Assessment of Acid Sulfate Soil Materials in Ramsar Wetlands of the Murray-Darling Basin: Narran Lake Nature Reserve

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Cover Photographs:

Typical landscape in the Narran Lake Nature Reserve Ramsar wetlands. Photographs was taken at one of the Kia Ora – Narran Lake sites (Site RSNL 19).

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EXECUTIVE SUMMARY

The Narran Lake Nature Reserve Ramsar wetlands are located approximately 75 km north west of Walgett and 50 km north east of Brewarrina in the north west of New South Wales. Narran Lake Nature Reserve covers part of a large terminal wetland of the Narran River in New South Wales at the end of the Condamine River system which flows from Queensland, and is an internationally recognised habitat for waterbird breeding. The wetland system occupies area of 5,531 hectares.

The Murray-Darling Basin Authority (MDBA), in partnership with its Partner Governments and scientists, instigated the Murray-Darling Basin Acid Sulfate Soils Risk Assessment Project (MDB ASSRAP), which aims to assess the spatial extent of, and risks posed by, acid sulfate soil materials in the Murray-Darling Basin. The MDB ASSRAP project also aims to identify and assess broad management options.

Due to their ecological significance, a decision was made by the MDB Acid Sulfate Soils Risk Assessment Advisory Panel to prioritise the Ramsar-listed wetland complexes of the Murray-Darling Basin for immediate detailed acid sulfate soil assessment. This report provides the results of Phase 1 of a two-phased detailed acid sulfate soil assessment procedure for the Narran Lake Nature Reserve. This Phase 1 report is aimed solely at determining whether or not acid sulfate soil materials are present in the Narran Lake Nature Reserve.

Sulfuric or sulfidic materials were not observed at the sites sampled in these wetlands. The data indicates that acidification as a result of sulfide oxidation is unlikely to present a major hazard to these wetlands.

The water soluble sulfate contents in the surficial soil materials did not exceed the trigger value of 100 mg kg^{-1} at all locations indicating that the formation of monosulfidic materials upon rewetting of these wetlands is unlikely.

The water data indicates that the surface water and groundwater has not been affected by acidification.

Based on the priority ranking criteria adopted by the Scientific Reference Panel of the Murray-Darling Basin Acid Sulfate Soils Risk Assessment Project no further assessment is recommended at the Narran Lake Nature Reserve Ramsar wetlands. As such, the Scientific Reference Panel of the Murray-Darling Basin Acid Sulfate Soils Risk Assessment Project agreed that Phase 2 detailed assessment of acid sulfate soil materials was not required for the Narran Lake Nature Reserve Ramsar wetlands.

1. INTRODUCTION

1.1. Wetland overview

Narran Lake Nature Reserve covers part of a large terminal wetland of the Narran River in New South Wales (NSW) at the end of the Condamine River system which flows from Queensland, and is an internationally recognised habitat for waterbird breeding (Figure 1-1). The wetland system occupies and area of 5,531 hectares. The Narran River flows intermittently as a result of heavy rainfall in Queensland and annual flows are highly variable. The Narran Lakes system receives water at lower flows than the lake beds further north along the Narran River and hence floods more often and holds water for longer periods. In moderate flows, water fills Clear Lake and then flows back into Narran Lake. The hydrology of this wetland system is highly dynamic and water-levels can drop very quickly if flows are not large enough to keep water levels up in both Narran and Clear Lakes (NPWS 1995).

The overview from the Ramsar Site Information Sheet (26^{th} March 1999) is as follows:

> *Narran Lake Nature Reserve consists primarily of Quaternary sediments which include floodplain, outwash areas and drainage flats of black, red and white sandy to silty clay and clayey sand, and silt with areas of black and grey clayey silt and sand deposited in claypans and lakes. Soils on the surrounding ridges are generally red sandy loams, with gravelly soils in the highest areas. These soft red soils are prone to erosion and gullying. Narran River floodplain which consists of dark organic lake muds in the lakes and adjacent wetlands, and light grey clays in nearby Playa Lakes. The Narran Land System is characterised by an extensive lake bed with its associated discontinuous lunette and sandy levee, which has a relief to 5m as well as drainage depressions and isolated salina which are periodically inundated by the Narran River.*

A typical wetland in this Ramsar wetland is shown in Figure 1-2, and a typical soil profile is shown in Figure 1-3. Further information on characteristics of the Narran Lake Nature Reserve can be found in the Ramsar Site Information Sheet can be found at NPWS (1999).

