scale of lake acidification.
4. Identification of available options for acid prevention, control and treatment, potentially applicable to the Lower Murray Lakes.
5. Preliminary assessment of ASS management approaches and options, based on ease of implementation, expected performance, timeframe for implementation and achievement of water quality objectives, costs and risks.
6. Detailed assessment and preliminary costing of ASS management approaches and options.
7. Identification of critical data gaps that are limiting evaluation and implementation of the most appropriate management option.
8. Identification of organisations that could facilitate a broader management program and their roles in such a program.

3.0 METHODOLOGY

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

- Review of existing strategies for managing ASS (Section 3.1).
- Site visit (Section 3.2).
- Review of existing information (Section 3.3), including a detailed assessment of the available water chemistry data.
- Development of an acidity generation model for the Lower Murray Lakes (Section 3.4).
- Identification and preliminary assessment of ASS management approaches and options for the Lower Murray Lakes (Section 3.5).
- Detailed assessment of preferred ASS management approaches and options for the Lower Murray Lakes (Section 3.6).
- Identify critical data gaps that are limiting evaluation of the most appropriate management option (Section 3.7)
- Identification of organisations that could facilitate a broader management program and their roles in such a program (Section 3.8).

3.1 REVIEW OF EXISTING STRATEGIES FOR MANAGING ASS

A literature review of common strategies for managing acid sulfate soils, within Australia and internationally, was conducted. Strategies for prevention, control and treatment of ASS were all considered, and those considered potentially relevant to the Lower Murray Lakes were assessed as described in Section 4.1.

3.2 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.

3.3 REVIEW OF EXISTING INFORMATION

3.3.1 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

3.3.2 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	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	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	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	2008
Literature Review: Seawater Incursion Lake Alexandrina	Maunsell Australia	Unpublished report	2008
Literature Review: Acid Sulfate Soil Mitigation Using Organic Mulch	Maunsell Australia	Unpublished report	2008
Water Monitoring Report – Ambient Water Quality Monitoring of Lake Alexandrina and Lake Albert Report No 1	n/a	Environment Protection Agency	1998

3.3.3 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).
- Soil geochemistry data for the Lower Murray Lakes (CSIRO, 2008).
- Water level data for the Lower Murray Lakes (DWLBC, 2008).
- Stage-volume and stage-area relationships for the Lower Murray Lakes (Mosley, 2008).
- Tributary flow data for Angus River (March 1969 – December 2006), Bremer River (May 1973 – March 2007) and Finniss River, Currency Creek and Tookayerta (January 1997 – December 2006 (DWLBC, 2008).

- Water quality data for the Lower Murray Lakes and key tributaries including the Murray River, Finniss River, Bremer River and Angas River (sourced from EPA SA, DWLBC, SA Water and Adelaide University). Refer to key monitoring locations in Figure 2.

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

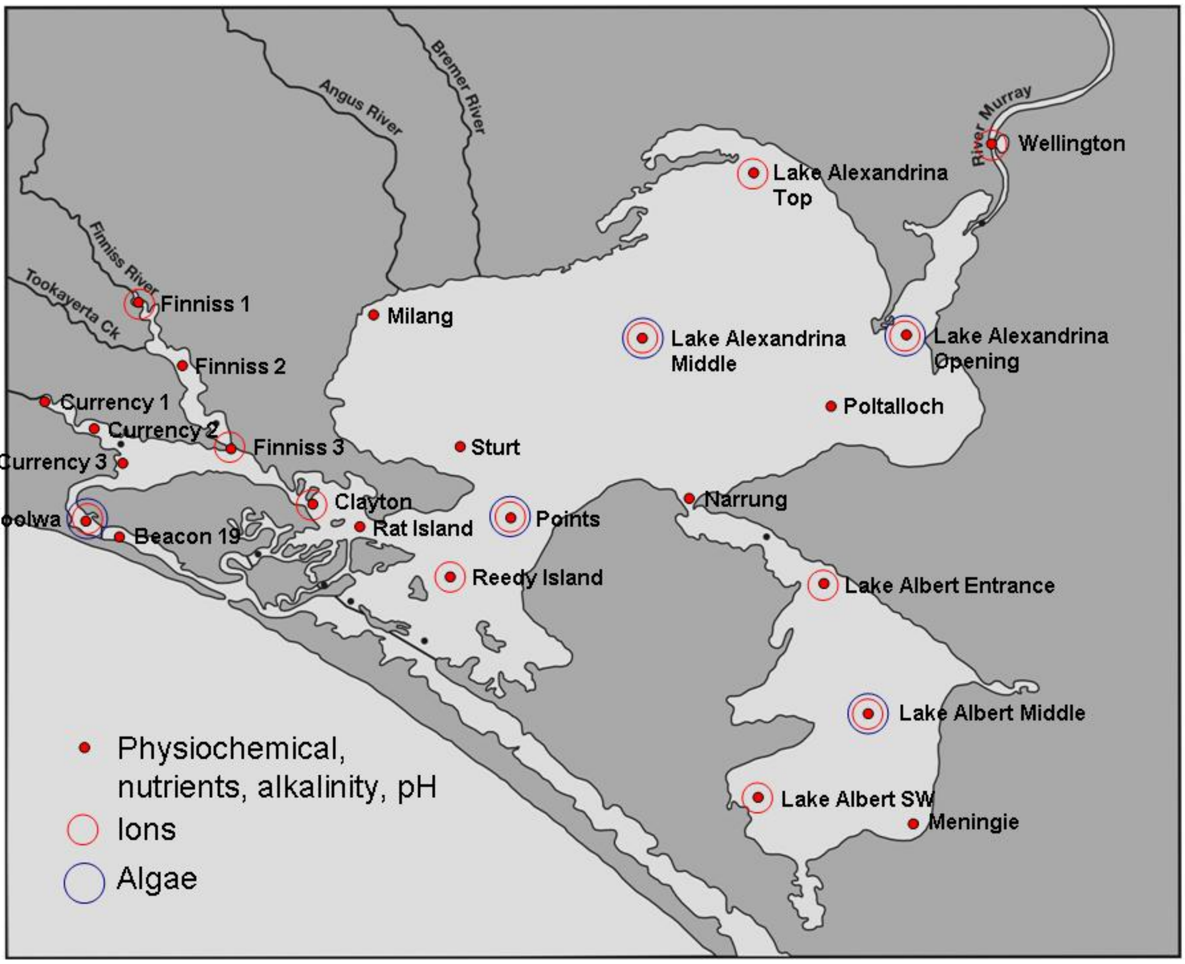

Figure 2. Key water quality monitoring sites in the Lower Murray Lakes and surrounding region. Figure courtesy of Robin Leaney from DWLBC.

3.4 DEVELOPMENT OF AN ACIDITY GENERATION MODEL

An acidity generation model was developed for the exposed sediments of the Lower Murray Lakes, using existing soil geochemical data provided in Fitzpatrick et al (2008). The acidity generation model was developed to investigate likely acidity fluxes from the exposed sediments as a function of the volume of exposed sediment, the mass of pyrite present and the effective oxidation rate of the pyrite.

3.5 IDENTIFICATION AND PRELIMINARY ASSESSMENT OF MANAGEMENT OPTIONS

A number of ASS management options were considered for the Lower Murray Lakes.

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).
- Timeframes for implementation and achievement of water quality objectives.
- Capital and operating costs of implementation.
- Risk.

Detailed assessment of the preferred management options was then conducted, as described in Section 3.6.

3.6 DETAILED ASSESSMENT OF PREFERRED MANAGEMENT OPTIONS

A detailed assessment of the preferred management options for the Lower Murray Lakes was conducted. This involved the development of more detailed methodologies for implementing the preferred options. Concept drawings were prepared to illustrate these methodologies and capital and operating costs were estimated.

3.7 IDENTIFICATION OF CRITICAL DATA GAPS AND FUTURE WORK PROGRAM

To assist in the selection of appropriate ASS management options for the Lower Murray Lakes, a number of critical data gaps were identified. Future work that would be required to obtain such critical data has also been documented in this report.

3.8 IDENTIFICATION OF ORGANISATIONS THAT COULD FACILITATE A BROADER MANAGEMENT PROGRAM

Organisations that could facilitate a broader ASS management program for the Lower Murray Lakes were identified, including their roles in such a program. These organisations include government organisations and technical specialists.

4.0 RESULTS

4.1 REVIEW OF EXISTING ASS MANAGEMENT STRATEGIES

A comparison of existing strategies for ASS management is provided in Table 4. The comparison is based on ease of implementation, expected performance, timeframe for implementation and achievement of water quality objectives, costs and risks. Strategies that may be applicable to the Lower Murray Lakes are described in further detail in Sections 3.5 and 3.6.

Table 4. Existing strategies for management of acid sulfate soils.

Strategy	Ease of Implementation	Expected Performance	Timeframe for Implementation & Achievement of Water Quality Objectives	Costs	Risks	Source
PREVENTION						
Avoidance or minimisation of disturbance						
Preventing exposure of sulfidic minerals to oxidation prevents acid generation. Care should be taken to avoid or minimise disturbance of acid sulfate soils wherever possible.	Easy	Good	N/A	None	None	6, 7
Seawater submergence						
Seawater submergence prevents oxidations of pyrite minerals and acid generation. Sea water also has buffering capacity to neutralise existing acid.	Easy. Tidal fluctuations remove the need for pumping.	Poor	N/A	None	H_2S gas emissions, ecological impacts, loss of agricultural land leading to social and economic impacts, loss of bicarbonate from seawater.	6

Strategy	Ease of Implementation	Expected Performance	Timeframe for Implementation & Achievement of Water Quality Objectives	Costs	Risks	Source
Freshwater submergence						
Maintaining water levels prevents exposure of sulfidic material beneath the soil surface. For farmland, groundwater loss can be minimised by using wide shallow drains, which allow surface water to soak into the soil partially before draining. Water levels can also be artificially raised using barriers or locks.	Variable	Good	N/A	Minimal	If sulfidic material has already begun to oxidise there is a risk that raising water levels will mobilise acidity.	6
CONTROL						
Retard oxidation						
Artificially raising groundwater levels to cover sulfidic mineral through freshwater ponding or the use of locks prevents exposure of sulfidic material and acid generation.	Variable	Good	Often rapid	Variable	If the sulfidic minerals have already begun to oxidise this technique may mobilise acidity.	1, 4, 5, 6
If sulfidic material is disturbed it is possible to control acid generation by reburial of the material below the water table. This technique relies on maintaining the water table above the sulfidic material.	Often difficult	Good	Variable	High	Burial of partially sulfuric material can generate groundwater contamination.	5
Reverse oxidation						
Adding organic matter to the soil or water can help re-establish reducing conditions thereby encouraging pyrite precipitation. Organic matter can also retard or prevent oxidation by consuming oxygen.	Easy	Moderate to good	Generally rapid	Generally low	The sulfides produced will be susceptible to rapid oxidation if exposed to air.	5, 8

Strategy	Ease of Implementation	Expected Performance	Timeframe for Implementation & Achievement of Water Quality Objectives	Costs	Risks	Source
TREATMENT						
Carbonate neutralisation in-situ						
A once-only addition of limestone to soils can provide alkalinity to neutralise acid in-situ. A disadvantage of this technique is that limestone may become inactivated over time due to passivation by neutralisation precipitates.	Variable	Moderate to good	Variable	Can be expensive	Acidity production may often continue if insufficient limestone is added. Toxic neutralisation products can be generated and may be difficult to manage.	7, 5
Limestone can be periodically added to soils to neutralise acidity as it is generated. This approach tends to provide for more efficient use of limestone than a once-only dose.	Variable	Moderate to good	Variable	Moderate to high	Toxic neutralisation products can be generated and may be difficult to manage.	5, 7
Sulfidic material can be hydraulically separated from less dense material using mechanical methods, such as sluicing or hydrocycloning. This reduces the mass of material that must be managed for acid generation. The separated sulfidic material must be managed by one of the techniques outlined above. This technique is effective in areas where the sediments have low organic matter content and contain less than 10–20% clay and silt. The separated sulfidic material is most appropriately managed by submergence.	Difficult	Poor	Long time frame	High		7
Passive water treatment						
Permeable Reactive Barriers (PRB) contain organic matter and/or limestone and are installed in groundwater flow paths. Acidic groundwater is neutralised as it passes though the PRB.	Moderate to difficult	Moderate to good in limited circumstances	Medium term	Often high	Only capable of dealing with low acidity loads. Can block flow in some circumstances.	2

Strategy	Ease of Implementation	Expected Performance	Timeframe for Implementation & Achievement of Water Quality Objectives	Costs	Risks	Source
Limestone can be added to drains, tributaries or preferential water flow pathways to neutralise acid drainage and acid groundwater before it reaches a water body.	Moderate	Variable. Depends on water chemistry.	Short time frame	Moderate to high	Minimal. Blockage of drains possible with some acid water.	6, 9
Sea water has natural acidity buffering capacity which can help neutralise acid. Allowing sea water to mix with acidic water can neutralise acid.	Easy	Variable	Rapid	Minimal	Loss of seawater bicarbonate can impact upon marine ecosystems.	6
Active water treatment						
Limestone can be added to water using several different techniques. For further details on these techniques refer to Earth Systems (2008).	Variable	Variable	Short time frame	Often high	Minimal.	3
OTHER TECHNIQUES						
Accelerated leaching/aging						
Leaching or aging involves accelerated sulfide oxidation and rapid leaching of acid salts with subsequent neutralisation.	Difficult	Moderate	Medium term	High	Potential for uncontrolled releases.	6, 9
COMBINED TECHNIQUES						
Two or more of the above techniques can be combined. For example, freshwater submergence to prevent acid generation can be combined with limestone addition to neutralise existing acidity.	Variable	Variable	Variable	Variable		

Sources

1. Arrowsmith & Smith (2005)
2. Golab et al (2006)
3. Green et al (2005)
4. Henderson & Tulau (Undated)
5. Hicks et al (2001)
6. National Heritage Trust (2000)
7. Queensland Government Department of Natural Resources and Water (2008)
8. Sanders et al (2003)
9. Thomas et al (2003)

4.2 REVIEW OF EXISTING INFORMATION

4.2.1 Topography / bathymetry

A bathymetric map of the Lower Murray Lakes is presented in Figure 3. The lake water levels on 1 September 2008 were -0.272 m above sea level (ASL) and -0.176 m ASL at Milang (Lake Alexandrina) and Meningie (Lake Albert), respectively. The lake boundaries therefore lie within the +0.1 m ASL (brown contour line) and -0.6 m ASL (blue contour line) in Figure 3. Refer to Section 4.2.4 for recent trends in lake water levels.

As shown in Figure 3, Lake Alexandrina is generally less than 3 m deep with significant areas less than 2 m deep. Lake Albert is shallower than Lake Alexandrina, with water depths generally ranging from 1-2 m.

The shorelines of both lakes have very shallow gradients, typically in the range 1:1500 to 1:5000. If the lake water levels continue to decline, significant areas of shoreline materials that were previously submerged will become exposed, particularly around the perimeter of Lake Albert and the northern and southern shorelines of Lake Alexandrina. For example, a water level decrease of 0.3 m from current levels would correspond to an increased shore width of around 0.5-1.5 km in some areas.

The estimated water volumes and surface areas of exposed lake sediments associated with different water levels in Lake Alexandrina and Lake Albert are presented in Table 5.

Table 5. Estimated water volumes and surface areas of exposed lake sediments associated with different water levels in the Lower Murray Lakes (Mosley, 2008).

Water level (m AHD)	Lake Alexandrina		Lake Albert		Total	
	Volume (GL)	Surface area of exposed sediment (ha)	Volume (GL)	Surface area of exposed sediment (ha)	Volume – total (GL)	Surface area of exposed sediment (ha)
0.75	1,661	0	271	0	1,932	0
0	1,201	4,868	147.9	1,500	1,348.9	6,368
-0.5	909	10,034	76.4	3,525	985.4	13,559
-1	642	14,976	21.7	7,459	663.7	22,435
-1.5	402	22,682	0.3	15,622	402.3	38,304

The areas indicated in yellow and green in Figure 3 will be the first to become exposed upon further lowering of lake water levels. The risk of AMD generation from these areas will primarily depend on their soil composition, specifically, the abundance of sulfidic materials exposed to air, and the intrinsic rate of sulfide oxidation. Refer to the discussion of soil characteristics in Section 4.2.6.

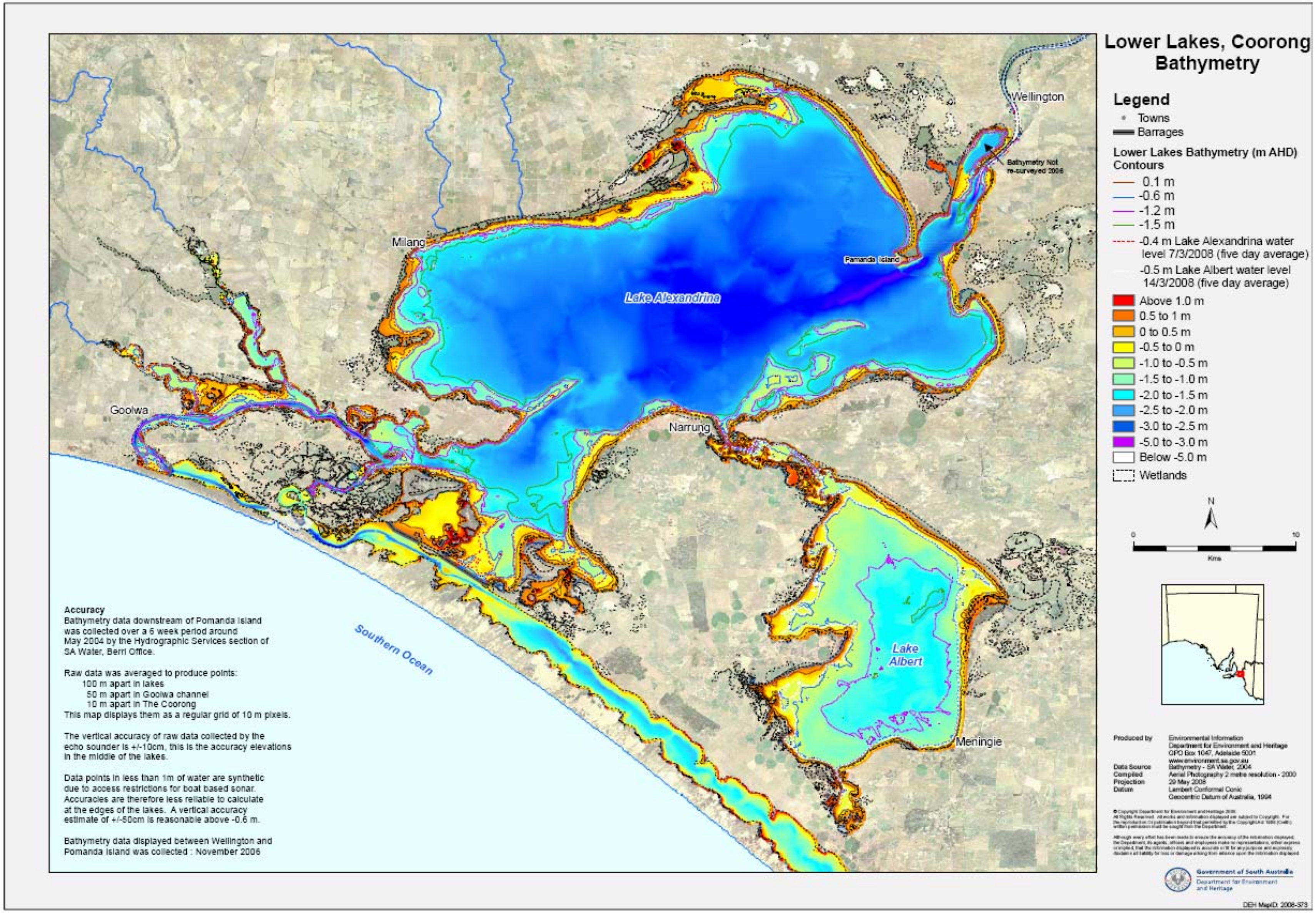

Figure 3. Bathymetry of the Lower Murray Lakes (DEH, 2008).

4.2.2 Regional geology

The regional geology of the Lower Murray Lakes area is shown in Figure 4.

Basement lithologies surrounding the lakes range in age from Cambrian to Ordovician, and include granites, mafic intrusives and volcanic rocks that have been subjected to the Dalamerian Orogeny. The metamorphic basement is only occasionally exposed and is most commonly unconformable overlain by Early to Mid Tertiary marine limestone and coastal to estuarine sands in the northern portion of the lakes and marginal to the lower reaches of the Murray River (ie. Murray Group). Further south, the basement is draped by Quaternary aeolian calcareous sand and calcrete of the Bridgewater Formation. This formation is succeeded by Quaternary aeolian quartz-rich sands, and then coastal fossiliferous mud, quartz sand, limestone and aeolian sands.

The Bridgewater Formation outcrops widely in the southern half of the Lower Lakes, and is unconformably overlain by the more recent sediment accumulations within the lakes. The lake sediments include fine to medium grained quartz-rich sands, organic-rich muds and narrow ligneous horizons.

The widespread occurrence of both Tertiary and Quaternary limestone bearing lithologies in the Lower Lakes catchment is responsible for the elevated alkalinity in both river and lake waters, and some groundwater feeding the lakes.

4.2.3 Rainfall, evapotranspiration and wind speed

The average annual rainfall in the vicinity of the Lower Murray Lakes is 336.9 mm per year and average annual evapotranspiration is 1173.6 mm per year. These figures are based on data collected at four sites: Mypolonga, Langhorne Creek, Currency Creek and Narrung, over a three year period from October 2005 to September 2008 (SA Murray Darling Basin Natural Resources Management Board, Undated).

Graphs showing monthly variations in rainfall and evapotranspiration are presented in Figures 5 and 6, respectively. The locations of rainfall and evapotranspiration monitoring stations are shown in Figure 1.

Average monthly rainfall data in the Lower Murray Lakes region indicate that rainfall was highest from late autumn to the end of winter (April to August), as presented in Figure 5. For example, the highest rainfall for Narrung occurred in August, with an average of 61.2 mm, compared to just 2.3 mm in February. The month of highest average rainfall at Currency Creek was June, while the highest rainfall for both Mypolonga and Langhorne Creek occurred in April. February recorded the lowest monthly average rainfall figures from all monitoring sites, ranging from 2.3 mm at Narrung to 10.3 mm at Currency Creek.

Evapotranspiration is clearly highest during the summer months of December and January, as shown in Figure 6. Peak evaporatranspiration occurred in December and January for all monitoring sites across the region, averaging 162.5 mm and 160.7 mm per month, respectively. Evapotranspiration was significantly lower during the winter months, with the lowest average monthly evapotranspiration, 30.6 mm, occurring in June.

The combination of low rainfall and high evapotranspiration during the summer months correspond to lower water levels in the Lower Murray Lakes (refer to Section 4.2.4).

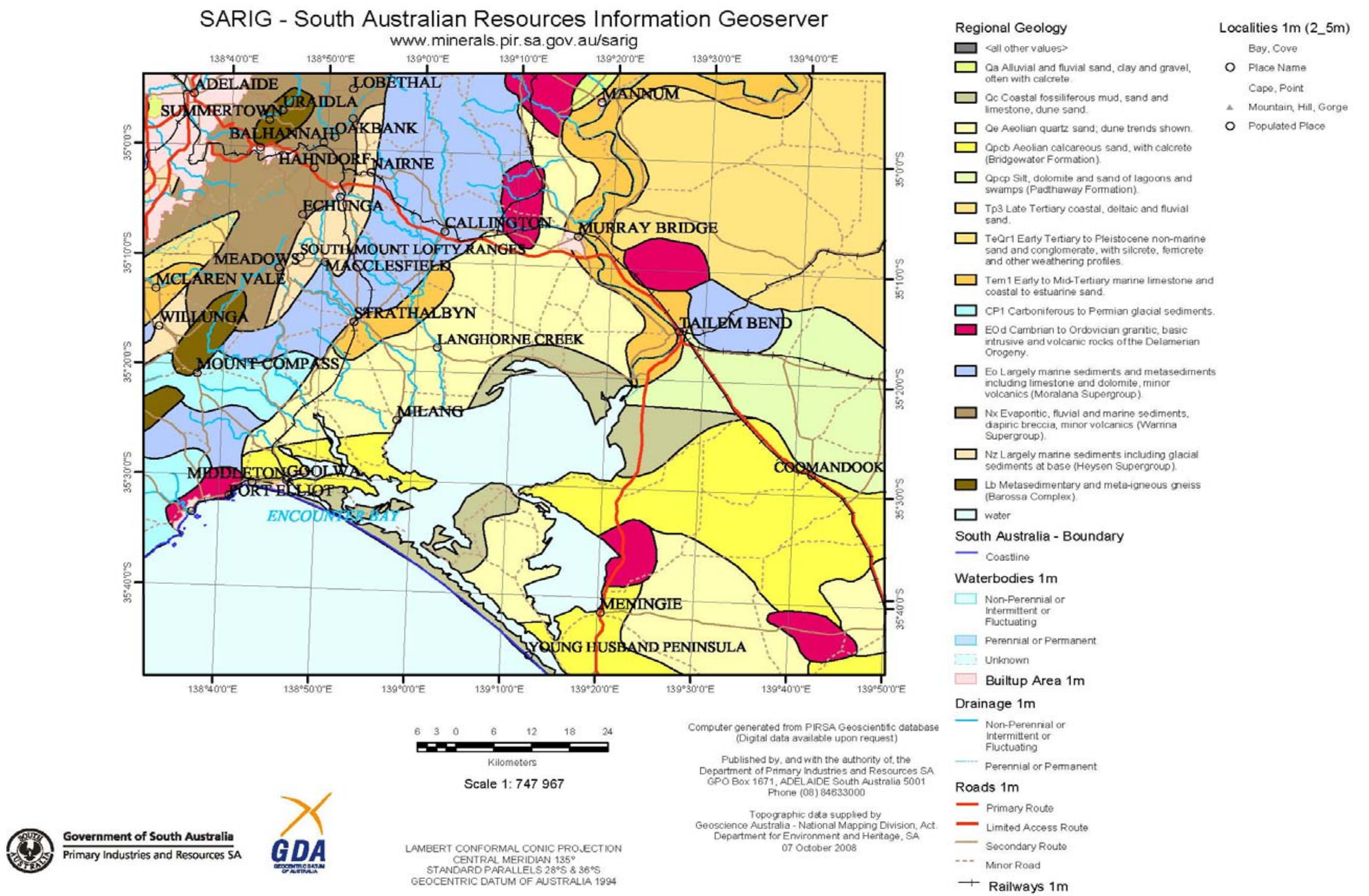

Figure 4. Geology of the Lower Murray Lakes and surrounding region (SARIG, 2008).