1.2. Acid sulfate soils in the Murray-Darling Basin

Acid sulfate soil is the term commonly given to soil and sediment that contain iron sulfides, or the products of sulfide oxidation. Pyrite (FeS_2) is the dominant sulfide in acid sulfate soil, although other sulfides including the iron disulfide marcasite (Sullivan and Bush 1997; Bush 2000) and iron monosulfides (Bush and Sullivan 1997; Bush *et al.* 2000) can also be found.

Sulfidic sediments accumulate under waterlogged conditions where there is a supply of sulfate, the presence of metabolisable organic matter and iron containing minerals (Dent 1986). Under reducing conditions sulfate is bacterially reduced to sulfide, which reacts with reduced iron to form iron sulfide minerals. These sulfide minerals are generally stable under reducing conditions, however, on exposure to the atmosphere the acidity produced from sulfide oxidation can impact on water quality, crop production, and corrode concrete and steel structures (Dent 1986). In addition to the acidification of both ground and surface waters, a reduction in water quality may result from low dissolved oxygen levels (Sammut *et al.* 1993; Sullivan *et al.* 2002a; Burton *et al.* 2006), high concentrations of aluminium and iron (Ferguson and Eyre 1999; Ward *et al.* 2002), and the release of other potentially toxic metals (Preda and Cox 2001; Sundström *et al.* 2002; Burton *et al.* 2008a; Sullivan *et al.* 2008a).