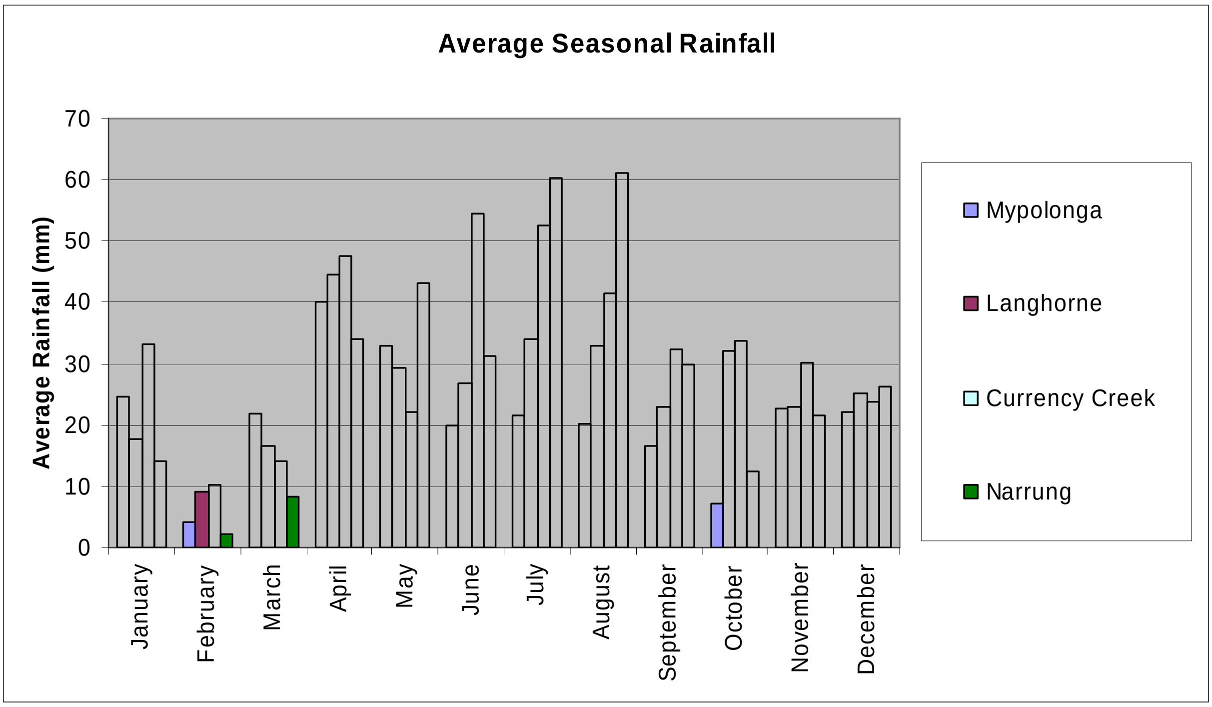

Figure 5. Average monthly rainfall at Mypolonga, Langhorne Creek, Currency Creek and Narrung.

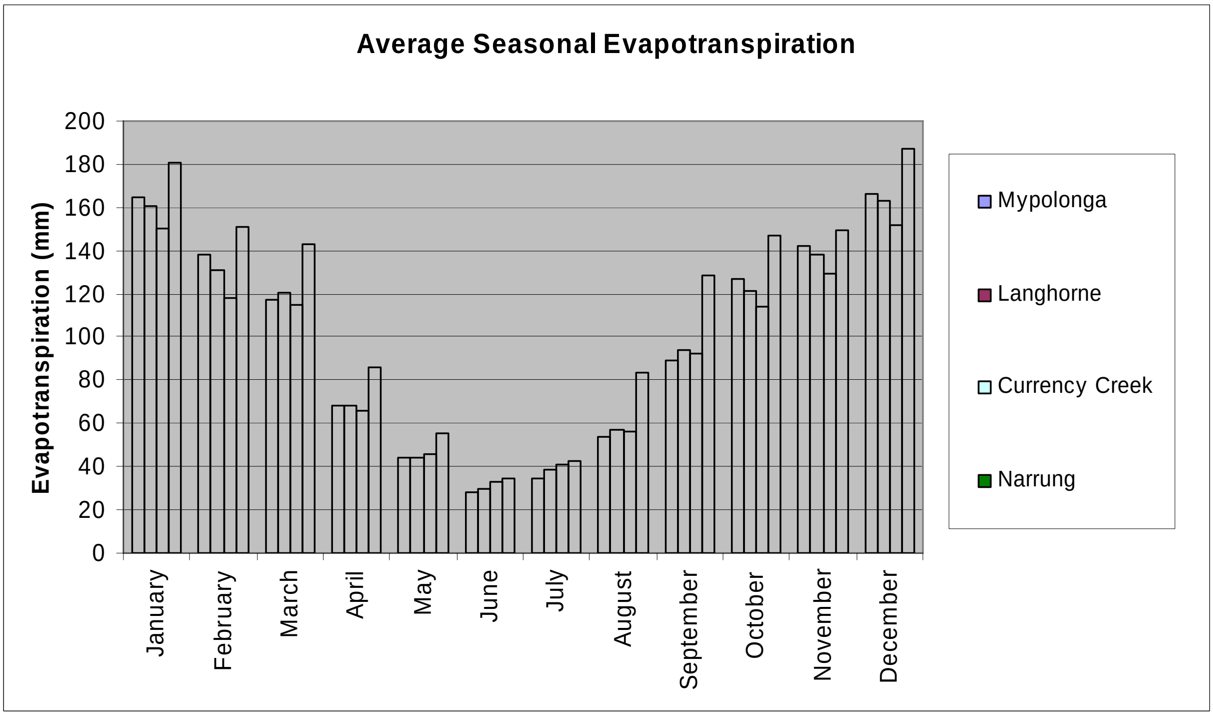

Figure 6. Average monthly evapotranspiration at Mypolonga, Langhorne Creek, Currency Creek and Narrung.

Wind speed and wind direction data measured at the Hindmarsh Island weather station, for the 12 month period from October 2007 to September 2008, are summarised in Table 6. The location of this weather station is shown in Figure 1.

The average monthly wind speeds ranged from 15 kilometres per hour (km/h) to 31 km/h with a 12 month average of 23.2 km/h, as shown in Table 6. The peak wind gusts throughout this 12 month period ranged from 19 km/h to 107 km/h with the average peak wind gust of 46.4 km/h.

The dominant wind directions recorded at the Hindmarsh Island weather station were generally South (S) and South South West (SSW), as shown in Table 6.

Table 6. Wind speed and direction over 12 months (October 2007 – September 2008).

Month	**Peak Wind Gust (km/h)**			**Average Wind Speed (km/h)**		**Maximum Wind Speed and Direction**			
	Min	**Max**	**Ave**	**9am**	**3pm**	**Wind speed (km/h), 9am**	**Wind direct-ion, 9am**	**Wind speed (km/h), 3pm**	**Wind direct-ion, 3pm**
October 2007	28.0	80.0	50.3	25.8	28.5	54	NW	52	WNW
November 2007	24.0	74.0	41.7	19.9	27.3	48	S	43	S
December 2007	28.0	81.0	46.8	21.3	27.9	54	SSW	46	SW
January 2008	37.0	74.0	49.0	23.9	30.2	46	SSW	46	S
February 2008	31.0	72.0	49.0	22.7	30.9	43	SSE/ SE	46	S
March 2008	24.0	69.0	45.0	18.1	25.3	37	SSW	44	NW
April 2008	19.0	107.0	42.2	17.0	22.2	46	W	39	W
May 2008	19.0	83.0	34.4	15.0	19.6	54	SSW	46	WSW
June 2008	19.0	98.0	46.7	17.4	24.5	37	SW	54	NNW
July 2008	20.0	76.0	50.2	21.0	23.5	39	S	54	SW
August 2008	24.0	81.0	52.0	21.9	25.1	43	S	43	SSW
September 2008	24.0	87.0	48.8	19.8	27.2	46	SW	52	WSW
12 Month Average	**24.8**	**81.8**	**46.4**	**23.2**		**45.6**	**-**	**47.1**	**-**

4.2.4 Lake water levels

Figure 7 shows the long term trends in the water level in Lake Alexandrina as measured monthly from May 1994 to October 2008. As shown in Figure 7, over the 12 year period from 1994 to 2006, the water level largely remained between 0.4 and 0.9 m ASL except for a brief period from February to June 2003 when the water level temporarily dropped below 0.4 m during drought conditions. Since September 2006 the water level has declined significantly, and in May 2008, the water level reached its lowest point in 14 years at -0.47 m ASL.

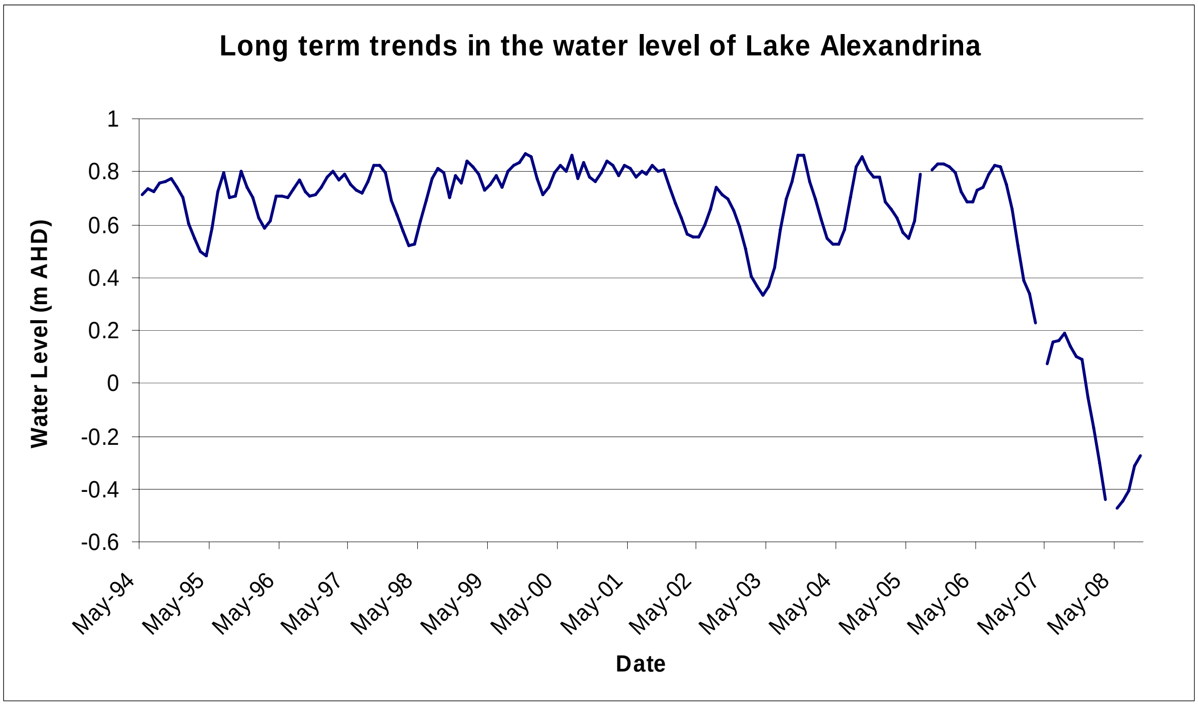

Figure 7. Long term trends in the water level of Lake Alexandrina.

Water levels in Lake Alexandrina and Lake Albert, measured on a monthly basis from April 2004 to October 2008, are graphed in Figure 8.

The water level in both lakes fluctuated between 0.5 and 0.9 m ASL prior to the end of 2006. From December 2006 to March 2007, the water levels dropped to around 0.2 m ASL. The water levels recovered slightly during the winter of 2007 but subsequently fell to a minimum of around -0.5 m AHD in both lakes. Over the winter months of 2008, the water levels have recovered to around -0.3 m ASL in Lake Alexandrina and -0.2 m ASL in Lake Albert, although they remain well below historic water levels prior to 2007, as shown in Figure 8. The latest rise in water levels is associated with increased releases to the Murray River at Blanchetown Weir (target flow of 900 ML/day), combined with higher rainfall and lower evaporative losses during the winter months (MDBC, 2008).

It is assumed that water levels in Lake Albert have followed a similar long term trend as those in Lake Alexandrina (Figure 7) based on the relatively consistent levels recorded in both lakes from April 2004 onwards. More recently, however, the Lake Albert water level has, at times, exceeded that in Lake Alexandrina by up to 0.1 m. These differences are presumably as a result of water pumping from Lake Alexandrina to reduce the risk of acidification in Lake Albert (MDBC, 2008).

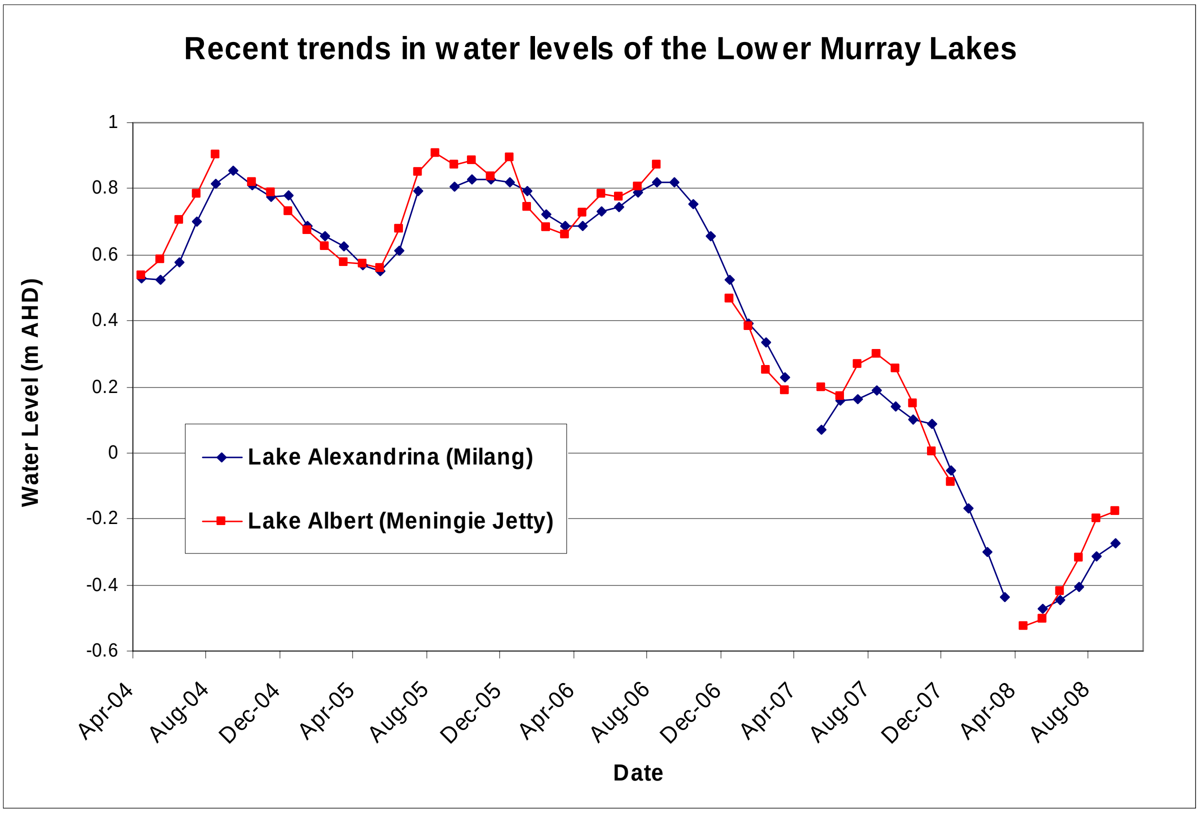

Figure 8. Recent trends in water levels of the Lower Murray Lakes.

4.2.5 Hydrogeology

A detailed description of the hydrogeology of the Lower Murray Lakes and surrounding region was provided by Haese et al (2008). Relevant sections have been extracted below:

> *"The Coorong and Lower Lakes are located in the south-western edge of the Murray Geological Basin. The significant aquifers (or geological formations which hold water) in this region are the Quaternary and Murray Group Limestone sequences, and the deeper confined Renmark Group sands. The limestone sequences are in good hydraulic connection (Barnett 1994) and form the shallow watertable aquifer. The Renmark and Murray Groups are separated by a series of confining clay aquitards (Brown et al 2001).*
>
> *A hydrogeological map of the Lower Lakes and Coorong region (Figure 9) and the associated description have been derived from three previously compiled map sheets (Barnett 1991, Barnett 1994, Cobb and Barnett 1994). Major processes such as groundwater recharge and discharge, dryland salinisation, irrigation and groundwater / surface water interaction were identified within this region. The map uses a matrix approach to display salinity and yield characteristics for the shallow aquifer.*
>
> *As was originally concluded by O'Driscoll (1961), groundwater flows radially from the zone of recharge at Dundas Plateau in the east, northward to the Murray River (Tyler et al 1983) or westward, discharging to the Coorong, the Lower Lakes or low-lying salinised areas (Barnett, 1994), demonstrated by the potentiometric contours (Figure 9).*

On the western side of Lake Alexandrina, the watertable is within a Quaternary clay which overlies and semi-confines the limestone aquifer. Elsewhere in low-lying areas around the Lower Lakes, the watertable occurs in organic-rich clays which were deposited when the Lower Lakes expanded in response to a higher sea level about 6000 years ago. These areas contain highly saline groundwater (>100 000 milligrams per litre) due to strong evaporative discharge which has lowered the watertable below sea level. The watertable contours show that these areas are the focus for regional groundwater discharge in preference to the Lower Lakes which are at a higher level of 0.75 metres Australian Height Datum (AHD). Lower Lake levels have subsequently declined in the 14 years since the publication of these map sheets."

Haese et al (2008)

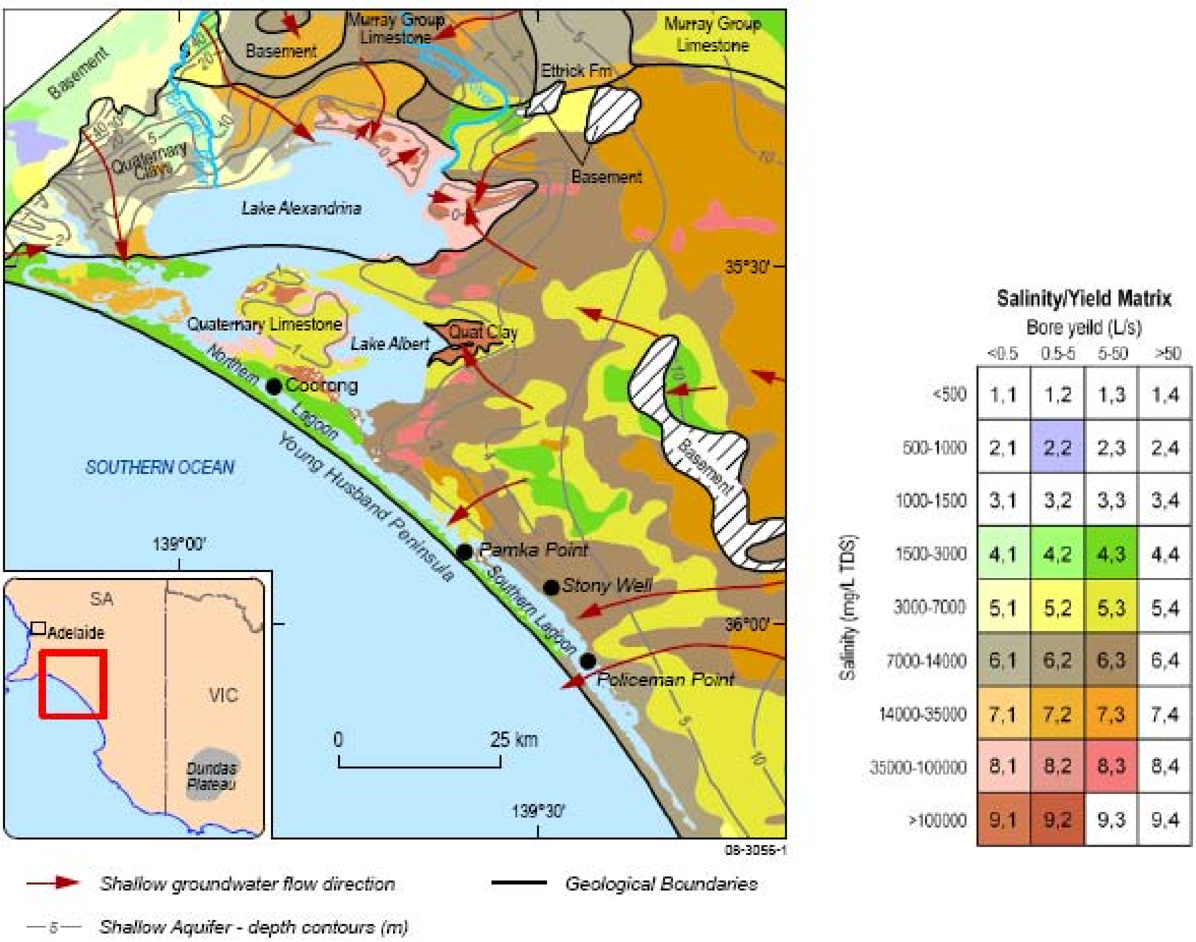

Figure 9. Hydrogeological map of the Coorong Lagoon and Lower Lakes Region (Haese et al, 2008).

4.2.6 Soil characteristics

A total of 103 representative soil profiles surrounding the Lower Murray Lakes were recently examined by Fitzpatrick et al (2008). Of these samples:

- 20 were extremely high risk of acid generation;
- 26 were very high risk;
- 21 were moderate risk; and
- 8 were low risk.

Therefore, more than 70% of the profiles investigated were considered to represent a moderate (or greater) risk of acid generation (Fitzpatrick et al., 2008).

Fitzpatrick et al (2008) identified three broad categories of ASS, comprising 16 subtypes, in the region surrounding the Lower Murray Lakes. The estimated distribution of these soils at drought water levels (-0.5 m AHD) is shown in Figure 10. Descriptions for the abbreviations used in Figure 10 are provided in Table 7.

As shown in Figure 10, with water levels at -0.5 m AHD the perimeter of Lake Alexandrina is dominated by waterlogged sulfidic hydrosols, characterised by a low (6-70%) probability of ASS occurrence, with waterlogged sulfidic organic soils further from shoreline. An area of drained sulfuric hydrosols near Point Sturt, shown in pink, is considered to represent a high risk ASS (also shown in Figure 1). The shoreline sediments adjacent to Poltalloch are also understood to represent a significant ASS risk (see Figure 1; pers. comm. Carter, M., 2008). Areas of waterlogged MBO sulfidic hydrosols and drained MBO hydrosols are generally confined to the southern-most extent of the lake near the Coorong.

The perimeter of Lake Albert is mainly comprised of waterlogged sulfidic hydrosols, characterised by a high (>70%) probability of ASS occurrence, with water levels at -0.5 m AHD. There are significant areas of drained sulfuric hydrosols (high risk ASS sites) on the east side of the lake north of Meningie and also on the west side of the lake near Campbell Park (also shown in Figure 1). The lake perimeter is otherwise dominated by sulfidic hydrosols and vertosols, with the latter soil type primarily found on the shores of Albert Passage, between the two lakes. Zones of waterlogged MBO sulfidic hydrosols and drained MBO hydrosols were identified at the north-eastern and southern extents of Lake Albert, respectively.

Simpson et al (2008) found that when dried samples of the soils were rewetted, concentrations of metals such as Al, Mn, Ni, Cu, Zn Co and Cd exceeded water quality guidelines. As expected, there was generally a significant relationship between pH and dissolved metal concentrations in the ASS leachate.

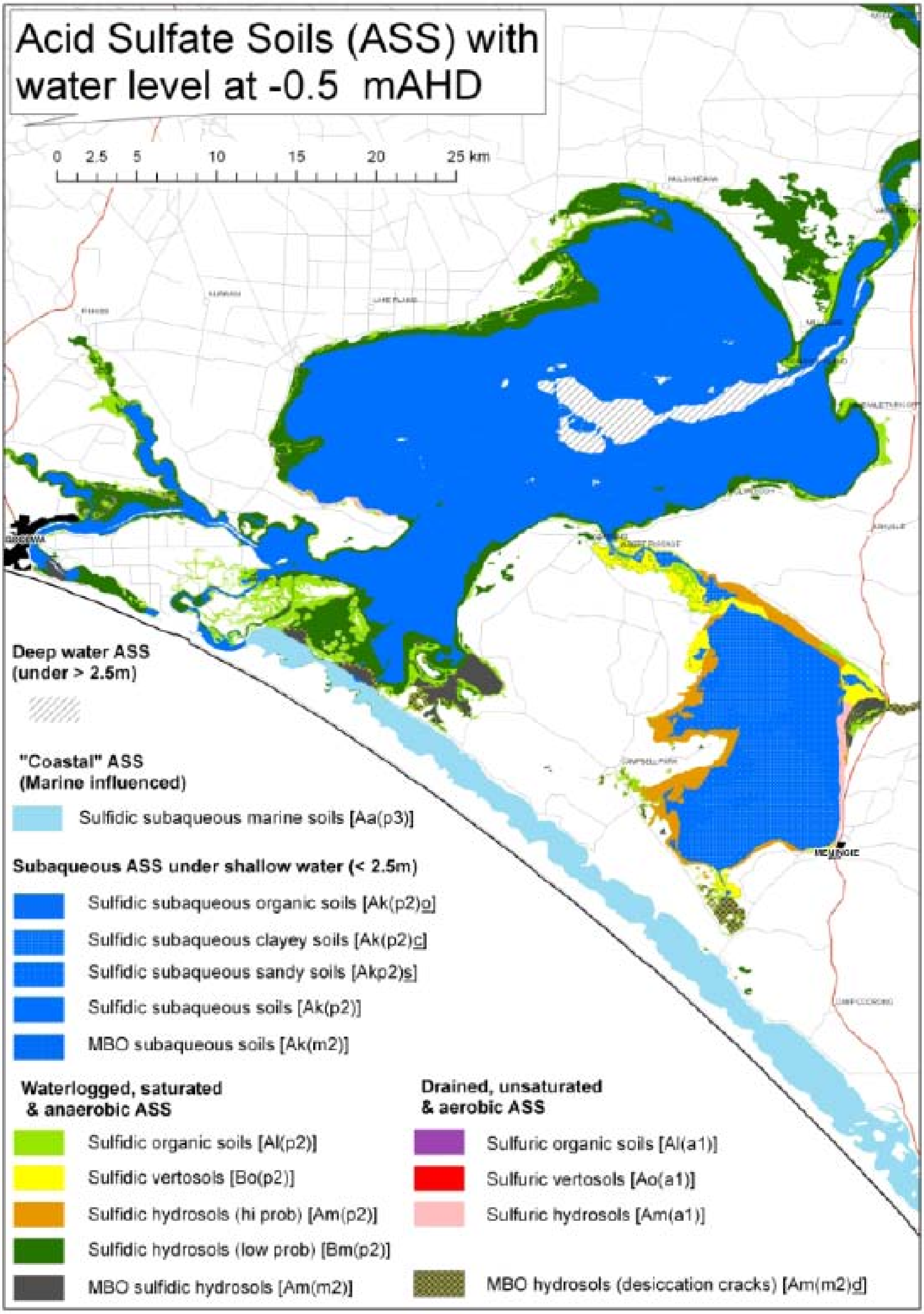

Figure 10. Predicted distribution of acid sulfate soils (ASS) of the Lower Murray Lakes at drought water levels (-0.5 m AHD). Taken from Fitzpatrick et al (2008). See Table 7 for description of soil categories.

Table 7. Explanation of ASS map legend in Figure 10 (Fitzpatrick et al, 2008).

Abbreviation	Description
Probability of Occurrence of Acid Sulfate Soils	
A	High probability of occurrence (> 70% of mapping unit)
B	Low probability of occurrence (6-70% of mapping unit)
C	Extreme low probability of occurrence (1-5% of mapping unit) with occurrences in small localised areas.
D	No probability of occurrence <1% of mapping unit (eg. outcrops of hard calcrete).
Codes	
k	Subaqueous soils (in shallow water <2.5 m depth)
l	Organosols (organic or peaty soils)
m	Hydrosols (Saturated in upper part to develop anaerobic conditions)
o	Vertosols (cracking clay soils with slickensides)
Subscripts to codes	
a	Sulfuric material (pH < 4)
m	Monosulfidic Black Ooze (MBO) material
p	Sulfidic material (pH > 4 but on aging pH drops below 4)
Confidence levels	
	Map polygon contains ASS, and:
(1)	- All necessary analytical and morphological data are available
(2)	- Analytical data are incomplete but are sufficient to classify the soil with a reasonable degree of confidence.
(3)	- No necessary analytical data are available but confidence is fair, based on a knowledge of similar soils in similar environments.
Descriptors (used where more information is available)	
o	Organic material (sapric and hemic material)
c	Clayey material (> 35 % clay; light, medium and heavy clay)
s	Sandy materials (= sand, loamy sand, clayey sand texture groups)
d	Desiccation cracks

4.2.7 Lake water quality

Table 8 provides a summary of key water quality parameters and major ion concentrations in the Lower Murray Lakes, including a comparison of historic data (1995-1998 average values) and available data for 2008. Concentration ratios between Lake Albert (Meningie) and Lake Alexandrina (Milang) have also been calculated. The degree of concentration in both lakes over time is indicated by the ratios of 2008 to 1995-1998 data for each lake, as shown in Table 8. Key results can be summarised as follows:

- Both lakes are alkaline, with an average pH of 8.3-8.5. There has been no significant change in pH between 1995-1998 and 2008, despite significant lowering of the water level in both lakes over the last 2 years (water levels dropped from around +0.6 m AHD in mid-2006 to around -0.5 m AHD in mid-2008).
- The average salinity of Lake Albert was generally twice that of Lake Alexandrina from 1995-1998, based on major ion concentrations.
- Lake Albert currently remains more saline than Lake Alexandrina by a factor of approximately 1.5, based on available data on major ions for 2008. The decrease in major ion ratios (Meningie:Milang), from around 2 in 1995-1998 to 1.5 in 2008, is likely to be associated with recent pumping of water from Lake Alexandrina to Lake Albert.
- The salinity of Lake Alexandrina has increased approximately five-fold, as indicated by the average conductivity increasing from 747 μS/cm in 1995-1998 to 3,811 μS/cm in 2008.
- Chloride concentrations in both lakes have increased by 5-6 times between 1995-1998 and 2008. It is assumed that chloride is conservative and the significant concentration of chloride is associated with evaporative processes within the lakes and possibly increasing concentrations in the Murray River and other tributaries of Lake Alexandrina. A comparable rise was observed in sodium (5-8), potassium (4-6) and magnesium concentrations (4-5).
- The average calcium concentration in both lakes only doubled from the 1995-1998 period to the present (2008), despite 5-6 fold increases in chloride, sodium, potassium and magnesium over the same period. Similar two-fold increases were also observed in bicarbonate, total alkalinity and total hardness. The relatively small increase in calcium, bicarbonate, total alkalinity and total hardness over time suggests that the lakes have become saturated with respect to calcium carbonate at some stage over the last 10 years. Hence, the precipitation of calcium carbonate is limiting ongoing increases in calcium, bicarbonate, total alkalinity and total hardness. This conclusion is supported by geochemical modelling conducted on 2008 data using PHREEQC software (Earth Systems, 2008). It is not clear when carbonate saturation commenced, but it is possible that at least 15,000 tonnes of calcite could be added to the lakes per year, based on a 50 mg/L total alkalinity reading at Wellington and an annual flow rate of 350 GL/year.

Table 8. Comparison of general water quality parameters and major ions in the Lower Murray Lakes from 1995-1998 to 2008.

Parameter	Unit	1995-1998 (average)			2008 (average)			Ratio (2008 average : 1995-1998 average)	
		Lake Alexandrina (Milang)	Lake Albert (Meningie)	Ratio (Meningie:Milang)	Lake Alexandrina (Milang)	Lake Albert (Meningie)	Ratio (Meningie:Milang)	Lake Alexandrina (Milang)	Lake Albert (Meningie)
pH	-	8.3	n/a	n/a	8.4	8.5	n/a	n/a	n/a
Conductivity	μS/cm	747	n/a	n/a	3811	5739	1.51	5.10	n/a
Sodium	mg/L	72.5 *	190 *	2.62	593.7	956.8	1.61	8.19	5.04
Potassium	mg/L	4.5 *	9.4 *	2.09	25.9	37.3	1.44	5.76	3.97
Calcium	mg/L	21.7	36.95 *	1.71	52.4	68.3	1.30	2.42	1.85
Magnesium	mg/L	17.4	34.14 *	1.96	80.7	136.5	1.69	4.64	4.00
Chloride	mg/L	159.4	315.9 *	1.98	984.3	1624.2	1.65	6.18	5.14
Sulfate	mg/L	25.7 *	62.7 *	2.44	173.3	292.2	1.69	6.74	4.66
Alkalinity	mg/L	82.6	151.5 [#]	1.83	180.3	241.7	1.34	2.18	1.59
Total hardness	mg/L	125.7	230.6 [#]	1.83	463.3	732.5	1.58	3.69	3.18
Bicarbonate	mg/L	99.8	133.5 *	1.34	207.7	270.1	1.30	2.08	2.02

* Data obtained from Water Quality Monitoring Report, October 1995 - December 1997 (EPA, 1998).

[#] Calculated from average ratio (Meningie:Milang) for calcium and magnesium.

Key processes producing variations in the chemistry of the lakes are expected to include dilution and concentration. Variations in the concentration of conservative ions like chloride can be expected almost exclusively in response to dilution (eg. rainfall, pumping) or concentration (eg. evaporation, evapotranspiration) processes. Figures 11 to 16, plots of chloride vs sulfate, and total hardness vs sulfate, are designed to assess the dominance of these processes for controlling water chemistry in both Lake Albert (Meningie; Water level recorder) and Lake Alexandrina (Milang).

Key conclusions from these graphs are summarised below:

- Chloride concentrations in Lake Albert have ranged from 1,120 mg/L (Water level recorder) to 1,920 mg/L (Meningie) between April and November 2008. The lowest concentrations are associated with the wetter months (July-August).
- Some indications of an overall increase in sulfate concentrations are evident in recent data from Lake Albert.
- Sulfate and total hardness in Lake Albert have followed relatively similar trends to chloride concentrations between April and November 2008.
- Insufficient water quality data exists for Lake Alexandrina (Milang) to establish clear trends, although sulfate appears to have remained relatively constant while chloride levels increased significantly (and total hardness to a lesser extent) from January to March 2008. Nevertheless, while sulfate trends are generally a good indicator of acid generation, changes in sulfate concentrations in Lake Alexandrina will be considerably more difficult to detect than in Lake Albert, due to the larger water volume (relative to surface area of exposed sediments) and the potential influence of variable chloride to sulfate ratios from the Murray River and other tributaries of Lake Alexandrina.
- The similarity of trends in chloride, sulfate and total hardness, particularly in Lake Albert indicates that most of the changes in major element chemistry in the lakes are due to concentration and dilution processes such as rainfall, tributary inflows, water pumping (from lakes and between lakes), evaporation and transpiration.

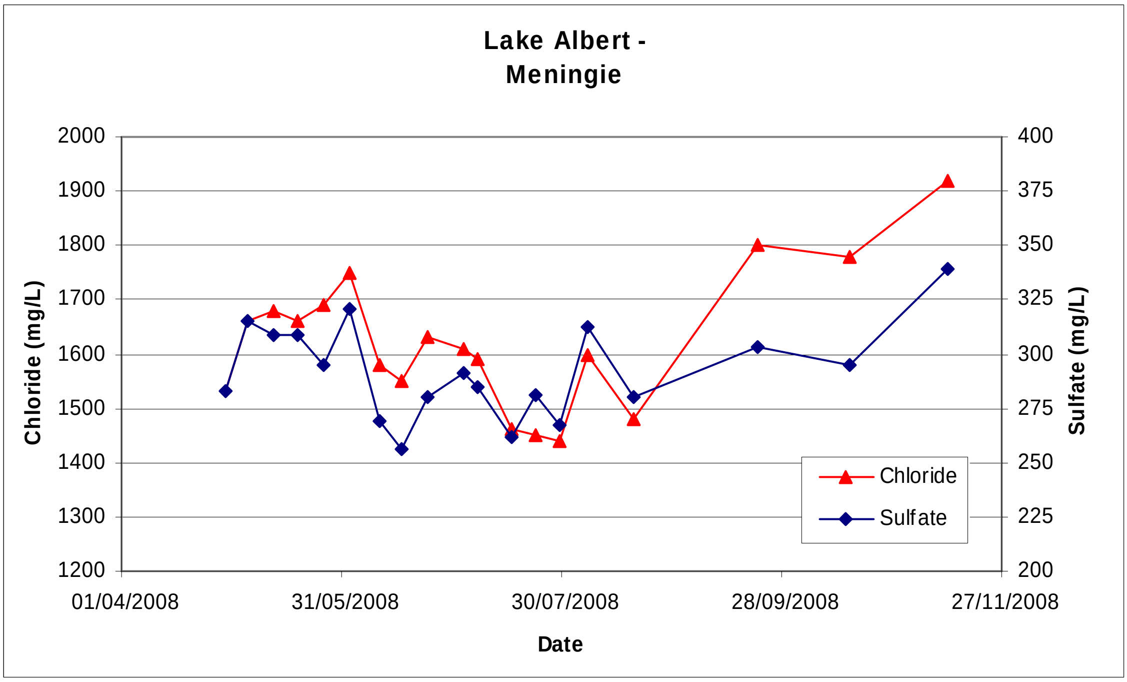

Figure 11. Recent trends in chloride and sulfate concentrations in Lake Albert (Meningie).

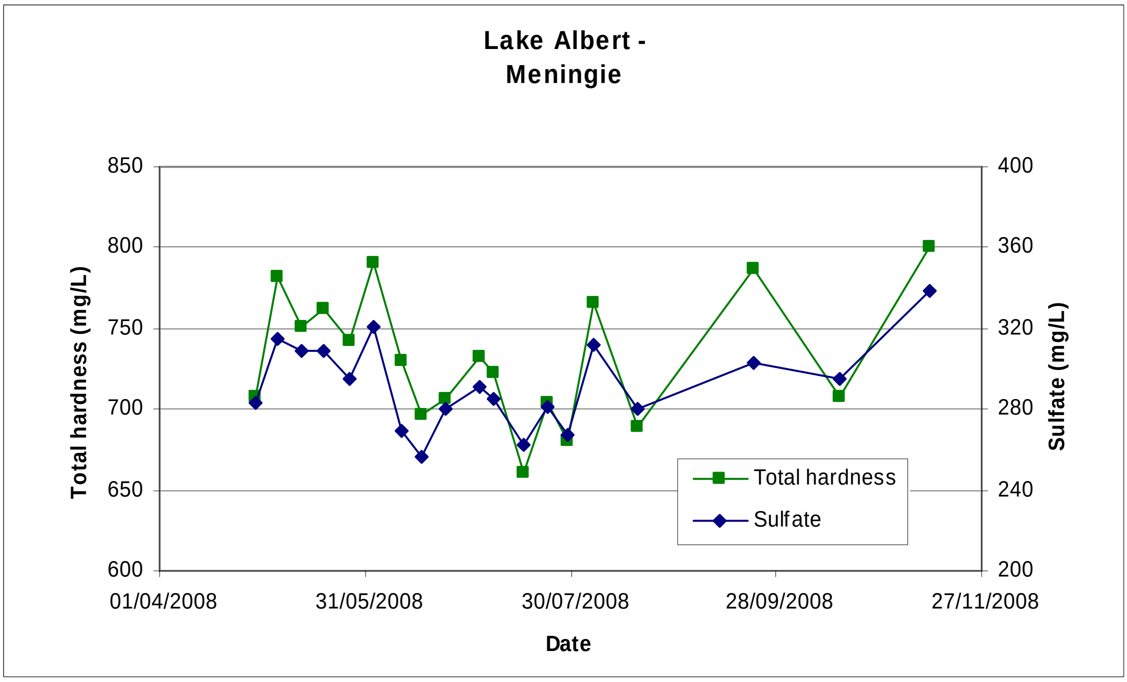

Figure 12. Recent trends in total hardness and sulfate concentrations in Lake Albert (Meningie).

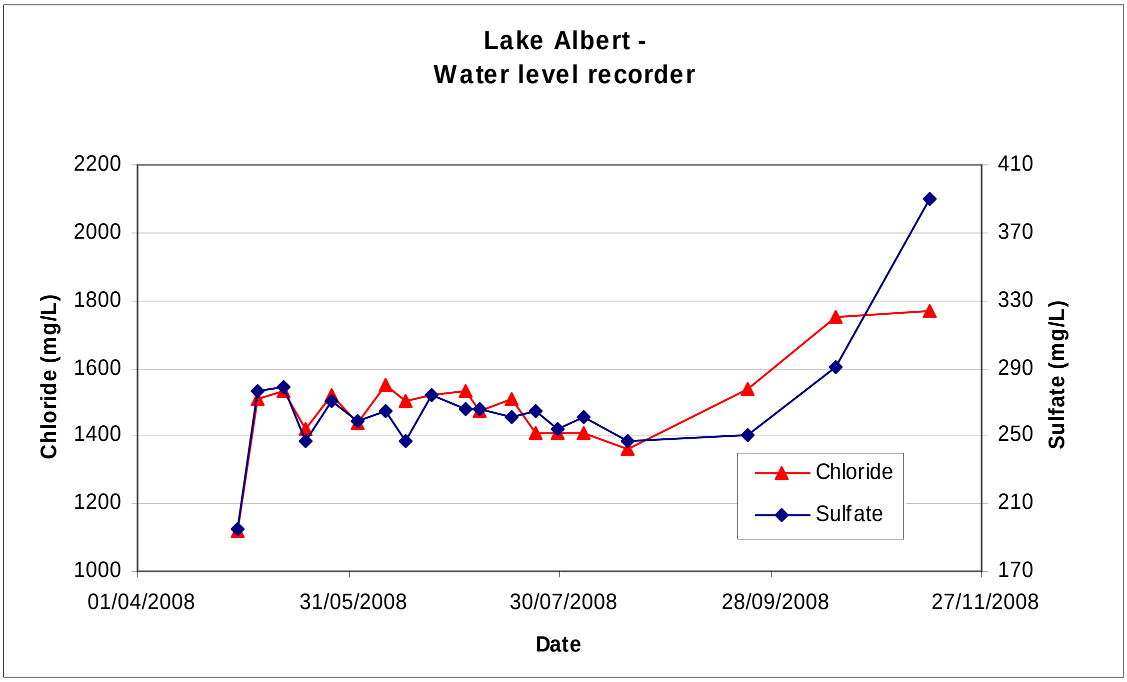

Figure 13. Recent trends in chloride and sulfate concentrations in Lake Albert (Water level recorder).

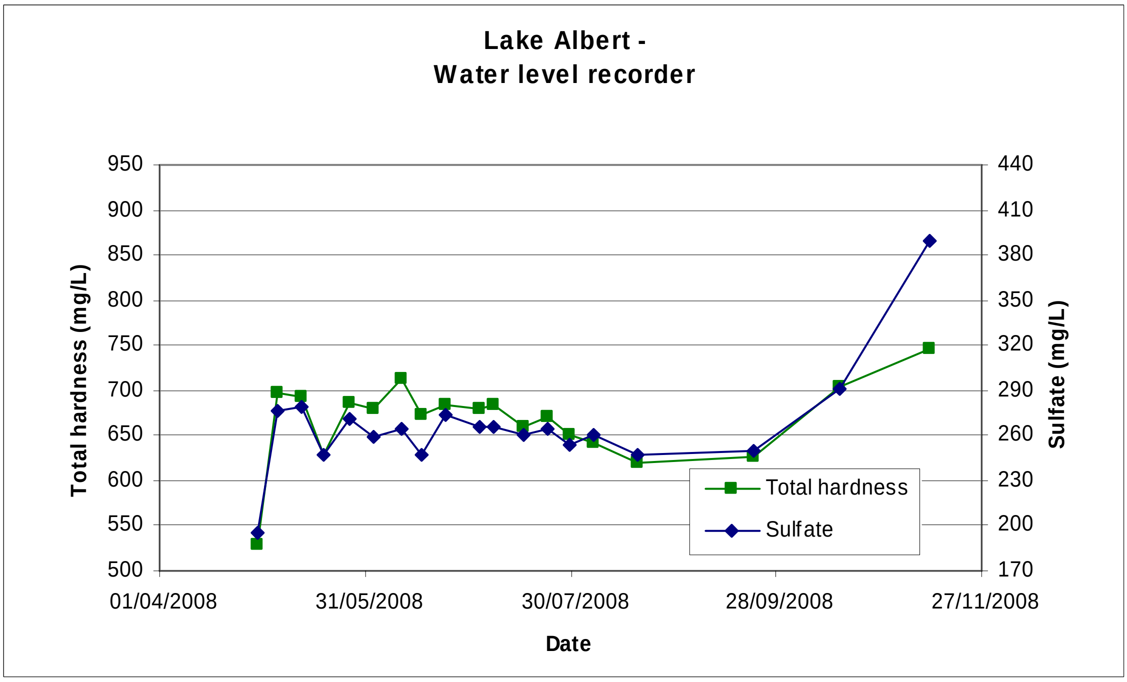

Figure 14. Recent trends in total hardness and sulfate concentrations in Lake Albert (Water level recorder).

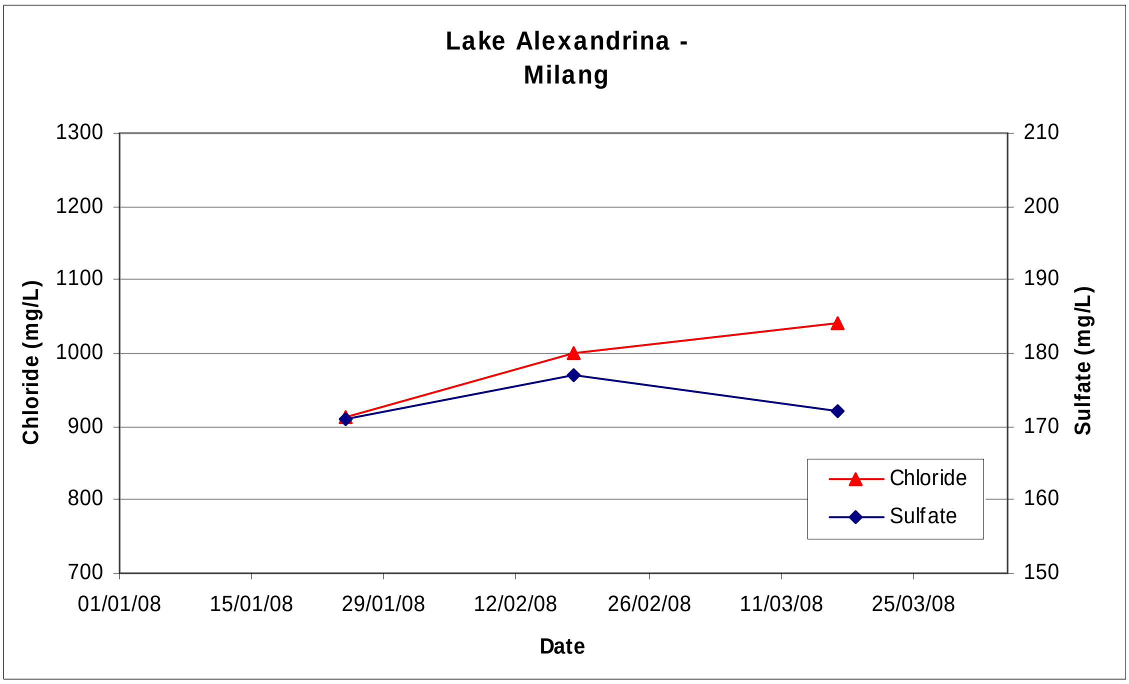

Figure 15. Recent trends in chloride and sulfate concentrations in Lake Alexandrina (Milang).

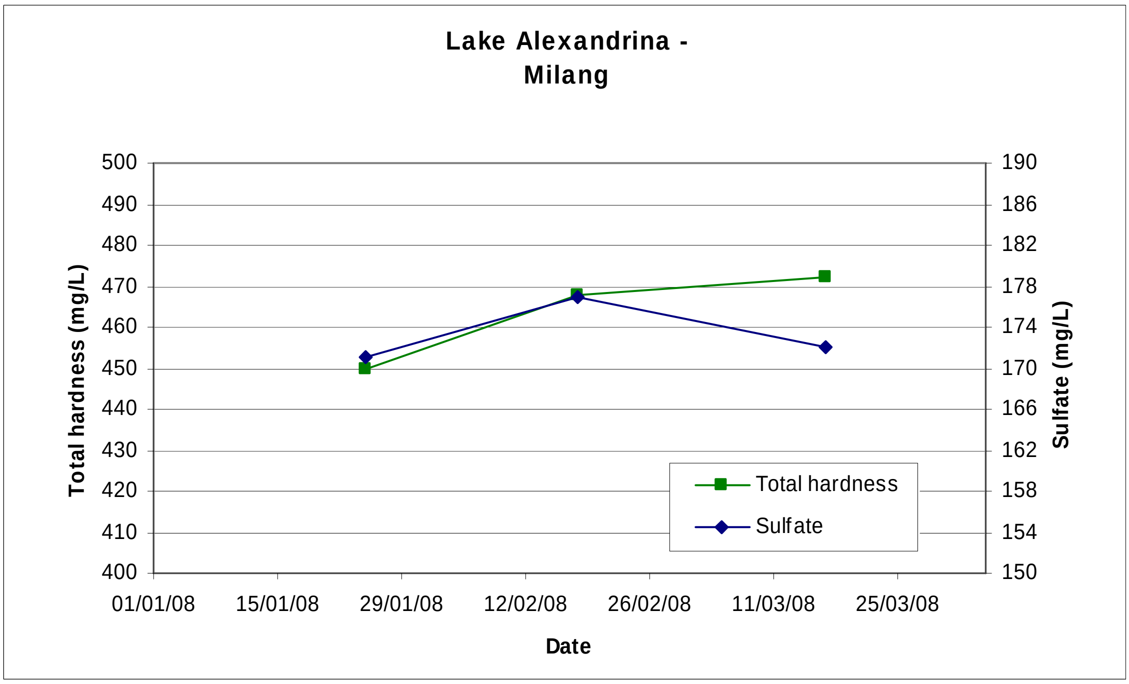

Figure 16. Recent trends in total hardness and sulfate concentrations in Lake Alexandrina (Milang).

Changes in the concentrations of ions that are not related dilution or concentration can often provide an indication of significant geochemical processes such as mineral dissolution or precipitation. In order to retrieve such information from the data, plots of sulfate vs calculated sulfate were prepared. Calculated sulfate data were generated by assuming that chloride is conservative and calculating dilution or concentration factors between sequential analytical values, and applying this factor to measured sulfate values.

Graphs of measured sulfate concentrations and calculated sulfate concentrations (based on chloride trends) for Lake Albert and Lake Alexandrina are shown in Figures 17 to 19. Daily rainfall data from Narrung are included on the plots.