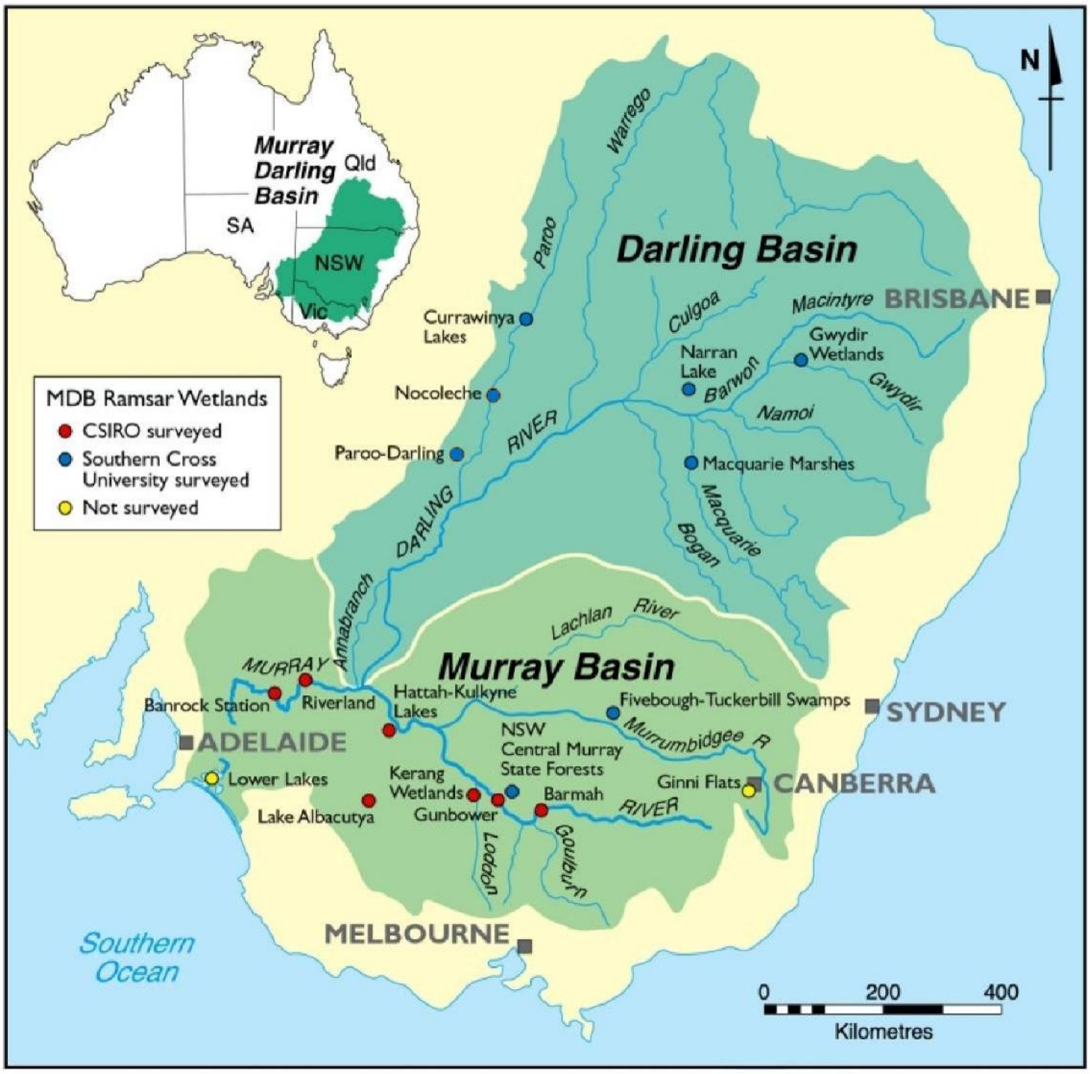

Figure 1-1 Map of Ramsar Wetlands surveyed in the Murray-Darling Basin.

Acid sulfate soils form naturally when sulfate in the water is converted to sulfide by bacteria. Changes to the hydrology in regulated sections of the Murray-Darling Basin (MDB) system (due to higher weir pool levels), and the chemistry of rivers and wetlands have caused significant accumulation of sulfidic material in subaqueous and wetland margin soils. If left undisturbed and covered with water, sulfidic material poses little or no threat of acidification. However, when sulfidic material is exposed to the air, the sulfides react with oxygen to form sulfuric acid (i.e. sulfuric materials with pH < 4). When these sulfuric materials are subsequently covered with water, significant amounts of sulfuric acid can be released into the water.

Other hazards associated with acid sulfate soil include: (i) mobilisation of metals, metalloids and non-metals, (ii) decrease in oxygen in the water column when monosulfidic materials are mobilised into the water column, and (iii) production of noxious gases. In severe cases, these risks can potentially lead to damage to the environment, and have impacts on water supplies, and human and livestock health.

Record low inflows and river levels in recent years have led to the drying of many wetlands in the MDB, resulting in the exposure of sulfidic material in acid sulfate soil, and soil acidification in many wetlands. The extent and potential threat posed by acid sulfate soil requires assessment.

Despite decades of scientific investigation of the ecological (e.g. Living Murray Icon Site Environmental Management Plan: MDBC 2006a,b,c), hydrological, water quality (salinity) and geological features of wetlands in the MDB, we have only recently advanced far enough to appreciate the wide spectrum of acid sulfate soil subtypes and processes that are operating in these contemporary environmental settings - especially from continued lowering of water levels (e.g. Lamontagne *et al.* 2006; Fitzpatrick *et al.* 2008a,b; Shand *et al.* 2008a,b; Simpson *et al*. 2008; Sullivan *et al*. 2008a). Hence, the MDB Ministerial Council at its meeting in March 2008 directed the then Murray-Darling Basin Commission (MDBC) to undertake an assessment of acid sulfate soil risk at key wetlands in the MDB.