Key conclusions from these graphs are summarised below:

- Overall the measured and calculated sulfate concentrations are very similar in Lake Albert from April to November 2008. Insufficient water quality data exists for Lake Alexandrina (Milang) to establish clear trends in measured and calculated sulfate concentrations.
- While the difference between measured and calculated sulfate concentrations in Lake Albert was generally within 5-10 mg/L, higher than expected sulfate was measured on some occasions (eg. 2 June, 23 June, 23 July, 6 August and 12 November 2008), while lower than expected concentrations were measured on others (eg. 10 June and 21 September 2008).
- The significant discrepancies between the measured and calculated sulfate concentrations may result from geochemical processes rather than simply concentration or dilution. For example, higher than expected sulfate levels could result from sulfide oxidation within exposed lake sediments, while lower than expected sulfate could represent sulfide precipitation (formation of FeS_2 and/or FeS) via sulfate reducing bacterial activity.
- A measured sulfate concentration exceeding the corresponding calculated value by 20 mg/L, for example, would correspond to a net addition of 1,500 tonnes of sulfate into Lake Albert over 2 weeks, based on a water volume of 76.4 GL at -0.5 m AHD.
- There are insufficient data to confirm whether sulfide oxidation and precipitation are the key processes affecting lake sulfate concentrations. Lake sulfate concentrations could be affected by a number of factors including variable chloride to sulfate ratios in flows from the Murray River and other tributaries. Discrepancies in the measured and calculated sulfate values could also be associated with analytical variability or even analytical errors to some degree.
- Based on this preliminary evaluation, no systematic relationship between rainfall and variations in sulfate concentrations in Lake Albert are evident.

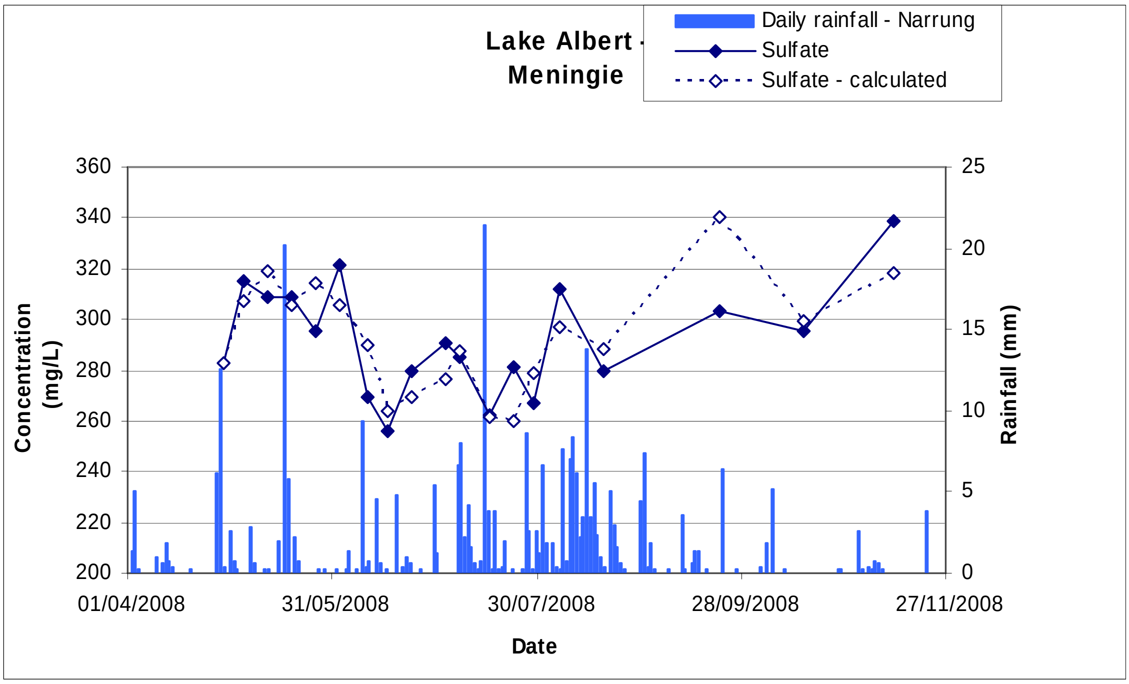

Figure 17. Measured and calculated sulfate concentrations in Lake Albert (Meningie).

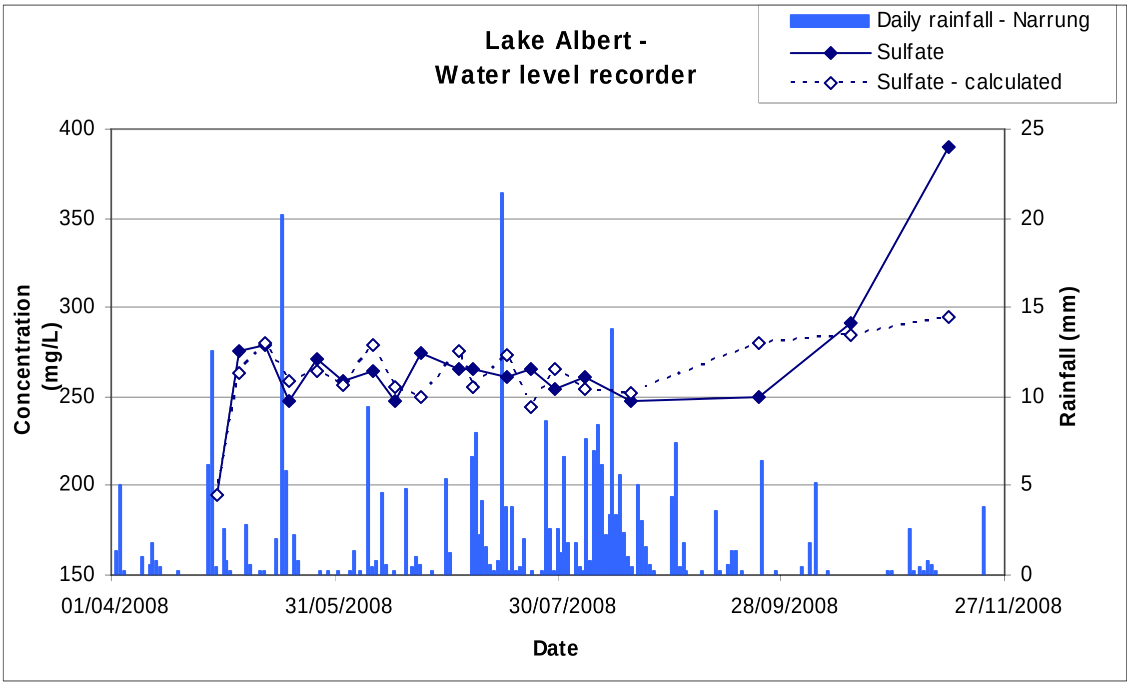

Figure 18. Measured and calculated sulfate concentrations in Lake Albert (Water level recorder).

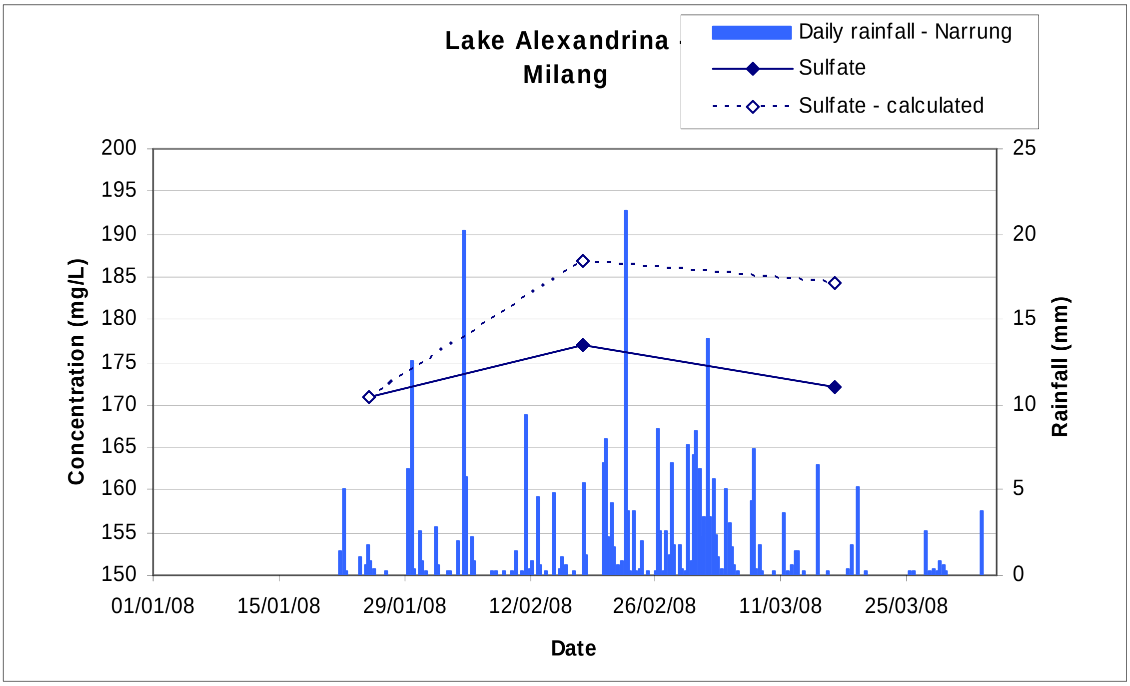

Figure 19. Measured and calculated sulfate concentrations in Lake Alexandrina (Milang).

4.3 ACIDITY GENERATION MODEL

The existing soil characterisation conducted by Fitzpatrick et al (2008) indicates significant potential for acid generation from exposed sediments, due to lowering of lake water levels. Timing of the onset of lake acidification and the likely scale of acidification remains uncertain at this stage.

An acidity generation model was developed for the exposed sediments, based on the Concept Drawing in Attachment B.

The acidity generation model was developed to investigate likely acidity fluxes from the exposed sediments as a function of the volume of exposed sediment, the mass of pyrite present and the effective oxidation rate of the pyrite. The effective sulfide oxidation rate refers to the net production of sulfuric acid (H_2SO_4) from sediments with variable moisture contents, but does not account for the potential for in-situ acid consumption (eg. by neutralisation and/or reduction processes). The effective sulfide oxidation rate is recorded as the weight percent of pyrite (FeS_2) exposed to atmospheric oxygen that decomposes to form H_2SO_4 per year.

The potential for acidification of the Lower Murray Lakes associated with a range of effective sulfide oxidation rates (1, 2, 5, 10, 20, 50, 75 and 100 wt% FeS_2 per year) was modelled. Effective sulfide oxidation rates refer to the proportion of exposed dry mass of pyrite (FeS_2) that oxidises to produce sulfuric acid (H_2SO_4) in one year. The term "effective", in this context, refers to the net effect of sulfide oxidation in lake sediments on the load of acid entering the lake water. The "effective" sulfide oxidation rate does not take into account the potential for in-situ acid consumption (eg. by neutralisation and/or reduction processes) nor the effects of soil moisture content, and therefore does not represent the actual "intrinsic" sulfide oxidation rate of shoreline sediments.

Model outputs are provided in Figure 20. The following assumptions and input parameters were used to develop the acidity generation model:

- The starting water level of both lakes is -0.5 m AHD. This corresponds to a storage volume of 909 GL in Lake Alexandrina and 76.4 GL in Lake Albert (total 985 GL).
- The average alkalinity of lake water is 200 mg/L $CaCO_3$ equivalent.
- The water level decreases by 1 m in both lakes, from -0.5 m AHD to -1.5 m AHD. To be conservative, the 1 m decrease was assumed to occur at the commencement of modelling (beginning of 2009).
- A 1 m decrease in lake water levels represents an average 0.5 m increase in the thickness of lake shoreline sediments exposed to oxidation, and a change in the surface area of exposed sediments of 24,745 ha.
- The combined perimeter of both lakes is 354 km.
- The average bulk density of exposed sediments is 1 t/m^3.
- The annual water volume entering the lakes from the Murray River is 350 GL/year. This water has an average alkalinity of 50 mg/L $CaCO_3$ equivalent. Alkalinity loads from other tributaries were assumed to be negligible in comparison.
- Acid neutralisation within the lake water can be achieved via existing dissolved alkalinity and additional soluble alkalinity inputs from the Murray River. Alkalinity addition associated with dissolution of $CaCO_3$ from the lake beds has not been modelled, nor has the potential for acid consumption via sulfate reduction in the presence of organic matter in the lake bed sediments.
- Acid generation rates for effective sulfide oxidation rates of 1, 2, 5, 10, 20, 50, 75 and 100 wt% FeS_2 per year were calculated.

In addition, the average sulfide-sulfur content of exposed sediments was estimated to be 0.18 wt% S, with all sulfide-sulfur assumed to be in the form of pyrite (FeS_2). The average sulfide-sulfur content of 0.18 wt% S was estimated as follows:

- The lake perimeters were divided into 19 segments (Lake Alexandrina: 13; Lake Albert: 6) of varying lengths, based on the locations of soil sampling sites in Fitzpatrick et al (2008).
- The weighted average sulfide-sulfur content was calculated for each sampling site (vertical profile), based on the S_{cr}% data and thickness of each soil horizon in the profile provided in Fitzpatrick et al (2008).
- The sulfide-sulfur content of each segment was estimated by averaging the sulfide-sulfur contents for all sampling sites within each segment.
- The weighted average sulfide-sulfur content for the lakes was then calculated according to the segment length relative to the total perimeter of both lakes.

Results of the acidity generation model over a 10 year period are shown in Figure 20. Key conclusions derived from the acid balance model include:

- The total acidity generation potential for the Lower Murray Lakes is around 680,000 tonnes H_2SO_4.
- An effective sulfide oxidation rate of 1 wt% FeS_2/year corresponds to an annual acid addition of 6,800 tonnes H_2SO_4 to the lakes. The relationship between effective sulfide oxidation rate and acid generation rate is linear (ie. a rate of 2 wt% FeS_2/year would generate 13,600 H_2SO_4 annually).
- An effective sulfide oxidation rate of 1 wt% FeS_2/year (6,800 tonnes H_2SO_4 / year) would cause sulfate concentrations to increase by around 15 mg/L per year based on a water level of -1.5 m AHD (volume 402.3 GL). This is significantly smaller than the

expected increase of 300 mg/L sulfate due to concentration (evaporation) effects associated with lake water levels decreasing from -0.5 m AHD to -1.5 m AHD.

- Approximately 200,000 tonnes of soluble alkalinity ($CaCO_3$ equivalent) is currently available within the lakes to neutralise any acid generated from exposed shoreline sediments. A further 17,500 tonnes of alkalinity ($CaCO_3$ equivalent) enters the lake system each year via the Murray River.
- Effective oxidation rates of less than 2 wt% FeS_2/year are not expected to result in any lake acidification.
- Effective oxidation rates of around 5 wt% FeS_2/year are expected to result in a gradual decline in lake water alkalinity over approximately 10 years followed by progressive acidification of the lakes. The annual acid addition of 34,000 tonnes H_2SO_4 could be expected to increase sulfate concentrations by 80 mg/L per year based on a water level of -1.5 m AHD (volume 402.3 GL).
- Effective oxidation rates of greater than 50 wt% FeS_2/year are expected to lead to rapid acidification of the lakes (over a period of months).
- If significant sulfate reduction is likely to occur or can be encouraged to occur within the exposed sediments, or is likely to occur or can be encouraged to occur in the basal lake sediments, then this model will be significantly overestimating the risk associated with acid generation.

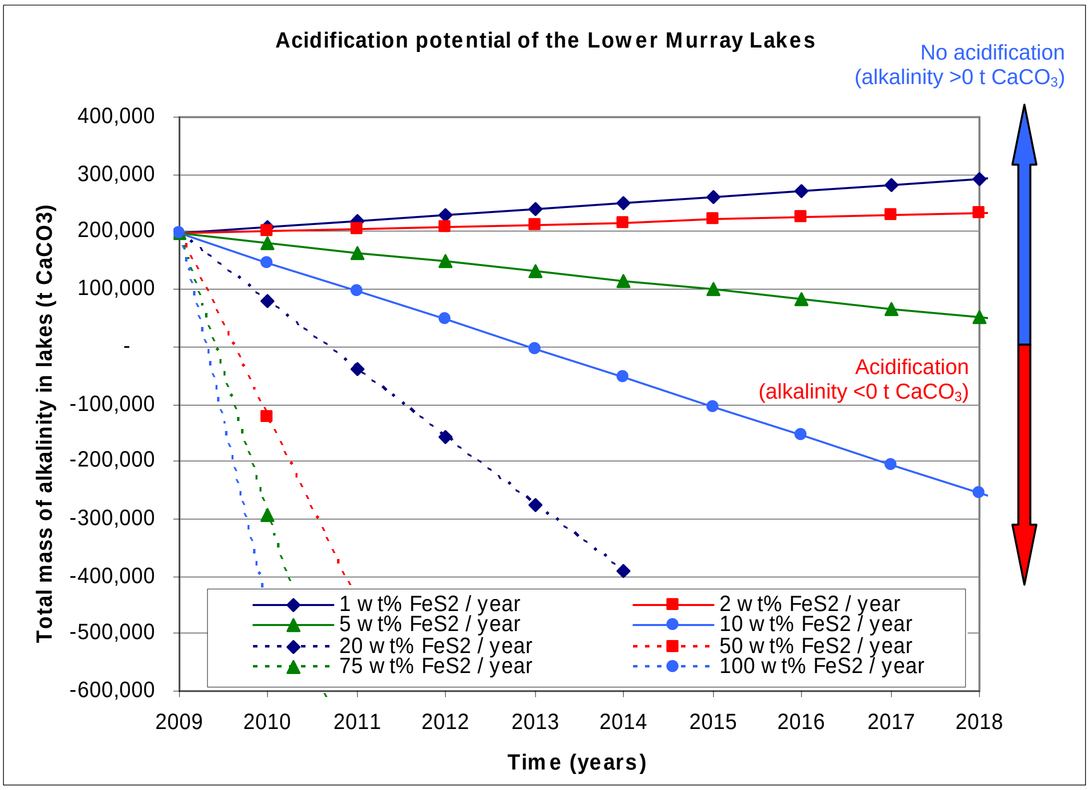

Figure 20. Effect of different effective sulfide oxidation rates on the acidification potential of the Lower Murray Lakes. The effective sulfide oxidation rate is expressed as the weight percent of pyrite exposed to atmospheric oxygen that is converted to sulfuric acid per year.

4.4 IDENTIFICATION AND PRELIMINARY ASSESSMENT OF ASS MANAGEMENT OPTIONS

Table 9 identifies 30 management options for exposed ASS marginal to the Lower Murray Lakes, including those identified in Earth Systems (2008). The options fall into the general categories of AMD "Prevention", "Control" and "Treatment". The options are summarised, key issues related to their implementation are introduced, key potential risks are highlighted and strategies to manage the risks are discussed where appropriate.

Table 9. Identification of ASS management options for the Lower Murray Lakes.

Option number	Option	Key issues related to method	Risks	Management strategies
PREVENTION				
	Seawater submergence			
1	Open barrages to ocean.	While technically easy to implement at low cost, there are several risks with long term environmental, human health, social and reputational implications. Refer to risk column.	Catastrophic ecological impacts on all freshwater fauna and flora in the lakes. Potential for uncontrolled H_2S odour issues from lakes due to imbalance between S and available Fe. Sterilisation of freshwater resources for all local landholders and farmers dependent on the lakes for a livelihood. Landowner compensation costs can be expected to be significant.	
	Freshwater submergence			
2	Increase flow from rivers.	No additional flows are readily available. Permanent submergence of sulfidic materials required to prevent acid generation.	Minimal risk.	

Option number	Option	Key issues related to method	Risks	Management strategies
3	Continue pumping from Lake Alexandrina to Lake Albert.	Greater evaporative losses can be expected per unit area from Lake Albert. This method does not address acid generation in Lake Alexandrina (indeed, lower water levels could exacerbate acid generation in Lake Alexandrina). Permanent submergence of sulfidic materials required to prevent acid generation.	Sediments between Lake Albert and Coorong may be too permeable to generate a sustainable water rise in Lake Albert.	
4	Apply evaporation reducing chemicals to the surface of lakes to minimise the loss of water. Evaporation influencing alcohol compounds form self installing monolayers and can be readily dosed from only a few locations to provide broad scale coverage.	The compounds appear to be safe for application to drinking water and ecologically sensitive environments, but are routinely consumed by bacteria, and hence require ongoing application.Permanent submergence of sulfidic materials required to prevent acid generation.Assuming lake surface areas of around 515 km^2 (Lake Alexandrina) and 170 km^2 (Lake Albert) and annual evaporation of 1.2 m, approximately 800 GL is evaporated from the lakes each year. If evaporation reducing methods are 50% effective, around 400 GL of water could be saved each year, preventing a water level drop of 0.5-1.0 m in both lakes.	Uncertainty in the degree of evaporation reduction associated with this option.	Test work to confirm the potential applicability of evaporation reducing chemicals to the Lower Murray Lakes would be necessary.
CONTROL				
	Keep exposed sediments wet			
5	Develop shallow terraces along clay-rich portions of the shoreline and mound water behind the terraces with pumps. Terraces could be constructed from potentially biodegradable bags filled with ultra-fine grained limestone. This would permit at least partial saturation of exposed sediments. Refer to Drawing 1.	Most of the exposed sediment banks are comprised of high permeability sandy sediments that would not permit sustainable surface water mounding behind terraces. Permanent saturation of sulfidic materials required to control acid generation.	Need to avoid breakdown of terraces by wind, wave or other erosional forces.	

Option number	Option	Key issues related to method	Risks	Management strategies
6	Install trenches along the landward side of exposed beaches. Dig shallow trenches and fill with limestone gravel. Use pumps to periodically or continuously fill trenches with lake water. This would recharge groundwater, increase the moisture content of the sediments and assist with minimising the oxidation of sulfidic material. Refer to Drawing 1.	Permanent saturation of sulfidic materials required to control acid generation.	Artificial recharge of groundwater has the potential to accelerate acidity discharges from sediment banks.	Test work to confirm the impacts of such activity would be necessary.
7	Install perforated pipes along the landward side of beaches and periodically or continuously pump lake water onto the exposed sediments. This would recharge groundwater, increase the moisture content of the sediments and assist with minimising the oxidation of sulfidic material. Refer to Drawing 2.	Permanent saturation of sulfidic materials required to control acid generation.	Artificial recharge of groundwater has the potential to accelerate acidity discharges from sediment banks.	Test work to confirm the impacts of such activity would be necessary.
8	Install irrigation systems on exposed sediments and periodically pump water over sediments. This would recharge groundwater, increase the moisture content of the sediments and assist with minimising the oxidation of sulfidic material. Refer to Option 18 for methods to encourage farmers to irrigate exposed banks. Refer to Drawing 3.	This approach is likely to generate higher evaporative losses than the two options provided above. Permanent saturation of sulfidic materials required to control acid generation.	Artificial recharge of groundwater has the potential to accelerate acidity discharges from sediment banks.	Test work to confirm the impacts of such activity would be necessary.
	Install low permeability groundwater barriers			
9	Install low permeability barriers within the sediments some distance from the shoreline to retard groundwater flow and permit groundwater mounding and partial submergence of the sulfides within the sediments up hydraulic gradient of the barrier. Barrier materials could include clay, limestone, silica gel or (slowly) biodegradable organic compounds. Difficulties would be encountered trying to install extensive barriers below the water table. Holding trenches open below the groundwater level with earth moving equipment may be difficult. Refer to Drawing 2.	Formation of barriers may involve the installation of shallow horizontal bores (eg. 1.0 to 2.0 m depth) containing perforated polyethylene pipes. Injection of compounds such as fine grained limestone slurry (eg. 30 wt. %) from the pipes would have the effect of creating lower permeability (and potentially reactive) zones within the sediments.	Permanent impacts on groundwater flow within the sediment banks are undesirable as they may disrupt broader scale groundwater flows over the longer term.	

Option number	Option	Key issues related to method	Risks	Management strategies
	Cap exposed sediments			
10	Cover exposed sediments with fine grained materials that will retard oxygen diffusion and infiltration, and therefore acidity fluxes. Materials could include clay or perhaps ultra-fine grained limestone. Refer to Drawing 3.		Possible dust issues when dry.	Irrigate cover into sediments.
	Add organic matter to lakes			
11	Revegetate extensive portions of the up wind shores of the lakes with large native trees. Leaf litter from the trees would provide slow, passive but ongoing organic matter addition to the lakes over the long term.	This is a long term approach to passive treatment of the lakes. It is possible that sufficient organic carbon is already available in basal lake sediments. Timing of implementation would be affected by seed / seedling availability (season dependent).	Some minor impact from enhanced evapotranspiration may occur. May be insufficient available iron in sediments to permit sulfide precipitation and associated alkalinity generation.	Locate forested areas on bedrock rather than lake sediments to minimise uptake of lake water during transpiration.
12	Add organic matter to lake water via barges. Floating or relatively dense organic matter could be added. Whether the organic matter is low or high density, or has the capacity to waterlog would depend on whether the aim is to emplace organic matter within the lake bed or around the shores of the lakes. Sources of organic matter could include; straw / hay, reeds from lake margins, timber waste, wood-chips, clean mulch, clean compost, fish waste, seaweed, grasses / reeds planted and harvested from new lake shore, recycled paper pulp, jute matting.	It is possible that sufficient organic carbon is already available in basal lake sediments. Perhaps available iron to generate iron sulfides is the key rate limiting component for sulfide precipitation.	Elevated nutrients in the organic matter may contribute to nutrient pollution within the lake water. Additional organic matter may lead to the development of unnatural, highly reducing conditions in parts of the lakes. May be insufficient available iron in sediments to permit sulfide precipitation and associated alkalinity generation.	Utilise only cellulose-rich compounds that contain little nitrogen or phosphorous.