The MDBC (now the Murray-Darling Basin Authority – MDBA), in partnership with its Partner Governments and scientists, designed the MDB ASS Risk Assessment Project, which aims to assess the spatial extent of, and risks posed by, acid sulfate soil in the Murray-Darling Basin. The project also aims to identify and assess broad management options.

The project established a list of more than 10,000 wetlands that were then assessed against a number of criteria aimed at identifying those that had potential for acid sulfate soil occurrence. Due to their ecological significance, the decision was made to prioritise Ramsar-listed wetland complexes of the Murray-Darling Basin for immediate detailed acid sulfate soil assessment (Figure 1-1). Wetlands within these complexes were then identified and selected for further assessment.

Southern Cross GeoScience carried out a detailed assessment at 19 representative sites within the Narran Lake Nature Reserve in June/July 2008 to determine whether acid sulfate soils were present, or if there was a potential for acid sulfate soil to form within these wetlands (Figure 1-4). This assessment included the determination of sulfide content within the soil profile at each site. Water-soluble sulfate was used as an indicator of the potential of monosulfide black ooze (MBO) formation in these wetland sites.

Figure 1-2 Typical landscape in the Narran Lake Nature Reserve Ramsar wetlands (Site RSNL 19).

Figure 1-3 Typical grey clay soil profile in the Narran Lake Nature Reserve Ramsar wetlands (RSNL 19).