Option number	Option	Key issues related to method	Risks	Management strategies
13	Flocculate algae from the water column of the lakes to add reactive organic matter to the lake beds. Iron salts such as ferric chloride or ferric sulfate could be applied to the lake surface in low concentrations to facilitate the settling of suspended solids (including micro-algae) to the lake sediments. Boats towing small barges could be modified to permit relatively rapid dosing.	The resulting elevated reactive iron content of the lake sediments could promote greater bacterial sulfate reduction (ie. sulfide precipitation) and hence in-situ remediation. Significant quantities of algae not always present. Potential acid inputs associated with flocculant addition would be negligible. It is possible that sufficient organic carbon is already available in basal lake sediments.	Small increases in the salinity of the lakes would be recorded. May be insufficient available iron in sediments to permit sulfide precipitation and associated alkalinity generation.	Environmentally sensitive organic polymers may be an alternative to iron salts.
14	Add organic matter to the basal lake sediments via helicopter. Only relatively dense organic matter (prone to water logging and settling) could be applied cost-effectively using this method.	It is possible that sufficient organic carbon is already available in basal lake sediments.	The potential for dust and pathogen distribution by air would need to be considered for aerial dispersion of organic matter. Elevated nutrients in the organic matter may contribute to nutrient pollution within the lake water. Additional organic matter may lead to the development of unnatural, highly reducing conditions in parts of the lakes. May be insufficient available iron in sediments to permit sulfide precipitation and associated alkalinity generation.	Utilise only large fragments of cellulose-rich compounds.
15	Pump organic-rich mud from the narrow area between the two lakes to the central portion of each lake. This could be achieved using hydraulic dredges.	It is possible that sufficient organic carbon is already available in basal lake sediments.	High turbidity conditions would be generated during such a process, potentially impacting on aquatic fauna. Smothering of aquatic flora may also occur. May be insufficient available iron in sediments to permit sulfide precipitation and associated alkalinity generation.	Flocculate suspended sediments.

Option number	Option	Key issues related to method	Risks	Management strategies
	Add organic matter to exposed sediments			
16	Add organic matter to sediments around the shoreline of the lake via swamp dozers. Sources of organic matter could include; straw / hay, reeds from lake margins, logs, timber waste, wood-chips, clean mulch, clean compost, fish waste, seaweed, recycled paper pulp, selected animal wastes.	Organic matter needs to be kept wet enough to promote at least partial decomposition. Fine grained organic matter needs to be carried down into the sediments from the surface. It is possible that sufficient organic carbon is already available in basal lake sediments.	Re-application of the organic matter may be required as the shoreline continues to recede.	
17	Add clean fine grained organic matter into single or multiple shallow trenches close to and parallel with the shoreline. Trenches need to be as deep as possible, at least encountering the upper part of the existing water table. Organic matter could include clean compost, wood chips, timber waste, seaweed, recycled paper pulp, clean mulch, jute matting, selected animal wastes or other locally available low-cost materials.	Holding trenches open to fill with organic matter would be difficult below the water table (at low cost) due to the likely collapse of the walls. It is possible that sufficient organic carbon is already available in basal lake sediments.	Some disruption to the exposed sediments would be necessary to achieve this outcome. Some acid generation from the excavated materials may be expected as a consequence.	Submerge excess material in lake water.
18	Conduct or encourage strategic planting of exposed sediment banks with deeply rooting, rapid growth plant species which produce a great deal of above ground biomass (eg. local reeds, grasses for stock). Planting activities needs to keep pace with the receding shoreline. Harvest the above ground biomass and lay down on sediment banks to contribute organic matter to sediments, or alternatively allow stock to graze on grasses. Refer to Drawing 4.	Seeding could be done on ground or from the air. Farmers could be encouraged to become involved with irrigating (see Option 8) the sediment banks to grow grasses for cattle or sheep grazing. Stock would also be adding organic matter (ie. faeces) to the banks. It is possible that sufficient organic carbon is already available in basal lake sediments. Timing of implementation would be affected by seed availability (season dependent).	Extensive plant growth can be expected to lower the groundwater table within the sediment banks via evapotranspiration, thereby potentially exacerbating acid generation.	Some trial work should be conducted to confirm the impact of revegetation on net acid generation from the sediments.

Option number	Option	Key issues related to method	Risks	Management strategies
	Add organic matter to river			
19	Add fine grained, relatively dense organic matter to rivers using flows to carry solids to centre of Lake Alexandrina.	It is possible that sufficient organic carbon is already available in basal lake sediments. Perhaps available iron to generate iron sulfides is the key rate limiting component for sulfide precipitation.	Potential significant ecological impacts from the addition of organic matter, depending on the dose rate. Elevated nutrients in the organic matter may contribute to nutrient pollution within the lake water. Additional organic matter may lead to the development of unnatural, highly reducing conditions in parts of the lakes. May be insufficient available iron in sediments to permit sulfide precipitation and associated alkalinity generation.	Do not exceed the river's natural sediment load carrying capacity (eg. during a flood). Utilise only cellulose-rich compounds that contain little nitrogen or phosphorous.
TREATMENT				
	Limestone addition along or within existing waterways feeding the lakes			
20	Refer to Earth Systems (2008).	Sufficient alkalinity may be present in lake water, lake sediments and tributary inflows, without the need for further alkalinity addition.		
	Alkalinity generating ponds along margins of waterways feeding the lakes			
21	Refer to Earth Systems (2008).	Sufficient alkalinity may be present in lake water, lake sediments and tributary inflows, without the need for further alkalinity addition.		
	Install vertical permeable reactive barriers			
22	Install vertical permeable reactive barriers within the sediments to interact with acidic groundwater flow. Barriers may contain organic matter ± limestone.	Similar installation issues would be experienced as those described above for low permeability barriers. Sufficient alkalinity may be present in lake water, lake sediments and tributary inflows, without the need for further alkalinity addition. Sufficient organic carbon may be available in lake sediments.	Potential for clogging of barrier (depending on barrier composition) and disruption of groundwater flows over the longer term.	Careful selection of barrier materials to reduce the risk of long term clogging.

Option number	Option	Key issues related to method	Risks	Management strategies
	Limestone addition to exposed sediments			
23	Add limestone as a surface amendment over exposed sediments (via swamp dozers and/or helicopters).	Refer to Earth Systems (2008). Sufficient alkalinity may be present in lake water, lake sediments and tributary inflows, without the need for further alkalinity addition.		
24	Add fine grained limestone to single or multiple shallow trenches constructed near to and parallel with the shoreline. The aim would be to achieve slow alkalinity addition to the lake water or groundwater via rain and wave action. The trenches may only be 10-30 cm deep, but the fine grainsize of the limestone may permit particles to be washed down into the profile to encounter potentially acidic leachate.	Sufficient alkalinity may be present in lake water, lake sediments and tributary inflows, without the need for further alkalinity addition.		
	Limestone addition to lakes via single static dosing into flowing water			
25	Refer to Earth Systems (2008).	Sufficient alkalinity may be present in lake water, lake sediments and tributary inflows, without the need for further alkalinity addition.		
	Limestone addition to lakes via multi-point dosing locations from access roads in lakes			
26	Refer to Earth Systems (2008).	Sufficient alkalinity may be present in lake water, lake sediments and tributary inflows, without the need for further alkalinity addition.		
	Limestone dosing into lakes from mobile barges			
27	Refer to Earth Systems (2008).	Sufficient alkalinity may be present in lake water, lake sediments and tributary inflows, without the need for further alkalinity addition.		

Option number	Option	Key issues related to method	Risks	Management strategies
	Limestone addition to lakes via helicopter			
28	Refer to Earth Systems (2008).	Sufficient alkalinity may be present in lake water, lake sediments and tributary inflows, without the need for further alkalinity addition.		
	Addition of hydrated lime slurry to exposed sediments			
29	Addition of controlled quantities of hydrated lime (calcium hydroxide) to the surface of exposed sediment to match acid generation rates. Passive dissolution during rainfall events would be needed to convey the alkalinity into the sediments. Sequential addition of hydrated lime to the surface of the sediments would be required due to its high solubility in water. Mechanical addition to the exposed sediments from shore would be necessary.	Wet hydrated lime slurry rapidly sequesters carbon dioxide from the atmosphere and converts to the less reactive calcium carbonate. Sufficient alkalinity may be present in lake water, lake sediments and tributary inflows, without the need for further alkalinity addition.	Dust may be generated on application. Excess addition of hydrated lime slurry could generate unnecessarily alkaline water.	Sequential addition of the required mass of hydrated lime for a specific rainfall event would be required.
	Addition of granular caustic magnesia (MgO) to exposed sediments			
30	Addition of specialised reactive caustic magnesia in a granular form to exposed sediments to permit rapid passive dissolution during rainfall events. Dose rates can be designed to proved sufficient alkalinity to deal with acid generation per unit area. This may be a useful emergency response approach to rapid acid generation. Mechanical addition to the exposed sediments from shore would be necessary.	Sufficient alkalinity may be present in lake water, lake sediments and tributary inflows, without the need for further alkalinity addition.	Dust may be generated on application. Elevated magnesium concentrations would be generated in the lakes. If minimal or no acid is generated in the lakes, the MgO may produce unnecessarily alkaline water.	Sequential addition of the required mass of MgO for a specific rainfall event would be required.

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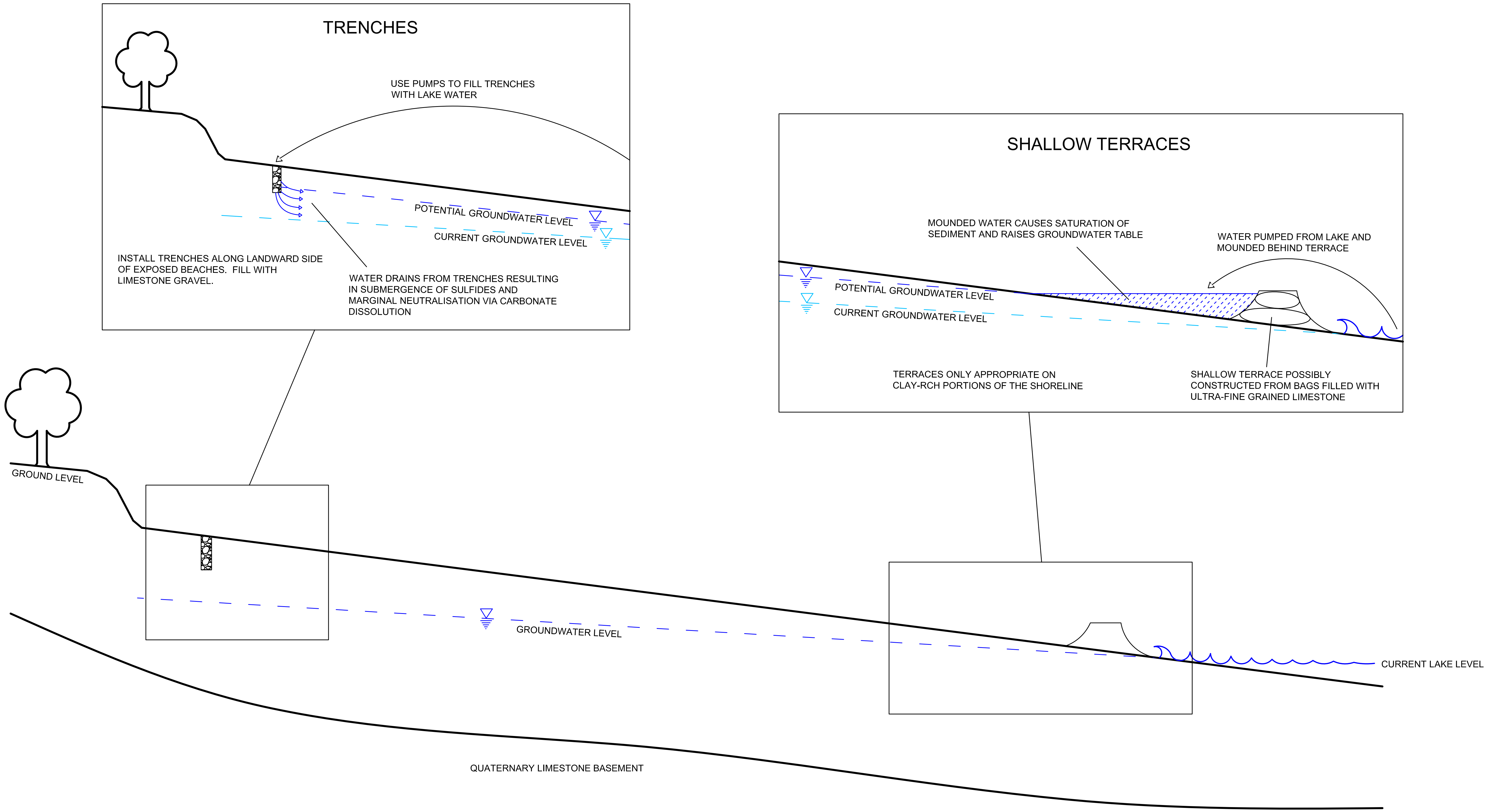

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CLIENT: PRIMARY INDUSTRIES AND RESOURCES SOUTH AUSTRALIA			DRAWING NO. 1
SCALE: NTS A3	DATE: NOV 2008	OFFICE: MELBOURNE	PROJECT NO: RSSA0823
DRAWN BY: DG	APPROVED BY: JRT	REVISION: 0	SHEET: 1 of 1

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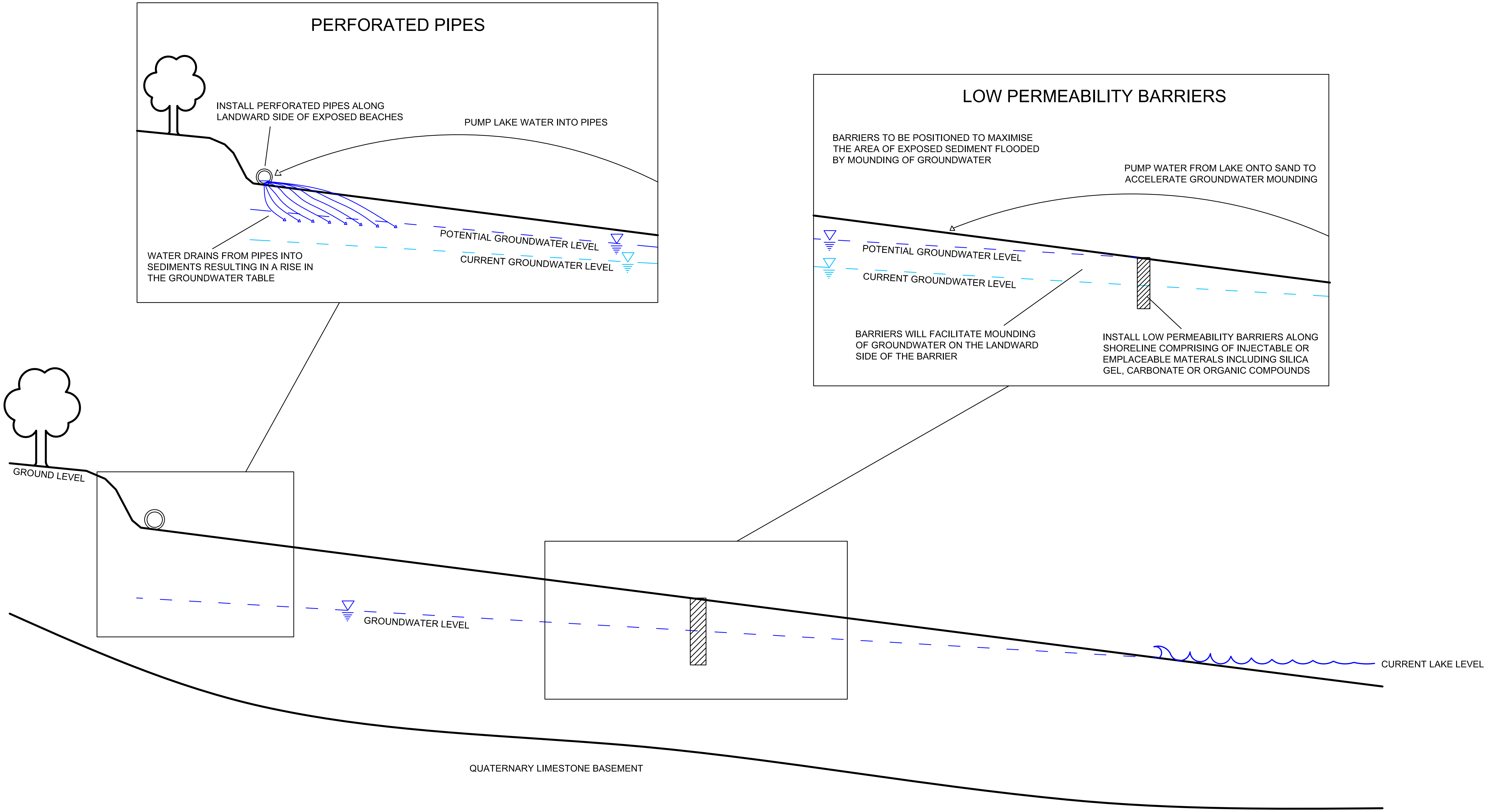

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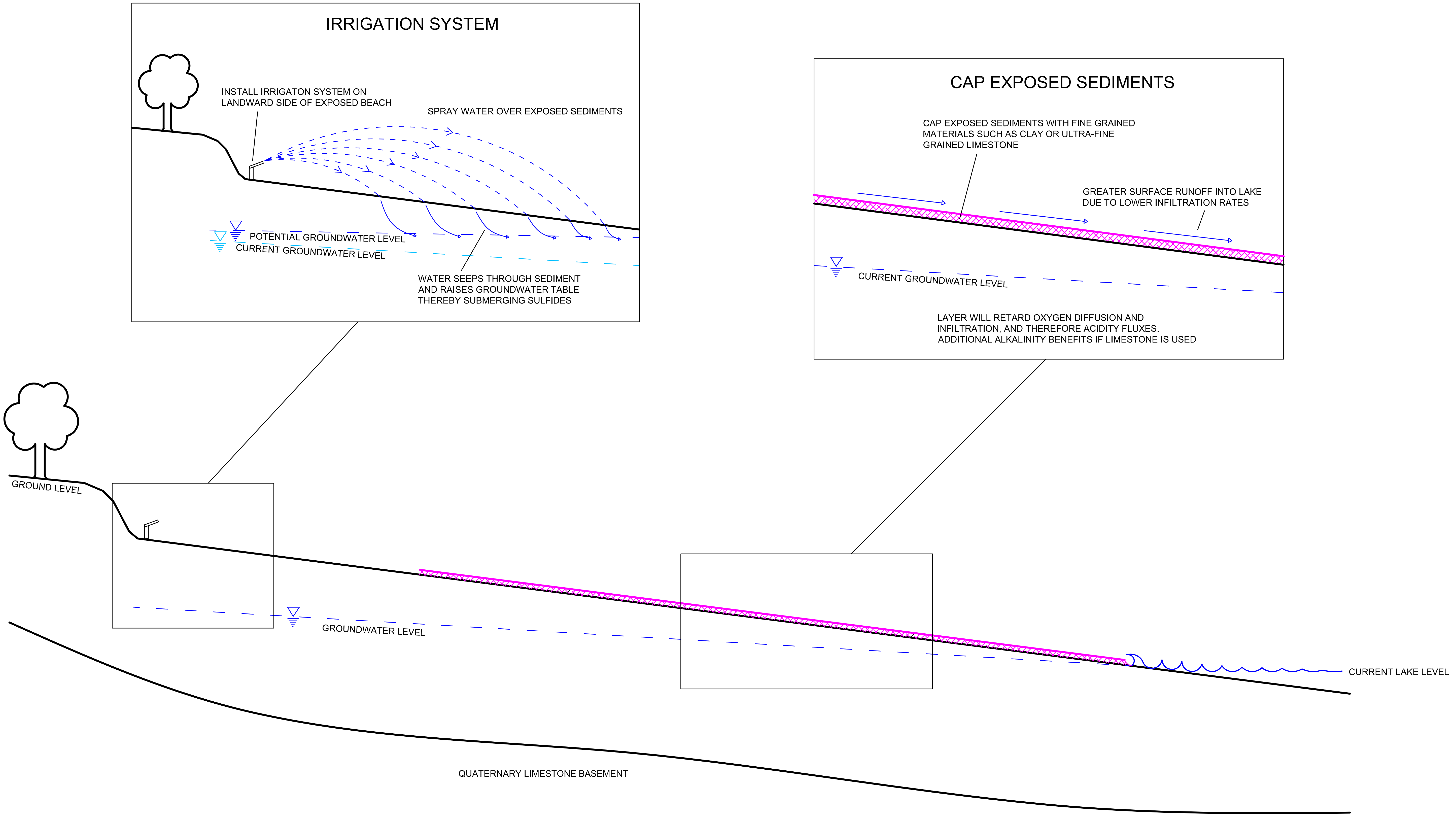

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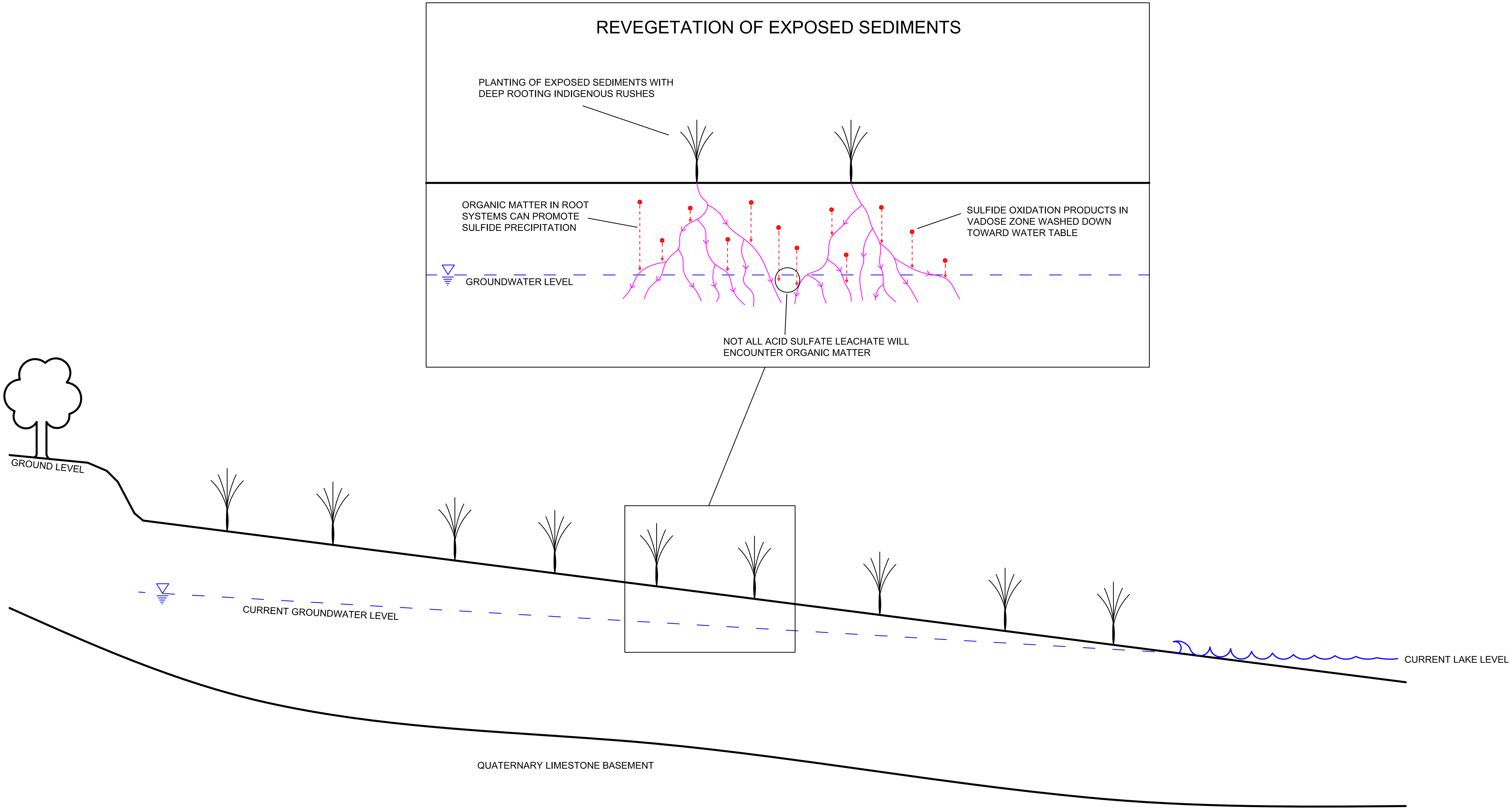

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4.5 PRELIMINARY ASSESSMENT OF ASS MANAGEMENT OPTIONS

Table 10 provides a preliminary assessment of each of the management options, including those identified in Earth Systems (2008), in terms of the following factors:

- Ease of implementation;
- Expected performance;
- Timeframe for implementation and achievement of water quality objectives;
- Cost; and
- Risk ranking.

Each of these factors was scored on a scale of 0-5, with 5 being the most favourable (ie. easiest to implement, best performance, quickest remediation timeframe, lowest cost and lowest risk). The overall ranking (highest score) was then used to identify the preferred management options.

Table 10. Preliminary assessment of ASS management options for the Lower Murray Lakes.

Option number	Method	Applicability to both lakes	Applicability to individual target sites	Preliminary assessment criteria (optimum score = 5)					Overall ranking (optimum score = 25)
				Ease of implementation	Expected performance	Time frame for implementation and achievement of water quality objectives	Costs	Risk ranking	
PREVENTION									
	Seawater submergence								
1	Open barrages to ocean.	✓	✓	5	0	0	0	0	**5**
	Freshwater submergence								
2	Increase flow from rivers.	✓	✓	0	5	5	1	5	**16**
3	Continue pumping between lakes.	×	×	4	2	2	3	4	**15**
4	Apply evaporation reducing chemicals.	✓	✓	4	3	3	1	3	**14**

Option number	Method	Applicability to both lakes	Applicability to individual target sites	Preliminary assessment criteria (optimum score = 5)					Overall ranking (optimum score = 25)
				Ease of implementation	Expected performance	Time frame for implementation and achievement of water quality objectives	Costs	Risk ranking	
CONTROL									
	Keep exposed sediments wet								
5	Develop shallow terraces.	✓	×	4	1	2	3	4	**14**
6	Install and fill trenches with water.	✓	✓	5	4	3	3	4	**19**
7	Install perforated pipes and irrigate banks.	✓	✓	5	4	3	3	4	**19**
8	Install and use irrigation systems.	✓	✓	5	4	3	3	4	**19**
	Install low permeability groundwater barriers								
9	Install low permeability barriers.	✓	✓	3	3	2	1	4	**13**
	Cap exposed sediments								
10	Cap exposed sediments.	✓	×	5	3	3	2	4	**17**
	Add organic matter to lakes								
11	Plant trees for leaf litter.	✓	✓	5	2	1	5	5	**18**
12	Add organic matter to lake via barges.	✓	✓	4	2	3	3	3	**15**
13	Flocculate algae from the water column.	✓	✓	5	2	2	4	3	**16**
14	Add organic matter to lake via helicopter.	✓	✓	4	2	3	1	2	**12**

Option number	Method	Applicability to both lakes	Applicability to individual target sites	Preliminary assessment criteria (optimum score = 5)					Overall ranking (optimum score = 25)
				Ease of implementation	Expected performance	Time frame for implementation and achievement of water quality objectives	Costs	Risk ranking	
15	Remobilise organic-rich mud.	✓	✓	4	2	2	3	2	**13**
	Add organic matter to exposed sediments								
16	Add organic matter to shoreline.	✓	✓	4	3	3	3	3	**16**
17	Add organic matter to trenches along shoreline.	✓	✓	4	3	3	3	3	**16**
18	Revegetate exposed sediments.	✓	✓	5	3	3	4	3	**18**
	Add organic matter to river								
19	Add organic matter to rivers.	×	×	4	2	3	3	3	**15**
TREATMENT									
	Limestone addition along or within existing waterways feeding the lakes (erosional dispersion of limestone)								
20	Refer to Earth Systems (2008).	×	×	5	2	2	5	1	**15**
	Alkalinity generating ponds along margins of waterways feeding the lakes								
21	Refer to Earth Systems (2008).	×	×	3	2	3	2	1	**11**
	Install vertical permeable reactive barriers								
22	Install vertical permeable reactive barriers.	✓	✓	3	4	4	1	4	**16**
	Limestone addition to exposed sediments								
23	Add limestone over exposed sediments.	✓	✓	3	3	3	3	4	**16**
24	Add limestone to trenches.	✓	✓	3	4	2	3	4	**16**

Option number	Method	Applicability to both lakes	Applicability to individual target sites	Preliminary assessment criteria (optimum score = 5)					Overall ranking (optimum score = 25)
				Ease of implementation	Expected performance	Time frame for implementation and achievement of water quality objectives	Costs	Risk ranking	
	Limestone addition to lakes via single static dosing into flowing water								
25	Refer to Earth Systems (2008).	✓	✓	4	4	5	4	4	**21**
	Limestone addition to lakes via multi-point dosing locations from access roads in lakes								
26	Refer to Earth Systems (2008).	✓	✓	3	3	4	3	4	**17**
	Limestone dosing into lakes from mobile barges								
27	Refer to Earth Systems (2008).	✓	✓	2	5	3	3	4	**17**
	Limestone addition to lakes via helicopter								
28	Refer to Earth Systems (2008).	✓	✓	3	4	5	1	1	**14**
	Addition of hydrated lime slurry to exposed sediments								
29	Add calcium hydroxide to exposed sediments.	✓	✓	4	3	4	1	3	**15**
	Addition of granular caustic magnesia (MgO) to exposed sediments								
30	Add caustic magnesia to exposed sediments.	✓	✓	4	3	4	1	3	**15**

4.6 PREFERRED MANAGEMENT OPTIONS

4.6.1 Natural remediation processes

A brief assessment of the water chemistry of the lakes suggests some natural remediation may be occurring in the deeper portion of the lakes. If this process is confirmed to be operating, it needs to be sustainable. The process is expected to benefit from the maintenance of carbonate saturation in lake waters and sulfate reducing bacterial (SRB) activity in basal lake sediments. Maintaining carbonate saturation may require limestone addition to the lakes at some point in time, depending how much is currently stored in lake sediments. SRB activity may require significant organic carbon storage and ongoing organic carbon inputs to the basal lake sediments. The precipitation of pyrite via SRB activity may also be limited by the availability of iron, thereby requiring artificial iron oxide (hematite) addition. The presence of excess iron could have the effect of accelerating sulfate (and acidity) removal from the water column. Analysis of basal sediments for key components that could limit natural remediation (ie. SRB activity) will assist with the assessment of critical lake water quality management decisions.

Hence, key preferred management options include maintaining limestone saturation and an excess of organic matter within the lakes to ensure ongoing natural remediation processes. This would primarily be achieved by:

- Limestone addition to lake if necessary to maintain carbonate saturation; and/or
- Organic matter (± iron oxide) addition to lake if necessary to maintain vigorous SRB activity in basal lake sediment; and/or

In addition, one or more secondary management options (Section 4.6.2) are likely to be required, depending on their performance in a series of monitored field trials and outcomes of other future investigations (Section 5).

4.6.2 Secondary management options

Management options described in Table 9 were assessed and scored in terms a) ease of implementation; b) expected (remedial) performance; c) timeframe for implementation and achievement of water quality objectives; d) cost, and e) overall risk (refer to Table 10). Of the total 30 potential management options, a subset of 6 was selected for more detailed assessment based on achieving an overall ranking of 17 or more points. The preferred management measures from Table 10 largely fall into the category of "source control" rather than treatment. These involve approaches that attempt to limit acidity discharges from the exposed sediment banks by retarding sulfide oxidation or encouraging SRB activity within the exposed sediments. Such methods aim to reduce the dependence on natural remediation (or passive/active treatment). None of the limestone treatment options (that would assist with maintaining limestone saturation) were included in this assessment as they were independently reviewed in Earth Systems (2008).

The six highest ranking control measures in Table 10, excluding limestone addition to the lakes, are provided below. Due to the high cost associated with most management strategies and the very large areas potentially requiring ASS management, it is recommended that Options 6-8, 10 and 18 detailed below only be considered for the most problematic sections of exposed sediment, rather than the entire perimeter of the lakes. Note that one or more of these options could be applied at any given site.

Option 6: Control – Keep exposed sediments wet (install and fill trenches with limestone and water)

Install shallow trenches (eg. 30 cm x 30 cm) along the landward side of exposed beaches. Dig shallow trenches and fill with limestone gravel. Use pumps to periodically or continuously fill trenches with lake water. This will recharge groundwater and assist with the submergence of sulfidic material or the minimisation of oxygen diffusion into the sediments.

Excavation could be conducted with backhoes, small excavators or trench diggers. Limestone aggregate will be used to infill the trenches within minutes of their excavation by controlled dumping from tip trucks. Land-based 3-phase electric pumps (grid power) will draw water from the lake and discharge below ground into the shallow trenches. The trenches will be protected from excessive collapse. Trenches will be constructed in segments up to 1.0 km long and each pump will feed 2 x 1 km segments from a central location. Pumps will sequentially direct water into adjacent segments. Water pump rates should ensure that much of the exposed sediment mass for each segment is significantly saturated in a single day. Pump rates of 40-60 L/s are envisaged. Once partially saturated, a segment of sediment bank may not require ongoing wetting for several more days (in the summer period).

Refer to Drawing 1.

Option 7: Control – Keep exposed sediments wet (install perforated pipes and irrigate banks)

Install perforated pipes along the landward side of beaches and periodically or continuously pump lake water onto the exposed sediments.

Water from the lake will be pumped via 3-phase electric pumps at approximately 40-60 L/s into segments of perforated polyethylene irrigation pipes up to 1 km long. Pipe segments may need to be anchored to the banks and sometimes may require shallow burial. Pumping at high flow rates may only be needed for a 24 hour period per 1.0 km segment, per fortnight. Each pump could sequentially feed adjacent 1.0 km segments of pipeline. Hence only periodic pumping may be required. The pumping will increase the moisture content of the exposed sediments in order to retard sulfide oxidation, rather than continuously submerge the exposed sediment banks.

Refer to Drawing 2.

Option 8: Control – Keep exposed sediments wet (install and use irrigation systems)

Install irrigation systems on exposed sediments and periodically pump water over sediments. This would recharge groundwater and assist with minimising sulfide oxidation by maintaining high moisture levels in the exposed sediments. Refer to Option 18 for methods to encourage farmers to irrigate exposed banks to lower implementation costs.

Refer to Drawing 3. Note that the drawing is schematic only and does not account for many of the assumptions made in the detailed cost estimate in Attachment D.

Option 10: Control – Cap exposed sediments

Cover exposed sediments with fine grained materials that will retard oxygen diffusion and infiltration, and therefore acidity fluxes. Materials could include clay or perhaps ultra-fine grained limestone. Such materials will need transported to site in truck, dumped and spread using graders. Only very thin layers (eg. 5 mm thick) may be necessary, but some irrigation of the banks may be necessary to wash the fine particles into the sand. The use of limestone provides for some alkalinity addition as well as retarding oxygen diffusion. It may also be appropriate to combine this option on problematic banks with some periodic irrigation.

Refer to Drawing 3.

Option 11: Control – Add organic matter to lakes (revegetate upwind shores)

Revegetate extensive portions of the up wind shores of the lakes with large native trees. Leaf litter from the trees will provide slow, passive but ongoing organic matter addition to the lakes over the long term. This option needs to be part of a long-term, coordinated strategy for management of the lakes. Farmer incentives, including stock sheltering, business diversification and carbon credits need to be introduced as part of this approach.

Option 18: Control – Add organic matter to exposed sediments (revegetate exposed sediments)

Conduct or encourage strategic planting of exposed sediment banks with deeply rooting, rapid growth plant species which produce a great deal of above ground biomass (eg. local reeds, grasses for stock). Planting activities need to keep pace with the receding shoreline. Harvest the above ground biomass and lay down on sediment banks to contribute organic matter to sediments, or alternatively allow stock to graze on grasses. It is possible that irrigation of the sediment banks could be combined with this option (eg. the production of additional pasture for stock) to provide extra income for farmers. In this way, farmers may be able to assist with management of the exposed sediments, and defray some of the costs.

Note that the very fine seeds of reeds/rushes are not suitable for aerial seeding. Lightweight seed dispensing machinery (suited to soft/wet sediments) are needed to distribute such seeds just below surface.

Refer to Drawing 4.

4.6.3 Risks and management measures

An initial identification and assessment of key risks for all of the potential management options is provided in Tables 9 and 10.

4.6.4 Monitoring and assessment of performance

As part of the field monitoring program to gather key data sets to quantify the likely impact of ASS on lake water quality, a strategy to verify the performance of several of the preferred management options is proposed (refer to Section 5 and Attachment C).

4.6.5 Preliminary cost estimates for preferred management options

A preliminary assessment of the expected costs associated with each of the 6 preferred management options is provided in Attachment D. Since it is proposed to focus one or more of these options on high risk ASS sites (Table 1) rather than implement them more widely, the budget data are provided in Attachment D as costs per unit length (km) of sediment bank, where possible. However, the option of planting of native vegetation upwind of the lakes was costed per unit length (km) of a 50 m wide vegetation strip, and is therefore not directly comparable with cost estimates for the other options.

The cost estimates for each of the preferred management options is summarised in Table 11.

Table 11. Summary of capital and operating cost estimates associated with implementation of 6 preferred ASS management options.

Site ID	Site Name	Length (km)	Width (km)	Area (ha)	OPTION 6 Keep exposed sediments wet using limestone trenches to deliver lake water		OPTION 7 Keep exposed sediments wet using perforated pipes to deliver lake water		OPTION 8 Keep exposed sediments wet using irrigation+		OPTION 10 Cap exposed sediments with fine grained clay and /or limestone		OPTION 11 Add organic matter to lakes by planting native vegetation on upwind lake shores* # ^ +		OPTION 18 Add organic matter to the exposed sediments by planting deeply rooting, rapid growth plant species	
					Capital Costs	Operating Costs / year	Capital Costs	Operating Costs / year	Capital Costs	Operating Costs / year	Capital Costs	Operating Costs / year	Capital Costs	Operating Costs / year	Capital Costs	Operating Costs / year
1	Point Sturt	7.7	0.894	688	$ 715,993	$ 296,324	$ 754,490	$ 269,759	$ 2,444,423	$ 181,053	$ 3,366,848	$ 1,247,400	$ 4,821,950	$ 1,008,263	$ 1,019,299	$ 170,016
2	Poltalloch	13	0.894	1162	$ 1,208,820	$ 500,287	$ 1,273,815	$ 455,437	$ 4,126,948	$ 305,674	$ 5,684,289	$ 2,106,000			$ 1,720,895	$ 287,040
3	Meningie	8.7	1.551	1349	$ 978,064	$ 334,807	$ 1,021,561	$ 304,792	$ 5,549,173	$ 220,798	$ 6,068,733	$ 1,620,810			$ 1,940,470	$ 309,155
4	Campbell Park	4.3	1.551	667	$ 483,411	$ 165,479	$ 504,909	$ 150,644	$ 2,742,695	$ 109,130	$ 2,999,489	$ 801,090			$ 959,083	$ 152,801
Total costs including 15% Contingency (AU$ ex. GST)**					**$ 3,386,287**	**$ 1,296,897**	**$ 3,554,775**	**$ 1,180,632**	**$ 14,863,238**	**$ 816,655**	**$ 18,119,359**	**$ 5,775,300**	**$ 4,821,950**	**$ 1,008,263**	**$ 5,639,746**	**$ 919,011**

+ Exposed sediment bank widths were estimated by dividing the area of exposed sediment bank are for a water level decrease from -0.5m AHD to -1.5m AHD for each Lake by the corresponding lake perimeter.

* The native revegetation option includes a 45 km x 0.05 km zone and a 25 km x 0.05 km zone located adjacent to the upwind shorelines of Lake Alexandrina and Lake Albert, respectively.

** Costs do not include decommissioning and /or removal of equipment and materials.

+ Costs for Option 8 (irrigation of exposed sediments) do not include potential benefits from grazing and / or cropping of irrigated land.

Potential financial benefits could be gained from the sale of carbon credits (generated from afforestation). Provisional estimate based on International Trading Schemes indicate a value of $400 per km lake perimeter ($28,000 if all 70 km proposed lake perimeter are revegetated). Further details will be released in the Australian Government Carbon Pollution Reduction Scheme White Paper due for publication in December 2008.

^ Legal costs associated with land acquisition for native revegetation have not been estimated.

4.6.6 Organisations that could facilitate a broader management program

At this stage, ASS management in the Lower Murray Lakes could benefit from the input of specialised stable isotope geochemists (see Section 5). Such expertise exists at ANSTO (Dr. Chris Waring), at Monash University (Dr. Ian Cartwright) and at CSIRO, and probably in several other organisations. An analytical program could be devised to estimate sulfate inputs from the exposed sediments on a fortnightly or monthly basis. This would provide far greater certainty about the oxidation process, and can be expected to independently quantify the bulk sulfide oxidation rate of the lake system. Remediation programs that can deal with the estimated acidity inputs can then be more confidently developed.

5.0 CRITICAL DATA GAPS AND FUTURE WORK PROGRAM

A series of ASS management options has been detailed in this report. The relative merit of these options is difficult to quantify as there are critical data gaps in our understanding of the lake acidification processes. Initial indications are that some acid production (sulfate addition) and acid neutralisation is occurring in the lakes. The scale and speed of the lake acidification as a function of declining lake water levels remains poorly understood.

To develop further understanding of these issues and guide the selection of appropriate ASS management options, the following data are required:

- Sulfide oxidation rate for the exposed sediments as a function of the sediment moisture content.
- The flux of acid from the sediment banks to the lakes. The acid flux is influenced by:
  - The hydrogeological characteristics of the sediment banks (ie. transmissivity).
  - Rainfall / evapotranspiration.
  - Wind speed and direction.
  - Sulfide content and spatial distribution of sulfides in the sediments.
  - The presence (and availability) of organic material.
  - The presence (and availability) of carbonates.
  - The presence (and availability) of iron.
  - Sediment moisture content.
- Lake sediment geochemistry (potential for natural bioremediation within basal lake sediments) including:
  - Net Acid Production Potential (NAPP).
  - Net Acid Generation Potential (NAG) at pH 4.5 and 7.0.
  - NAG pH.
  - Metal concentrations in NAG leachate.
  - Total sulfur and sulfide-sulfur (chromium reduceable sulfur).
  - Total carbon, organic carbon and inorganic (carbonate) carbon.
  - Available iron.

To gather data relating to the critical areas described above, the following work program is recommended:

1. Investigation of lake sediment geochemistry (including parameters listed above).

   Characterisation of lake sediment geochemistry will assist in understanding the nature and extent of natural bioremediation processes currently occurring at the base of the lakes, and thus the potential capacity for ongoing bioremediation. This will determine the likely requirement for limestone and/or organic matter addition to the lake waters to facilitate natural processes and the need (if any) for implementing secondary management options such as those described in Section 4.6.2

2. Investigation of the proportion of sulfate contributed by recent sulfide oxidation processes based on sulfur and oxygen isotope geochemistry.

   This investigation would assist in quantifying the extent of acidity generation in the lakes associated with increased exposure of ASS due to falling water levels over the last two years. This would enable the potential scale of future acidity generation to be more accurately estimated.

3. Establishment of a field monitoring and laboratory test work program to develop further understanding of the processes of acid generation, transport, and in-situ neutralisation / reduction within sediments and lake waters.

   Field monitoring data (eg. 8 test sites) will provide fundamental information on the behaviour of exposed sulfidic sediments and groundwater migration as a function of a range of environmental variables.

   Laboratory test work will provide well-constrained and quantitative data on acidity generation rates (ie. sulfide oxidation rates) from typical lake sediments as a function of their moisture content.

   By combining the field and laboratory components and conducting 2 or 3 dimensional hydrogeological modelling, it will be possible to estimate acidity fluxes from the exposed sediments.

4. Field trials of secondary ASS management options.

   To confirm the potential benefits of the preferred management options, it is recommended that field trials are conducted at a number of the test sites established for the field monitoring program (Item 3 above). Baseline data would be collected at all test sites prior to commencing the trials at selected sites (eg. 3 sites). The remaining test sites (eg. 5 sites) would provide ongoing baseline data throughout the trials. Implementation of field trials will ensure that the most appropriate ASS management options are selected.

Further detail on the proposed work program is detailed in Attachment C. A schematic diagram of the proposed field monitoring program is also provided in Attachment C. No cost estimate for the proposed work program has been developed at this stage.

6.0 CONCLUSIONS

The following key conclusions can be drawn from this study:

- The total acidity generation potential for the Lower Murray Lakes is around 680,000 tonnes H_2SO_4, based on a 1.0 m drop in lake levels.
- Approximately 200,000 tonnes of soluble alkalinity ($CaCO_3$ equivalent) is currently available within the lakes to neutralise any acid generated from exposed shoreline sediments. A further 17,500 tonnes of alkalinity ($CaCO_3$ equivalent) enters the lake system each year via the Murray River.
- Effective oxidation rates of (i) less than 2 wt% FeS_2/year are not expected to result in any lake acidification, (ii) around 5 wt% FeS_2/year could result in a gradual decline in lake water alkalinity over approximately 10 years followed by progressive acidification of the lakes, (iii) greater than 50 wt% FeS_2/year could lead to rapid acidification of the lakes (over a period of months).
- If significant sulfate reduction is likely to occur or can be encouraged to occur within the exposed sediments, or is likely to occur or can be encouraged to occur in the basal lake sediments, then this model will be significantly overestimating the risk associated with acid generation.
- Between 1995-1998 and the present, key largely conservative ions with the lakes have been concentrated by evaporation by a factor of approximately 5. These components include Na, Cl, K and Mg.
- Over the same time period, Ca, HCO_3, total alkalinity and total hardness have only increased by a factor of approximately 2. This strongly indicates that since 1995-1998, carbonate saturation has been achieved. Hence, it is likely that Ca, HCO_3, total alkalinity and total hardness reached a maximum at some time between 1998 and 2008 and have remained unchanged since due to carbonate precipitation. This means that minerals such as calcite, aragonite and dolomite have been precipitating from the lake water for a number of years. The mass of carbonate stored in the lake sediments over this period could be up to 17,500 tonnes $CaCO_3$ per year, based on inputs from the Murray River of 350 GL/year containing 50 mg/L $CaCO_3$ alkalinity.
- From the 1995-1998 period to present, SO_4 values (in Lake Albert) have concentrated by a factor of approximately 5, indicating typical enrichment relative to the conservative ions such as Cl.
- Key changes in the water chemistry during 2008 in both lakes are due largely to concentration and dilution processes. This is supported by sympathetic changes in at least Na, Cl, Mg, SO_4 and total hardness.
- Concentration processes include evaporation and evapotranspiration, while dilution processes include river inflows, water pumping between lakes and rainfall.
- Using chloride as a conservative component, and therefore a direct measure of the extent of concentration or dilution, variations in sulfate concentrations tend to indicate small but significant independent rises and falls relative to dilution and concentration trends. A simple explanation for rises in sulfate concentration is addition from exposed sediments due to sulfide oxidation. Falls in sulfate concentration in lake water may be in response to sulfide precipitation in basal sediments due to bacterial activity. Changes in sulfate concentration could also be explained by changes in $Cl:SO_4$ ratios associated with a) variable $Cl:SO_4$ ratios from the Murray Rivers (and possibly other tributaries), or b) variable concentrations of seawater mixing with freshwater in Lake Alexandrina. The substantial and relatively rapid changes in

external Cl:SO_4 ratio inputs to the lakes required to affect the overall Cl:SO_4 ratio of the lakes suggests that these potential explanations are unlikely.

- If sulfide oxidation and bacterial sulfide precipitation processes are responsible for the observed fluctuations in sulfate relative to chloride, then the following mechanisms are indicated:
  - Sulfide oxidation in the exposed sediments leading to the discharge of sulfate-rich groundwater that is sometimes acidic. This suggests that, at least in some locations, no significant sulfate reducing bacterial activity is occurring in the exposed sediments.
  - Once elevated sulfate concentrations reach the lakes, any acidity is being dealt with by the soluble and stored (carbonate precipitates) alkalinity in the lakes. No significant falls in soluble alkalinity, total hardness or even pH appear to be associated with the periods of elevated sulfate concentrations. Hence, at present, the lake systems (water and sediments) are effectively handling sequential acidity inputs from the exposed sediments.
  - Sulfate reduction appears to be occurring in the basal lake sediments, as indicated by substantial periodic drops in soluble sulfate concentrations in lake water relative to chloride variations.
- This model for natural acidification and effective remediation within the lakes, if accurate, provides strong direction for the selection of appropriate management measures, namely:
  - The exposed sediments may not be playing a large role in sulfate reduction and are possibly only locally providing carbonate neutralisation.
  - Carbonate saturation in the lakes is vital for ensuring that sulfate reducing bacteria can reverse the oxidation process within basal sediments in the lake.
  - Much of the remediation process is occurring in the deeper portion of the lakes within organic-rich, iron-bearing sediments.
  - It is not known whether there is sufficient organic carbon, inorganic carbon (carbonate) or iron to facilitate the ongoing precipitation of pyrite within basal lake sediments.
  - It is important to ensure that there is sufficient organic carbon, inorganic carbon (carbonate) and iron to continue the natural remediation process within basal lake sediments.

The preferred ASS management strategy for the lakes, at this stage, comprises the following:

- Maintain or ensure limestone saturation within the lakes;
- Redress potential shortfalls or imbalances in the mass of available organic and inorganic carbon and iron within basal lake sediments.
- Modify the exposed banks to minimise and control acidity generation. Potential control measures could include:
  - Keep exposed sediments wet (install and fill trenches with limestone and water).
  - Keep exposed sediments wet (install perforated pipes and irrigate banks).
  - Keep exposed sediments wet (install and use irrigation systems).
  - Cap exposed sediments.
  - Add organic matter to lake (revegetate upwind shores).
  - Add organic matter to exposed sediments (revegetate exposed sediments).

7.0 RECOMMENDATIONS

Key recommendations arising from this study are outlined below:

- Conduct a more rigorous assessment of the available lake and river water chemistry to develop a better understanding of the processes influencing chemical changes. Provide this detailed assessment to all stakeholders every time new data is available.
- Undertake to monitor and maintain carbonate saturation in water within the lakes. This will involve routine assessment of saturation indices from water chemistry.
- Quantify the mass of available organic and inorganic carbon, iron and iron sulfide within the basal lake sediments and redress potential shortfalls or imbalances if necessary.
- Assess the potential to use sulfur (S) and oxygen (O) isotope analysis to quantify the bulk sulfide oxidation rates for the lake system, and assist with quantification of suitable management strategies.
- Implement the future work program detailed in Attachment C in order to fill critical data gaps.
- Utilise 3-5 of the proposed instrumented sediment banks (refer to Attachment C) to trial some of the preferred management options for the exposed sediments.
- Use the results of the future work program and stable isotope analytical program to refine the acidity generation, lake water quality and remediation models.

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Sullivan, L., Burton, E., Bush, R., Watling, K. and Bush, M. (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*. Centre for Acid sulfate soil Research Southern Cross Geoscience, Southern Cross University, Lismore New South Wales.