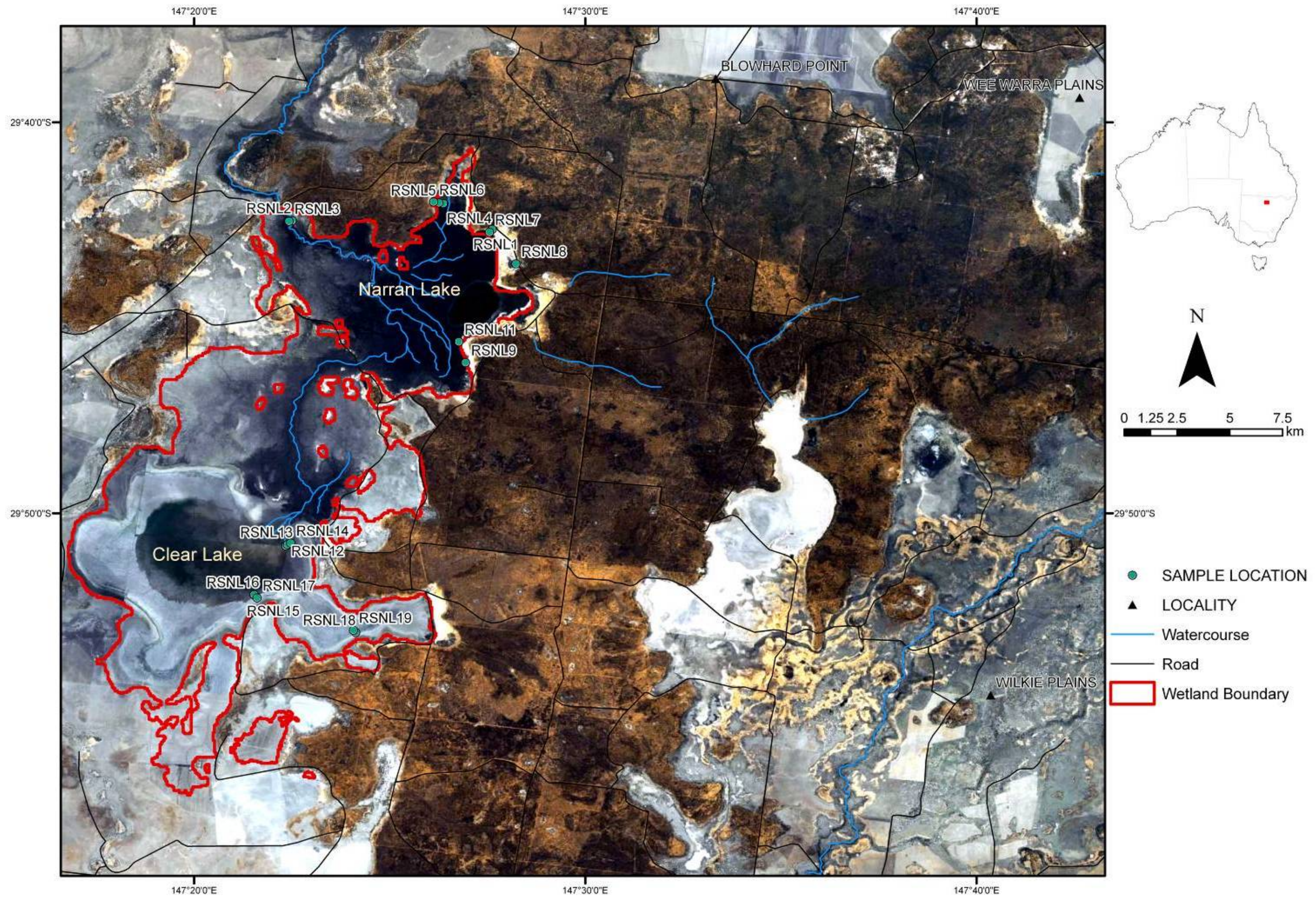

Figure 1-4 Map showing the areas assessed in the Narran Lake Nature Reserve.

1.3. Detailed Acid Sulfate Soil assessments using two phases

The detailed assessment stage of the MDB ASS Risk Assessment Project involves comprehensive analysis using a set of established and tested field and laboratory methods to determine the presence and extent of acid sulfate soil and associated hazards, including potential for acidification, metal mobilisation and deoxygenation.

In summary, the protocol being developed by the MDB ASS Risk Assessment Project Scientific Reference Panel requires a two-phase procedure.

Phase 1 aims to determine whether or not acid sulfate soil materials are present in each wetland by:

a. Consulting with relevant managers of that wetland.
b. Field descriptions of soils and sampling, including pH (e.g. using Merck test strips) and specific electrical conductance (SEC) testing.
c. Photographic record of sites and soil profiles.
d. Sampling and sub-sampling in chip trays.
e. Field testing of water quality parameters (pH, specific electrical conductance (SEC), redox potential (Eh), dissolved oxygen (DO), alkalinity by titration, and turbidity).
f. Laboratory analyses to conclusively identify the presence or absence of sulfuric, sulfidic or MBO acid sulfate soil materials using incubation ("ageing pH") in chip trays, pH peroxide testing and sulfur suite and partial acid base accounting: S_{CR} (sulfide % S), pH_{KCl}, and TAA (titratable actual acidity: moles H^+/tonne), acid neutralising capacity (ANC) where soil materials were sulfidic, acid volatile sulfide (AVS) and water-extractable SO_4 (1:5 soil:water suspension).
g. Surface water and groundwater chemical and nutrient analyses.

Phase 2 is only pursued if results of Phase 1 dictate and the MDB ASS Risk Assessment Advisory Panel recommend further detailed investigation. Phase 2 aims to determine the nature and severity of the environmental hazards posed by the acid sulfate soil materials, if present, by:

a. Continued incubation of samples in chip trays.
b. More detailed acid/base accounting (e.g. elemental sulfur).
c. Rapid metal release.
d. Contaminant and metalloid dynamics.
e. MBO formation potential.
f. Mineralogy by X-ray diffraction (XRD).
g. Major and trace elements by X-ray fluorescence spectroscopy (XRF).
h. Archiving of all soil samples in CSIRO archive (as chip trays and bulk samples).

Following a request from the Murray-Darling Basin Authority (MDBA), Southern Cross GeoScience were engaged to conduct a Phase 1 detailed assessment of acid sulfate soils at the Narran Lake Nature Reserve Ramsar wetlands.