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Attachment A:

Acidity Generation in the Lower Murray Lakes – General Reactions

Acidity 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 (Fe^{2+}), 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 (Fe^{2+}) released by pyrite oxidation may be further oxidised to ferric iron (Fe^{3+}) 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 (Fe^{3+}) 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:

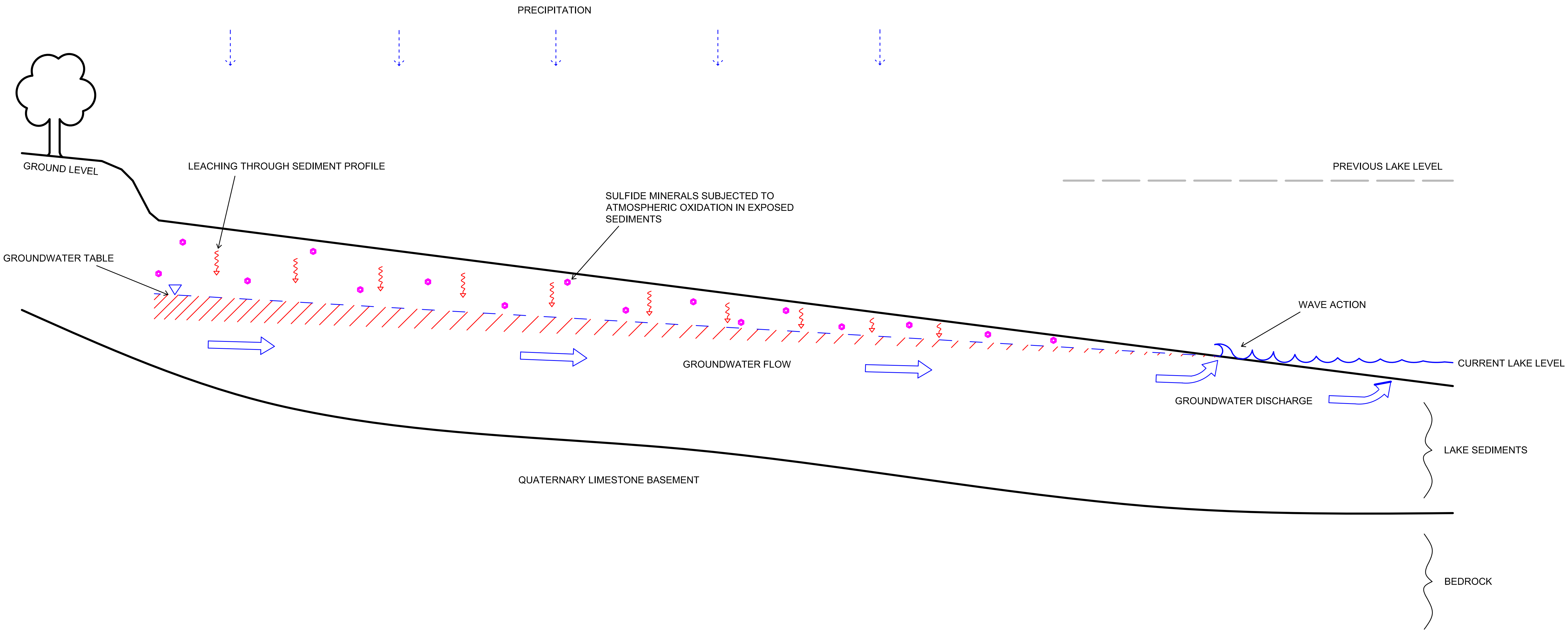
1. Acid (H^+) is directly generated by the oxidation of sulfur (Reaction 1).
2. Acid (H^+) is generated by the precipitation of metal hydroxides (eg. $Fe(OH)_3$, $Mn(OH)_4$: Reaction 3) during oxidation / neutralisation / dilution reactions.

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).

Attachment B:
Acidity Generation in the Lower Murray Lakes – Concept Drawing

RevNo	Revision note	Date	Signature	Checked



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TITLE: LOWER MURRAY LAKES CONCEPT DRAWING OF LAKE ACIDIFICATION PROCESS			
CLIENT: PRIMARY INDUSTRIES AND RESOURCES SOUTH AUSTRALIA			DRAWING NO. AB 1.1
SCALE: NTS A3	DATE: NOV 2008	OFFICE: MELBOURNE	PROJECT NO: RSSA0823
DRAWN BY: DG	APPROVED BY: JRT	REVISION: 0	SHEET: 1 of 1

Attachment C:
Proposed Laboratory and Field Monitoring Program

Proposed field monitoring testwork program

The proposed field testwork program is based on several monitoring sites located in high risk areas of exposed sediment (ie. high sulfide contents close to the surface). A total of approximately 8-10 monitoring sites will be necessary. Each monitoring site should consist of at least 3 sets of (3) nested piezometers and soil moisture probes, distributed perpendicular to the shoreline and spaced approximately 100 m apart across the banks and into the lake (see Drawing AC.2).

The purpose of the monitoring sites is to:

- Estimate the acid flux from the sediments into the lake using groundwater velocity and water chemistry data.
- Develop an understanding of the soil moisture profile. This data can be used with laboratory data relating oxidation rates to soil moisture content to estimate potential acidity fluxes from the sediments as a function of moisture content.
- Investigate the influence of organic matter, carbonates, hydrogeology and sediment types on acidity fluxes.

Water chemistry data are required to estimate the acidity flux from the exposed sediments. To determine the spatial variations in water chemistry in the sediments, each nested piezometer set should consist of the following:

- Three piezometers (constructed in separate boreholes each approximately1 m apart), screened sequentially starting from the groundwater level to a provisional depth of 0.3 m below the groundwater level (see cross section A – B in Drawing AC.2). This will allow representative water samples to be collected at three water depth intervals.
- All piezometers should be surveyed at the time of construction and referenced to a common datum to allow water chemistry and water level data from different monitoring sites to be compared.

To estimate the groundwater velocity, the groundwater hydraulic gradient and the sediment hydrogeological properties (eg. hydraulic conductivity) are required. The groundwater velocity will be used with groundwater chemistry data to estimate local acidity fluxes into the lake. To achieve these outcomes, each monitoring site requires:

- A water level sensor (provisionally an In-Situ LevelTroll 500 vented pressure sensor with internal power supply and data logger) should be installed at each set of nested piezometers. The sensor should be located in the deepest well and be configured to log water depth data over time. Monitoring the groundwater level will assist with determination of the groundwater hydraulic gradient.
- (A minimum of one water level sensor should be installed for each monitoring site to log variations in groundwater depth over time. A portable water level sensor may be used to regularly monitor water depth at other nested piezometer sets).
- At the time of bore construction, geological logs are required to characterise the local sediments.
- 1-2 kg soil samples should be collected for each 0.5 m of the bore, or at key lithological boundaries if they are <0.5m. Samples should be saturated with local water and stored in airtight containers for transportation to the laboratory for Acid Base Accounting analysis and grain size distribution. These analyses will provide further characterisation of the local sediments at each site.
- Falling (or rising) head tests should be carried out at each nested piezometer site to measure the hydraulic conductivity of the sediments for each bore.

To characterise the soil moisture profile between the ground surface level and the water table level, a soil moisture monitoring pipe should be installed adjacent to each set of nested piezometers. This characterisation will be used with meteorological data to develop a relationship between rainfall, wind, solar radiation and the soil moisture profile. The soil moisture monitoring pipe should consist of the following:

- A sealed PVC pipe suitable for the soil moisture sensor should be installed 1 to 2 m form the nested piezometer sets (to ensure that no interference is caused) to a depth of 0.2 m below the likely lowest groundwater level.
- An EnviroScan soil moisture probe fitted with multiple sensors to allow monitoring of the soil moisture profile in 0.1 m increments and connected to a data logger with a solar and/or 12 volt power supply should be installed at a minimum of one per set of nested piezometers for each monitoring site.
- A portable EnviroScan soil moisture probe should be used to regularly monitor the soil moisture profile at other nested piezometers where continual monitoring is not carried out.

Water chemistry data is required to use with groundwater velocity data to estimate the acidity flux from the sediments into the lakes. The following water chemistry data collection schedule is proposed for each Monitoring site:

- Field water quality parameters (pH, EC, ORP, T°C and DO) are to be collected on a weekly basis from each piezometer.
- Water samples are to be collected from selected piezometers (or monitoring sites) on a fortnightly basis. Water samples are to be refrigerated for transportation to the laboratory for analysis of:
    - General water quality parameters (pH and EC)
    - Major ions (Na, K, Mg, Ca, Cl and SO_4),
    - Dissolved metals (Al, As, Cu, Fe, Mn, Pb, Zn)
    - Total metals (Al, As, Cu, Fe, Mn, Pb, Zn)
    - Total alkalinity, bicarbonate.
    - Nutrients (total N, NO_3, total P, PO_4)
    - Sulfide (depending on the field measured ORP values).
    - Possibly stable isotope analysis (S and O).

- Soil moisture profile data (in 10 cm depth increments) is to be collected on a weekly basis at all nested well sites where soil moisture is not monitored remotely / continuously.

Proposed laboratory testwork program

The proposed laboratory testwork program involves establishing a set of column leach tests with objective of developing a relationship between the sulfide oxidation rate and sediment moisture content. This relationship can be used with soil moisture profile data from the field (see above) to estimate the acidity generation potential of the exposed sediment banks.

The proposed column leach test will involve a set of 5 column filled with representative soil samples from the lake bank sediments. The moisture content in each column will be controlled and monitored. Water will periodically be drawn from the base of the column to gather data relating to SO_4 concentration over time. The mass rate of SO_4 release is considered directly proportional to the mass rate of sulfide oxidised. Using this data the average soil moisture content in each column may be related to the sulfide oxidation rate.

A provisional methodology for the column leach tests is described below:

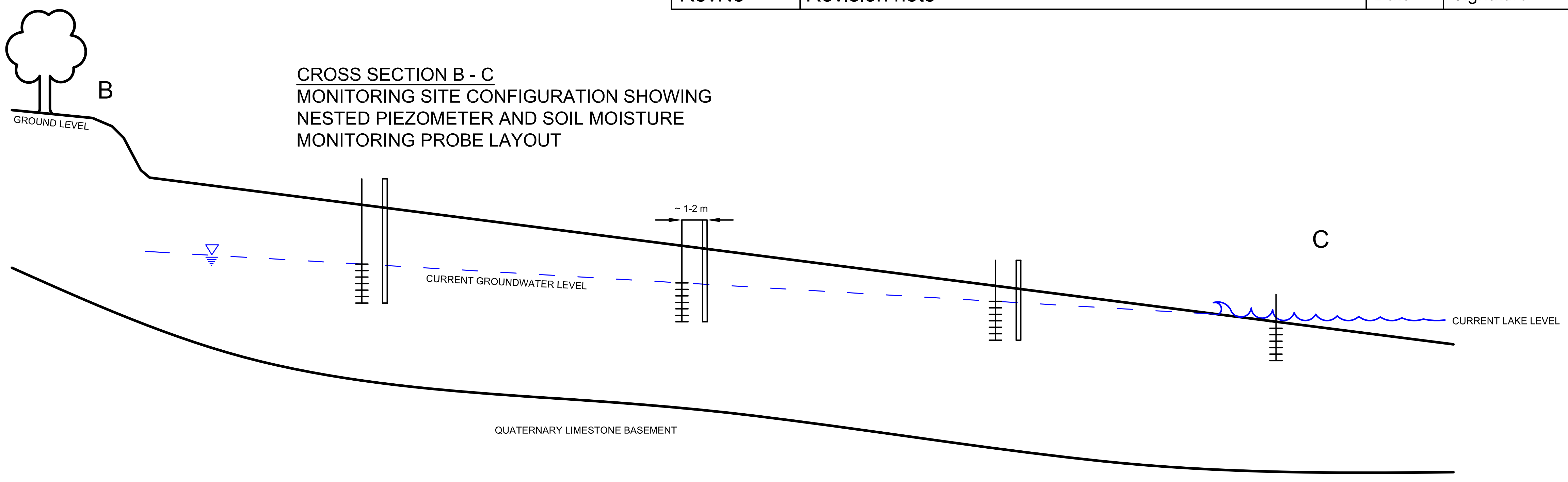
- Bulk representative samples of the lake sediments are to be collected (and logged) from below groundwater level from priority sites that have monitoring installations. The samples are to be saturated with groundwater water upon collection and stored in air tight containers for transport to the laboratory. Samples are to be analysed for:
  - o Field monitoring of groundwater pH, EC, ORP, T°C and DO.
  - o Grain size distribution.
  - o Acid-base accounting characteristics.
  - o Major elements.
  - o Trace metals.
  - o Carbon content (total C and organic C)
  - o Sulfur content (total S, Chromium reducible sulfur and SO_4).

- The size of each column should be nominally 2 m tall and 0.3 m in diameter, with an inner pipe for soil moisture monitoring. The bulk sample nature of the column leach tests will enable more accurate characterization of the sulfide oxidation rates.
- Periodic moistening of the columns with distilled water will be used to simulate the natural effects of rainfall.
- A heat lamp will be used to simulate the natural drying of the upper parts of the sediments.
- The average moisture content in each column will be controlled by varying the amount of distilled water added, and will be continuously monitored using an EnviroScan soil moisture meter with sensors at 0.2 m depth intervals down the centre of the column.
- Water samples will be collected every 1-2 weeks from the base of each column and analysed for
  - o General water quality parameters (pH and EC)
  - o Major ions (Na, K, Mg, Ca, Cl and SO_4),
  - o Dissolved metals (Al, As, Cu, Fe, Mn, Pb, Zn)
  - o Total metals (Al, As, Cu, Fe, Mn, Pb, Zn)
  - o Total alkalinity, bicarbonate.
  - o Nutrients (total N, NO_3, total P, PO_4)
  - o Sulfide (depending on the field measured ORP values).
  - o Possibly stable isotope analysis (S and O).

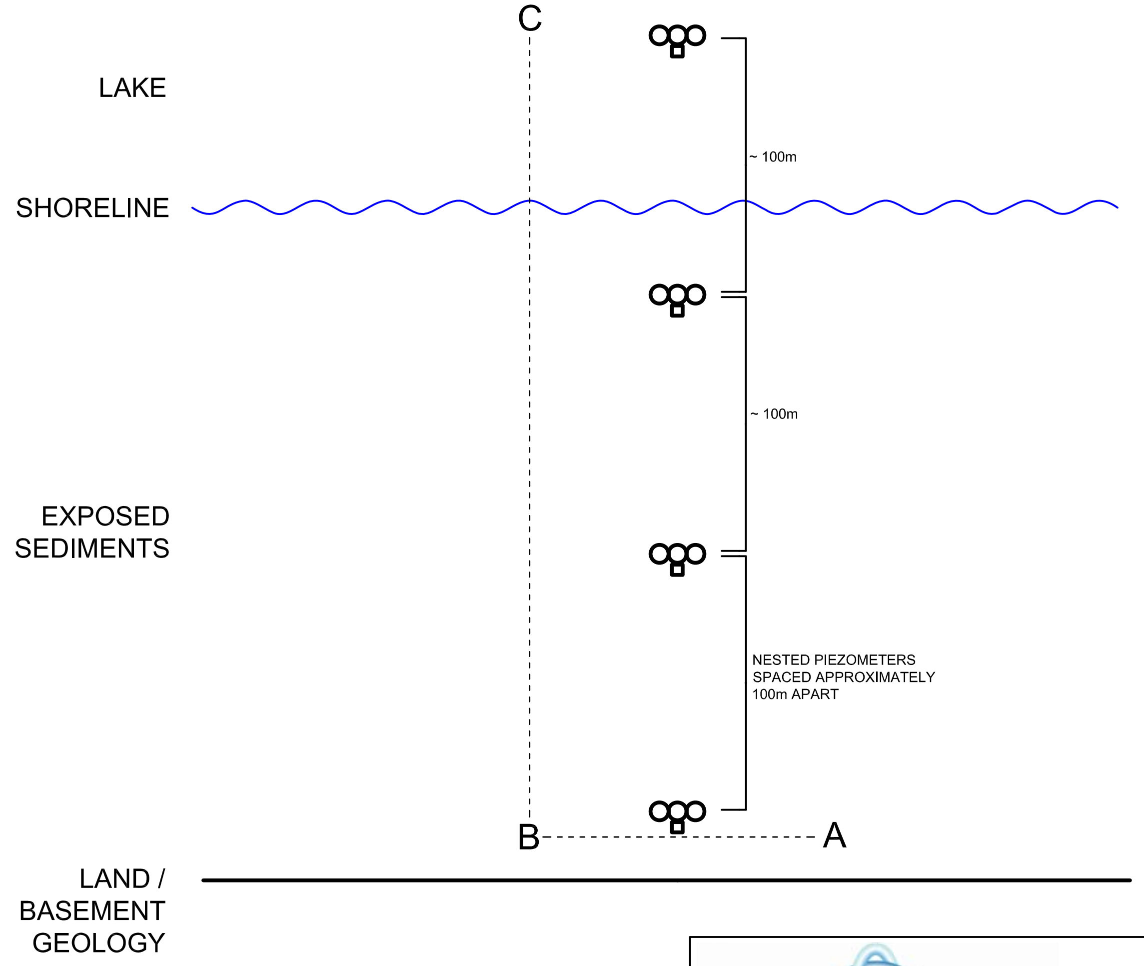
- Testwork should proceed for a period of at least 12 months.
- Upon completion of the column leach tests, representative soil samples from each column should be collected and analysed as described for the start of the testwork.

RevNo	Revision note	Date	Signature	Checked

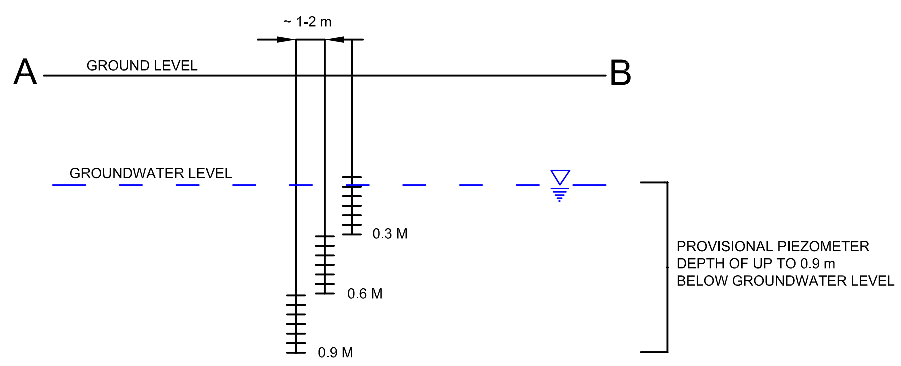
CROSS SECTION B - C
MONITORING SITE CONFIGURATION SHOWING NESTED PIEZOMETER AND SOIL MOISTURE MONITORING PROBE LAYOUT



PLAN VIEW - EXAMPLE SITE
MONITORING SITE CONFIGURATION SHOWING NESTED PIEZOMETERS AND SOIL MOISTURE MONITORING PROBE LAYOUT



CROSS SECTION A - B
NESTED PIEZOMETER SCREEN CONFIGURATION



LEGEND
- PIEZOMETER
- SOIL MOISTURE PROBE
- PIEZOMETER SCREEN
- SOIL MOISTURE PROBE PIPE

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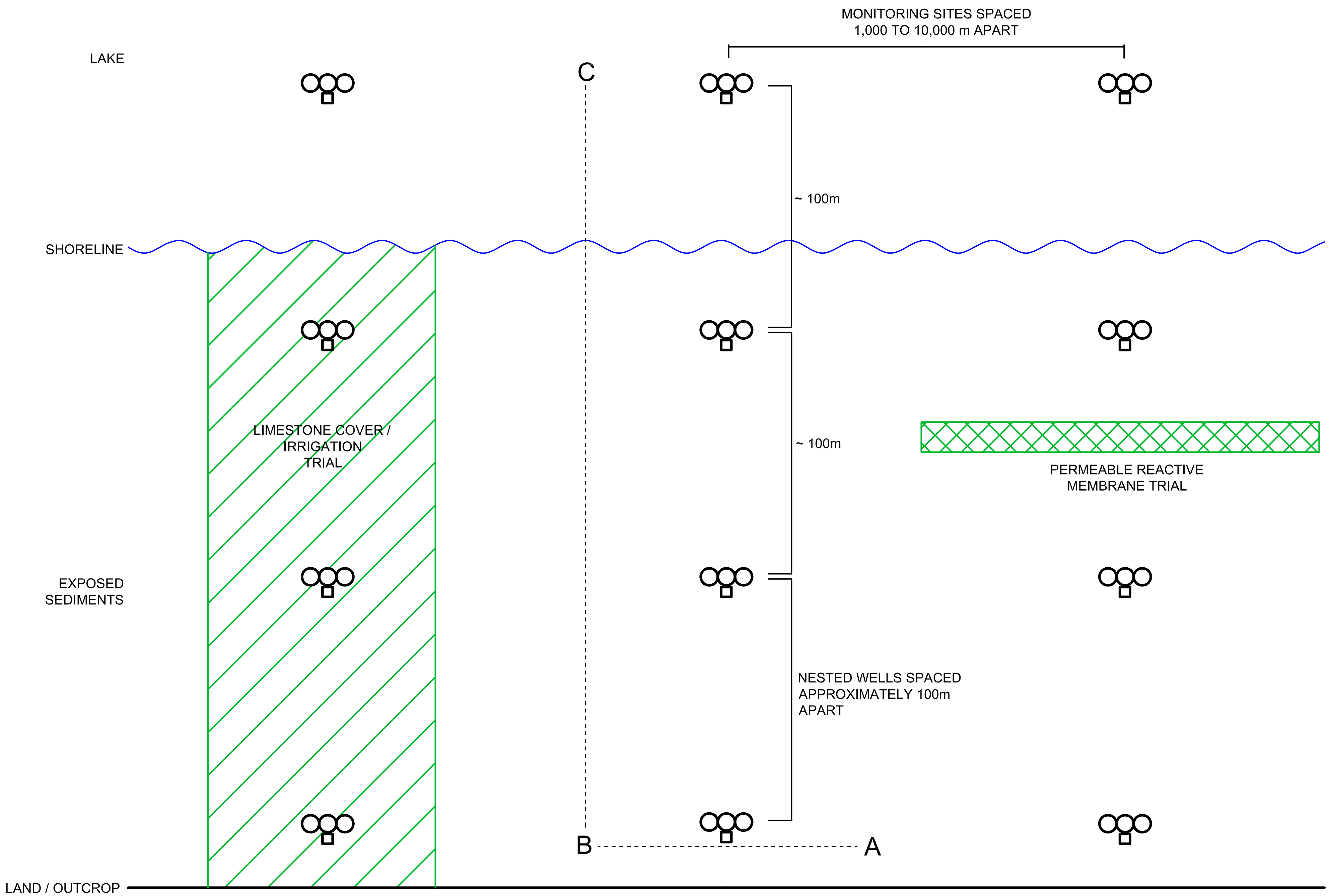
TITLE: LOWER MURRAY LAKES PROPOSED FIELD TESTWORK PROGRAM SCHEMATIC LAYOUT			
CLIENT: PRIMARY INDUSTRIES AND RESOURCES SOUTH AUSTRALIA			DRAWING NO. AC 1.1
SCALE: NTS A3	DATE: NOV 2008	OFFICE: MELBOURNE	PROJECT NO: RSSA0823
DRAWN BY: NB	APPROVED BY: JRT	REVISION: 0	SHEET: 1 of 1

RevNo	Revision note	Date	Signature	Checked



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TITLE: LOWER MURRAY LAKES PROPOSED SECONDARY MANAGEMENT OPTION TESTWORK PROGRAM			
CLIENT: PRIMARY INDUSTRIES AND RESOURCES SOUTH AUSTRALIA			DRAWING NO. AC 1.2
SCALE: NTS A3	DATE: NOV 2008	OFFICE: MELBOURNE	PROJECT NO: RSSA0823
DRAWN BY: NB	APPROVED BY: JRT	REVISION: 0	SHEET: 1 of 1

Attachment D:

Preliminary Cost Estimate for Preferred Management Options and Trials

COST ESTIMATE FOR PROPOSED ASS MANAGEMENT OPTIONS FOR THE LOWER MURRAY LAKES

OPTION 6: Install trenches along the landward side of exposed beaches. Dig shallow trenches and fill with limestone gravel. Use pumps to periodically or continuously fill trenches with lake water. This would recharge groundwater and assist with the saturation of sulfidic material.

CAPITAL COSTS

Items		Unit Rate	Unit	Lake Albert*		Lake Alexandrina*		Comments / assumptions
				Quantity	Subtotal per km shoreline	Quantity	Subtotal per km shoreline	
Project Management (Detailed Design Phase)	Design and management personnel	$ 2,800	per day	1	$ 2,800	1	$ 2,800	
Project Management (Construction Phase)	Project Director	$ 2,800	per day	0.75	$ 2,100	0.75	$ 2,100	Quantity is based on a trench construction rate of 3 days per shoreline km per construction team and one project director / manager required day per 4 construction teams (ie. per 4 installation sites).
	Project Manager	$ 2,200	per day	0.75	$ 1,650	0.75	$ 1,650	
	Site Superintendent	$ 1,600	per day	3	$ 4,800	3	$ 4,800	Quantity is based on a trench construction rate of 3 days per shoreline km per construction team and one site superintendent required day per construction team (ie. per installation site).
Civil / Mechanical Works	Access road construction / improvement (for construction / delivery vehicles)	$ 10,000	per upgrade	0.2	$ 2,000	0.2	$ 2,000	Assumed one road upgrade per 5 km.
	Surveying	$ 500	per day	2	$ 1,000	2	$ 1,000	Quantity includes 2 surveyors for trench construction at a trench construction rate of 1 day per shoreline km.
	Personnel for trench construction	$ 500	per day	2	$ 1,000	2	$ 1,000	Construction of 0.3m x 0.3m trench at a trenching rate of 1 day per shoreline km. Quantity assumes 2 people. No material disposal costs included.
	Personnel for limestone gravel installation	$ 500	per day	2	$ 1,000	2	$ 1,000	Unit rate is for filling in trench (0.3m x 0.3m) with limestone gravel, based on a construction rate of 1 shoreline km per day. Quantity assumes 2 people.
	Pump installation and commissioning	$ 2,000	per pump	0.5	$ 1,000	0.5	$ 1,000	Includes delivery to site, electricity connection and commissioning.
	Supply and installation of water pipe from lake to limestone trench	$ 26	per m	1600	$ 41,600	950	$ 24,700	Unit rate is for 225mm PVC irrigation pipe supplied and delivered to site, and 1 person for welding. Quantity includes pipe along width of sediment bank (1550m for Lake Albert and 900m for Lake Alexandrina) and an additional 50 m into the lake.
	Additional personnel for water pipe installation	$ 500	per day	3	$ 1,500	3	$ 1,500	Quantity assumes a pipe installation and welding rate of 3 days per shoreline km.
Equipment & Materials	Pump (50-60 L/sec @ 2m head)	$ 50,000	ea.	0.5	$ 25,000	0.5	$ 25,000	Unit rate is for a 28kW electric pump (flow rate of 50-60 L/sec at 25m head). Quantity assumes 1 pump alternating between two 1 km sections of perforated water pipe on a regular basis (ie. 1 pump for every 2 shoreline km)
	Pipe fittings	$ 1,500	per km shoreline	1	$ 1,500	1	$ 1,500	Unit rate includes fittings for pump and pipe where required.
	Limestone gravel 20mm aggregate	$ 45	per tonne	140	$ 6,278	140	$ 6,278	Unit rate is bases on a limestone gravel (bulk density of 1.55 t/m^3) cost of $45 per tonne (delivered to site). 90 m^3 is required to fill a trench 0.3 m x 0.3 m x 1000 m.
	Backhoe for trench construction	$ 600	per day	1	$ 600	1	$ 600	Unit rate is for the hire of a backhoe or similar trench digging machinery. Quantity assumes a trench construction rate of 1 shoreline km per day.
	Machinery for limestone gravel installation	$ 500	per day	1	$ 500	1	$ 500	Unit rate is for the hire of a bobcat or similar machinery. Quantity assumes a trench construction rate of 1 shoreline km day.

Items	Unit Rate	Unit Rate	Unit	Lake Albert*		Lake Alexandrina*		Comments / assumptions
				Quantity	Subtotal per km shoreline	Quantity	Subtotal per km shoreline	
Equipment & Materials	Machinery for water pipe installation	$ 400	per day	3	$ 1,200	3	$ 1,200	Rate assumes tractor or similar machinery for unloading and moving PVC water pipe. Quantity assumes a construction rate of 3 days per shoreline km.
	Equipment for surveying	$ 400	per day	1	$ 400	1	$ 400	
	Hire vehicles	$ 120	per vehicle per day	3	$ 360	3	$ 360	Quantity assumes one light vehicle per site per day, based on a construction rate of 3 days per shoreline km.
Miscellaneous	Food & accommodation	$ 160	per person per day	7	$ 1,120	7	$ 1,120	Quantity assumes all site personnel.
	Sundry expenses	$ 50	per person per day	7	$ 350	7	$ 350	Quantity assumes all site personnel.
				Contingency @ 15%	$ 14,664		$ 12,129	
				TOTAL (AU$ ex. GST)	**$ 112,421**		**$ 92,986**	

OPERATING COSTS

Items		Unit Rate	Unit	Lake Albert*		Lake Alexandrina*		Comments / assumptions
				Quantity	Subtotal per km shoreline per year	Quantity	Subtotal per km shoreline per year	
Operation	Electricity for pumps	$ 0.1	per kW/hr	122640	$ 12,264	122640	$ 12,264	Unit rate is based on an electricity price of 0.1 $/ per kW/hr and assumes 12hr operation. The quantity is based on a 28 kW pump operating 12 hours per day.
Maintenance	Pump and pipe maintenance	$ 18,200	per year	1	$ 18,200	1	$ 18,200	Rate assumes fortnightly inspection and/or repairs for one person for one day with light vehicle. Materials not included.
Performance Assessment	Review of operation and performance of treatment option	$ 3,000	per day	1	$ 3,000	1	$ 3,000	Unit rate includes mobilisation, equipment and expenses for monitoring personnel and analytical expenses.
				Contingency @ 15%	$ 3,180		$ 3,180	
				TOTAL (AU$ ex. GST)	**$ 38,484**		**$ 38,484**	

* For a water level decrease of 1m AHD, the typical exposed sediment bank width is estimated at 1550m for Lake Albert and 900m for Lake Alexandrina.

COST ESTIMATE FOR PROPOSED ASS MANAGEMENT OPTIONS FOR THE LOWER MURRAY LAKES

OPTION 7: Install perforated pipes along the landward side of beaches and periodically or continuously pump lake water onto the exposed sediments. This would recharge groundwater and assist with the saturation of sulfidic material.

CAPITAL COSTS

Items		Unit Rate	Unit	Lake Albert*		Lake Alexandrina*		Comments / assumptions
				Quantity	Subtotal per km shoreline	Quantity	Subtotal per km shoreline	
Project Management (Detailed Design Phase)	Design and management personnel	$ 2,200	per day	1	$ 2,200	1	$ 2,200	
Project Management	Project Director	$ 2,800	per day	0.75	$ 2,100	0.75	$ 2,100	Quantity is based on a pipe installation rate of 3 days per shoreline km per construction team and one project director / manager required day per 4 construction teams (ie. per 4 installation sites).
	Project Manager	$ 2,200	per day	0.75	$ 1,650	0.75	$ 1,650	
	Site Superintendent	$ 1,600	per day	3	$ 4,800	3	$ 4,800	Quantity is based on a pipe installation rate of 3 days per shoreline km per construction team and one site superintendent required day per construction team (ie. per installation site).
Civil / Mechanical Works	Access road construction / improvement (for construction / delivery vehicles)	$ 10,000	per upgrade	0.2	$ 2,000	0.2	$ 2,000	Assumed one road upgrade per 5 km.
	Supply and installation of water pipe from lake to perforated pipe	$ 26	per m	1600	$ 41,600	950	$ 24,700	Unit rate is for 225mm PVC irrigation pipe supplied and delivered to site, and 1 person for welding. Quantity includes pipe along width of sediment bank (1550m for Lake Albert and 900m for Lake Alexandrina) and an additional 50 m into the lake.
	Supply and installation of perforated water pipe	$ 16	per m	1000	$ 16,000	1000	$ 16,000	Unit rate is for 160mm OD PVC irrigation pipe supplied and delivered to site, and one person for welding.
	Additional personnel for water pipe installation	$ 500	per day	2	$ 1,000	2	$ 1,000	Quantity assumes a pipe installation and welding rate of 3 days per shoreline km.
	Pump installation and commissioning	$ 2,000	per pump	0.5	$ 1,000	0.5	$ 1,000	Includes delivery to site, electricity connection and commissioning.
Equipment & Materials	Pump (50-60 L/sec @ 2m head)	$ 50,000	ea.	0.5	$ 25,000	0.5	$ 25,000	Unit rate is for a 28kW electric pump (flow rate of 50-60 L/sec at 25m head). Quantity assumes 1 pump alternating between two 1 km sections of perforated water pipe on a regular basis (ie. 1 pump for every 2 shoreline km)
	Pipe fittings	$ 2,000	ea.	1	$ 2,000	1	$ 2,000	Unit rate includes fittings for water supply pipe and perforated pipe.
	Water pipe perforating equipment	$ 5,000	ea.	0.05	$ 250	0.05	$ 250	Unit rate includes the purchase / manufacture of equipment to perforate the pipe on-site as required. Quantity assumes one piece of equipment per 20 km shoreline.
	Machinery for water pipe installation	$ 400	per day	3	$ 1,200	3	$ 1,200	Rate assumes tractor or similar machinery for unloading and moving PVC water pipe. Quantity assumes a construction rate of 3 days per shoreline km.
	Hire vehicles	$ 120	per vehicle per day	3	$ 360	3	$ 360	Quantity assumes one light vehicle per site per day, based on a construction rate of 3 days per shoreline km.
Miscellaneous	Food & accommodation	$ 160	per day	4.5	$ 720	4.5	$ 720	Quantity assumes all site personnel.
	Expenses	$ 50	ea.	4.5	$ 225	4.5	$ 225	Quantity assumes all site personnel.
Contingency @ 15%					$ 15,316		$ 12,781	
TOTAL (AU$ ex. GST)					**$ 117,421**		**$ 97,986**	

OPERATING COSTS

Items		Unit Rate	Unit	Lake Albert*		Lake Alexandrina*		Comments / assumptions
				Quantity	Subtotal per km shoreline per year	Quantity	Subtotal per km shoreline per year	
Operation	Electricity for pumps	$ 0.1	per kW/hr	122640	$ 12,264	122640	$ 12,264	Unit rate is based on an electricity price of 0.1 $/ per kW/hr and assumes 12hr operation. The quantity is based on a 20 kW pump operating 12 hours per day.
Maintenance	Pump and pipe maintenance	$ 700	per day	26	$ 18,200	26	$ 18,200	Rate assumes fortnightly inspection and /or repairs for one person for one day with light vehicle. Materials not included.
Performance Assessment	Review of operation and performance of treatment option	$ 3,000	per day	1	$ 3,000	1	$ 3,000	Unit rate includes mobilisation, equipment and expenses for monitoring personnel and analytical expenses.
Contingency @ 15%					$ 5,020		$ 5,020	
TOTAL (AU$ ex. GST)					**$ 38,484**		**$ 38,484**	

* For a water level decrease of 1m AHD, the typical exposed sediment bank width is estimated at 1550m for Lake Albert and 900m for Lake Alexandrina.

COST ESTIMATE FOR PROPOSED ASS MANAGEMENT OPTIONS FOR THE LOWER MURRAY LAKES

OPTION 8: Install irrigation systems on exposed sediments and continuously or periodically pump water over sediments. This would recharge groundwater and assist with the saturation of sulfidic material. Refer to Option 18 for methods to encourage farmers to irrigate exposed banks.

CAPITAL COST

Items		Unit Rate	Unit	Lake Albert*		Lake Alexandrina*		Comments / assumptions
				Quantity	Subtotal per km shoreline	Quantity	Subtotal per km shoreline	
Project Management (Detailed Design Phase)	Design and management personnel	$ 1,600	per day	1	$ 1,600	1	$ 1,600	
Project Management	Project Director	$ 2,800	per day	0.75	$ 2,100	0.75	$ 2,100	Quantity is based on an irrigation pipe installation rate of 3 days per shoreline km per construction team and one project director / manager required day per 4 construction teams (ie. per 4 installation sites).
	Project Manager	$ 2,200	per day	0.75	$ 1,650	0.75	$ 1,650	
	Site Superintendent	$ 1,600	per day	3	$ 4,800	3	$ 4,800	Quantity is based on an irrigation pipe installation rate of 3 days per shoreline km per construction team and one site superintendent required day per construction team (ie. per installation site).
Civil / Mechanical Works	Access road construction / improvement (for construction / delivery vehicles)	$ 10,000	per upgrade	0.2	$ 2,000	0.2	$ 2,000	Assumed one road upgrade per 5 km.
	Personnel for site preparation (grading to suitable condition for centre-pivot irrigation system)	$ 500	per day	0.5	$ 250	0.5	$ 250	Quantity assumes that some grading may be required in certain areas to provide a relatively flat zone for centre-pivot operation.
	Construction of centre-pivot irrigation system	$ 110,000	per 50 ha	3.1	$ 341,000	1.8	$ 198,000	Assumed system includes fixed position 400m radius centre-pivot irrigation system inclusive of frame, concrete pad, nozzles and pump. Electrically powered pumps and drive system.
	Supply and installation of water pipe from lake to limestone trench	$ 26	per m	3565	$ 92,690	900	$ 23,400	Unit rate is for 225mm PVC irrigation pipe supplied and delivered to site, and 1 person for welding. Quantity includes pipe from lake to centre of each irrigation system.
	Additional personnel for water pipe installation	$ 500	per day	3	$ 1,500	3	$ 1,500	Quantity assumes a pipe installation and welding rate of 3 days per shoreline km.
Equipment & Materials	Water pipe from lake to centre of pivot	$ 20	per m	5115	$ 102,300	1800	$ 36,000	Unit rate is for 200mm rubber ring irrigation pipe at $115 per 6m length. Quantity includes pipe from centre of pivot to shoreline plus an additional 500 m into the lake for each centre pivot system.
	Pipe fittings	$ 2,000	ea.	1	$ 2,000	1	$ 2,000	Unit rate includes fittings for pump and pipe for a 1 km section.
	Grader for site preparation	$ 1,000	per day	0.5	$ 500	0.5	$ 500	Quantity assumes that some grading may be required in certain areas to provide a relatively flat zone for centre-pivot operation.
	Hire vehicles	$ 120	per vehicle per day	3	$ 360	3	$ 360	Quantity assumes one light vehicle per site per day, based on a pipe installation rate of 3 days per shoreline km.
Miscellaneous	Food & accommodation	$ 160	per day	9	$ 1,440	9	$ 1,440	Quantity includes site superintendent and pipe installation personnel, based on an installation rate of 3 days per shoreline km.
	Expenses	$ 50	ea.	9	$ 450	9	$ 450	Quantity includes all site personnel
Contingency @ 15%					$ 83,196		$ 41,408	
TOTAL (AU$ ex. GST)					**$ 637,836**		**$ 317,458**	

OPERATING COSTS

Items		Unit Rate	Unit	Lake Albert*		Lake Alexandrina*		Comments / assumptions
				Quantity	Subtotal per km shoreline per year	Quantity	Subtotal per km shoreline per year	
Operation	Electricity for pumps	$ 0.1	per kW/hr	38688	$ 3,869	22464	$ 2,246	Unit rate is based on an electricity price of 0.1 $/ per kW/hr and assumes 12hr operation. The quantity is based on a 20 kW pump operating 12 hours per day, once per week (52 days per year).
Maintenance	Pump and pipe maintenance	$ 700	per day	26	$ 18,200	26	$ 18,200	Rate assumes fortnightly inspection and /or repairs for one person for one day with light vehicle. Materials not included.
Performance Assessment	Review of operation and performance of treatment option	$ 3,000	per day	1	$ 3,000	1	$ 3,000	Unit rate includes mobilisation, equipment and expenses for monitoring personnel and analytical expenses.
Contingency @ 15%					$ 3,760		$ 3,517	
TOTAL (AU$ ex. GST)					**$ 28,830**		**$ 26,963**	

* For a water level decrease of 1m AHD, the typical exposed sediment bank width is estimated at 1550m for Lake Albert and 900m for Lake Alexandrina.

COST ESTIMATE FOR PROPOSED ASS MANAGEMENT OPTIONS FOR THE LOWER MURRAY LAKES

OPTION 10: Cover exposed sediments with fine grained materials that will retard oxygen diffusion and infiltration, and therefore acidity fluxes. Materials could include clay or perhaps ultra-fine grained limestone.

CAPITAL COSTS

Items		Unit Rate	Unit	Lake Albert*		Lake Alexandrina*		Comments / assumptions
				Quantity	Subtotal per km shoreline	Quantity	Subtotal per km shoreline	
Project Management (Detailed Design Phase)	Design and management personnel	$ 1,600	per day	1	$ 1,600	1	$ 1,600	
Project Management	Project Director	$ 2,800	per day	2	$ 5,600	2	$ 5,600	Quantity is based on a capping layer installation rate of 8 days per shoreline km for Lake Albert and 5 days per shoreline km for Lake Alexandrina per construction team and one project director / manager required day per 4 construction teams (ie. per 4 installation sites).
	Project Manager	$ 2,200	per day	2	$ 4,400	2	$ 4,400	
	Site Superintendent	$ 1,600	per day	8	$ 12,800	5	$ 8,000	Quantity is based on a capping layer installation rate of 8 days per shoreline km for Lake Albert and 5 days per shoreline km for Lake Alexandrina per construction team and one site superintendent required day per construction team (ie. per installation site).
Civil / Mechanical Works	Access road construction / improvement (for construction / delivery vehicles)	$ 10,000	per upgrade	0.2	$ 2,000	0.2	$ 2,000	Assumed one road upgrade per 5 km.
	Personnel for laying and spreading material	$ 500	per day	32	$ 16,000	25	$ 12,500	Quantity is based on construction rates of 8 days per shoreline km for Lake Albert and 5 days per shoreline km for Lake Alexandrina.
	Personnel for initial wetting of clay layer to promote particle distribution into sediments and prevent erosion.	$ 500	per day	32	$ 16,000	25	$ 12,500	Quantity is based on construction rates of 8 days per shoreline km for Lake Albert and 5 days per shoreline km for Lake Alexandrina.
Equipment & Materials	Equipment for laying and spreading material	$ 1,000	per day	32	$ 32,000	25	$ 25,000	Quantity is based on construction rates of 8 days per shoreline km for Lake Albert and 5 days per shoreline km for Lake Alexandrina.
	Machinery for initial wetting of clay layer.	$ 400	per day	32	$ 12,800	25	$ 10,000	Quantity is based on construction rates of 8 days per shoreline km for Lake Albert and 5 days per shoreline km for Lake Alexandrina.
	Clay or fine grained limestone (delivered to site)	$ 45	tonnes	10850	$ 488,250	6,300	$ 283,500	Unit rate is for fine-grained clay / limestone delivered to site. Quantity is based on a 5mm layer of material with an assumed bulk density of 1.4 t/m3 spread across an exposed sediment bank width of 1550m for Lake Albert and 900m for Lake Alexandrina.
Miscellaneous	Food & accommodation	$ 160	per day	72	$ 11,520	72	$ 11,520	Quantity assumes nine people working on-site per day
	Expenses	$ 50	ea.	72	$ 3,600	72	$ 3,600	Quantity assumes nine people working on-site per day
Contingency @ 15%					$ 90,986		$ 57,033	
TOTAL (AU$ ex. GST)					**$ 697,556**		**$ 437,253**	

OPERATING COSTS

Items		Unit Rate	Unit	Lake Albert*		Lake Alexandrina*		Comments / assumptions
				Quantity	Subtotal per km shoreline per year	Quantity	Subtotal per km shoreline per year	
Maintenance	Dust suppression	$ 900	per day	180	$ 162,000	180	$ 162,000	Unit rate is for one tanker and one operator. Quantity is based on 180 days operation.
Performance Assessment	Review of operation and performance of treatment option	$ 3,000	per day	1	$ 3,000	1	$ 3,000	Unit rate includes mobilisation, equipment and expenses for monitoring personnel and analytical expenses.
Contingency @ 15%					$ 24,750		$ 24,750	
TOTAL (AU$ ex. GST)					**$ 189,750**		**$ 189,750**	

* For a water level decrease of 1m AHD, the typical exposed sediment bank width is estimated at 1550m for Lake Albert and 900m for Lake Alexandrina.

COST ESTIMATE FOR PROPOSED ASS MANAGEMENT OPTIONS FOR THE LOWER MURRAY LAKES

OPTION 11: Revegetate extensive portions of the up wind shores of the lakes with large native trees. Leaf litter from the trees would provide slow, passive but ongoing organic matter addition to the lakes over the long term.

CAPITAL COSTS

Items		Unit Rate	Unit	Lake Albert and Lake Alexandrina*		Comments / assumptions # ^
				Quantity	Subtotal per km of lake perimeter (average width of native vegetation strip 0.050 km)	
Project Management (Detailed Design Phase)	Design and management personnel	$ 1,600	per day	1	$ 1,600	
Project Management	Project Director	$ 2,800	per day	2.5	$ 7,000	Quantity is based on a planting rate of 5 days per km of lake perimeter per construction team and one project director / manager required day per Lake (ie. per 2 installation sites).
	Project Manager	$ 2,200	per day	2.5	$ 5,500	
	Site Superintendent	$ 1,600	per day	5	$ 8,000	Quantity is based on a planting rate of 5 days per km of lake perimeter per construction team and one site superintendent required day per Lake (ie. per 2 installation sites).
Civil Works	Weed control (Site preparation)	$ 400	per ha	5	$ 2,000	Unit rate based on 3 applications using Boom/Line spraying (inclusive of contractor costs, chemicals, fuel and equipment hire).
	Soil disturbance (Site preparation)	$ 500	per ha	5	$ 2,500	Unit Rate is for deep ripping, and includes fuel and mobilisation costs.
	Fencing	$ 450	per km	1.5	$ 675	Unit rate is based on 30 labour hours per km of fencing. Quantity assumes 1 km fencing required per km lake perimeter (ie. fencing only needed on one side of vegetation as fences should already be in place on boundary).
Equipment & Materials	Fencing materials	$ 1,750	per km	1.5	$ 2,625	Unit rate includes materials to install a 'cattle fence'. Quantity assumes 1km fencing required per km lake perimeter (ie. fencing only needed on one side of vegetation as fences should already be in place on boundary).
	Tree guards	$ 1.00	per plant	5000	$ 5,000	Unit rate is for a plastic sleeve and 3 stakes suitable for one plant. Quantity is based on the assumption of planting 1000 seedlings per hectare.
	Hire vehicles	$ 120	per vehicle per day	5	$ 600	Quantity assumes one vehicle per site per day and based on a planting rate of 5 days per km of lake perimeter.
Revegetation	Revegetation	$ 2,500	per ha	5	$ 12,500	Unit rate is based on $1.50 to obtain each seedling, contractor costs (including delivery, planting and hand planter hire) of $1 per seedling, and assuming that 1000 seedlings are planted per ha. Assumed no soil amendments needed (eg. fertiliser or topsoil).
	Watering	$ 700	per day	5	$ 3,500	Unit rate is for one tanker and operator. Quantity is based on a planting rate of 5 days per km of lake perimeter.
Miscellaneous	Food & accommodation	$ 160	per day	40	$ 6,400	Quantity assumes 8 people working per day
	Expenses	$ 50	ea.	40	$ 2,000	Quantity assumes 8 people working per day
				Contingency @ 15%	$ 8,985	
				TOTAL (AU$ ex. GST)	**$ 68,885**	

OPERATING COSTS

Items		Unit Rate	Unit	Lake Albert and Lake Alexandrina*		Comments / assumptions
				Quantity	Subtotal per km of lake perimeter per year	
Maintenance	Weed and pest control	$ 100	per ha	5	$ 500	Unit rate based on Spot Spraying where needed, and assumes only one application per year.
	Refill planting	$ 125	per ha	5	$ 625	Assumed initial seedling success rate of 95%. Refill planting may need to be undertaken 6 months to 1 year after initial planting.
	Watering	$ 700	per day	12	$ 8,400	Unit rate is for one tanker and operator. Quantity is based on one day of watering per month.
Performance Assessment	Review of operation and performance of treatment option	$ 3,000	per day	1	$ 3,000	Unit rate includes mobilisation, equipment and expenses for monitoring personnel and analytical expenses.
				Contingency @ 15%	$ 1,879	
				TOTAL (AU$ ex. GST)	**$ 14,404**	

* For a water level decrease of 1m AHD, the typical exposed sediment bank width is estimated at 1550m for Lake Albert and 900m for Lake Alexandrina.

[#] Potential financial benefits could be gained from the sale of carbon credits (generated from afforestation). Provisional estimated based on International Trading Schemes indicate a value of $400 per km lake perimeter ($28,000 if all 70 km proposed lake perimeter are revegetated). Further details will be released in the Australian Government Carbon Pollution Reduction Scheme White Paper due for publication in December 2008.

^ Legal costs associated with land acquisition for native revegetation have not been estimated.

COST ESTIMATE FOR PROPOSED ASS MANAGEMENT OPTIONS FOR THE LOWER MURRAY LAKES

OPTION 18: Conduct or encourage strategic planting of exposed sediment banks with deeply rooting, rapid growth plant species which produce a great deal of above ground biomass (eg. local reeds, grasses for stock). Planting activities needs to keep pace with the receding shoreline.

CAPITAL COSTS

Items		Unit Rate	Unit	Lake Albert*		Lake Alexandrina*		Comments / assumptions
				Quantity	Subtotal per km shoreline	Quantity	Subtotal per km shoreline	
Project Management (Detailed Design Phase)	Design and management personnel	$ 1,600	per day	1	$ 1,600	1	$ 1,600	
Project Management	Project Director	$ 2,800	per day	3.75	$ 10,500	2.25	$ 6,300	Quantity is based on a direct seeding rate of 10 ha per day per construction team and one project director / manager required day per 4 construction teams (ie. per 4 installation sites).
	Project Manager	$ 2,200	per day	3.75	$ 8,250	2.25	$ 4,950	
	Site Superintendent	$ 1,600	per day	15	$ 24,000	9	$ 14,400	Quantity is based on a direct seeding rate of 10 ha per day per construction team and one site superintendent required day per construction team (ie. per 4 installation sites).
Civil Works	Access road construction / improvement (for construction / delivery vehicles)	$ 10,000	per upgrade	0.2	$ 2,000	0.2	$ 2,000	Quantity is based on the assumed of one road upgrade per 5 km.
Equipment & Materials	Hire vehicles	$ 120	per vehicle per day	15	$ 1,800	9	$ 1,080	Quantity assumes vehicle per site per day and based on a direct seeding rate of 10 ha per day.
Revegetation	Direct seeding of the exposed sediment banks	$ 900	per ha	155	$ 139,500	90	$ 81,000	Unit rate based on $400 per kilogram to purchase seeds, require 1 kilogram of seeds per hectare, and assumed a rate $500 per ha to sow seeds (inclusive of equipment hire and personnel). Assumed a niche seeding machine used. Direct seeding machine must be appropriate for use on soft sandy sediment and can be used close to lake edge. Assumed no soil amendments required (eg. soil disturbance, weed control, fertiliser, topsoil or watering upon sowing).
Miscellaneous	Food & accommodation	$ 160	per day	30	$ 4,800	18	$ 2,880	Quantity assumes two people working on-site everyday
	Expenses	$ 50	ea.	30	$ 1,500	18	$ 900	Quantity assumes two people working on-site everyday
Contingency @ 15%					$ 29,093		$ 17,267	
TOTAL (AU$ ex. GST)					**$ 223,043**		**$ 132,377**	

OPERATING COSTS

Items		Unit Rate	Unit	Lake Albert*		Lake Alexandrina*		Comments / assumptions
				Quantity	Subtotal per km shoreline per year	Quantity	Subtotal per km shoreline per year	
Maintenance	Re-seeding where required	$ 900	per ha	31	$ 27,900	18	$ 16,200	Assumed initial seeding success rate of 80%
Performance Assessment	Review of operation and performance of treatment option	$ 3,000	per day	1	$ 3,000	1	$ 3,000	Unit rate includes mobilisation, equipment and expenses for monitoring personnel and analytical expenses.
Contingency @ 15%					$ 4,635		$ 2,880	
TOTAL (AU$ ex. GST)					**$ 35,535**		**$ 22,080**	

* For a water level decrease of 1m AHD, the typical exposed sediment bank width is estimated at 1550m for Lake Albert and 900m for Lake Alexandrina.