1.4. Methodologies used to assess acid generation potential

As detailed previously, sulfide minerals are generally stable under reducing conditions, however, on exposure to the atmosphere the acidity produced from sulfide oxidation can impact on water quality, crop production, and corrode concrete and steel structures (Dent 1986). In addition to the acidification of both ground and surface waters, a reduction in water quality may result from low dissolved oxygen levels (Sammut *et al.* 1993; Sullivan *et al.* 2002a; Burton *et al.* 2006), high concentrations of aluminium and iron (Ferguson and Eyre 1999; Ward *et al.* 2002), and the release of other potentially toxic metals (Preda and Cox 2001; Sundström *et al.* 2002; Burton *et al.* 2008a; Sullivan *et al.* 2008a).

In nature, a number of oxidation reactions of sulfide minerals (principally pyrite: FeS_2) may occur which produce acidity, including:

$$2FeS_2 + 7O_2 + 2H_2O \text{ ---> } 2Fe^{2+} + 4SO_4^{2-} + 4H^+$$

$$4FeS_2 + 15O_2 + 10H_2O \text{ ---> } 4FeOOH + 8H_2SO_4$$

A range of secondary minerals, such as jarosite, sideronatrite and schwertmannite may also form, which act as stores of acidity i.e. they may produce acidity upon dissolution (rewetting).

Acid-base accounting (ABA)

Acid-base accounting (ABA) is used to assess both the potential of a soil material to produce acidity from sulfide oxidation and also its ability to neutralise any acid formed (e.g. Sullivan *et al*. 2001, Sullivan *et al*. 2002b). The standard ABA applicable to acid sulfate soil is as described in Ahern *et al*. (2004) as shown below:

Net Acidity = Potential Sulfidic Acidity + Existing Acidity – ANC*/Fineness Factor

*** ANC = Acid Neutralizing Capacity**

The components in this ABA are further discussed below and by Ahern *et al*. (2004).

Potential Sulfidic Acidity

The Potential Sulfidic Acidity is most easily and accurately determined by assessing the Chromium Reducible Sulfur. This method was developed specifically for analysing acid sulfate soil materials (Sullivan *et al*. 2000) to, inter alia, assess their Potential Sulfidic Acidity (PSA) also known as the 'acid generation potential' (AGP). The method is also described in Ahern *et al*. (2004), which includes the chromium reducible sulfur (S_{CR} or CRS: Method Code 22B) and its conversion to PSA.

Existing Acidity
This is the sum of the Actual Acidity and the Retained Acidity (Ahern *et al*. (2004). Titratable Actual Acidity (TAA) is a measure of the actual acidity in acid sulfate soil materials that have already oxidised. TAA measures the sum of both soluble and exchangeable acidity. The Retained Acidity is the acidity 'stored' in minerals such as jarosite, schwertmannite and other hydroxysulfate minerals. Although these minerals may be stable under acidic conditions, they can release acidity to the environment when these conditions change. The methods for determining both TAA and Retained Acidity are given by Ahern *et al*. (2004).

Acid Neutralising Capacity (ANC)
Soils with pH values > 6.5 may potentially have ANC in the form of (usually) carbonate minerals, principally of calcium, magnesium and sodium. The carbonate minerals present are estimated by titration, and alkalinity present is expressed in $CaCO_3$ equivalents. By accepted definition (Ahern *et al*. 2004), any acid sulfate soil material with a pH < 6.5 has a zero ANC. The methods for determining ANC are given by Ahern *et al*. (2004).

Fineness Factor (FF)
This is defined by Ahern *et al*. (2004) as "A factor applied to the acid neutralising capacity result in the acid base account to allow for the poor reactivity of coarser carbonate or other acid neutralising material. The minimum factor is 1.5 for finely divided pure agricultural lime, but may be as high as 3.0 for coarser shell material". Fine grinding of soil materials may lead to an over-estimate of ANC when carbonates are present in the form of hard nodules or shells. In the soil environment, they may provide little effective ANC when exposure to acid may result in the formation of surface crusts (iron oxides or gypsum), preventing or slowing further neutralisation reactions. For reasons including those above, the use of the "Fineness Factor" also applies to those naturally occurring alkalinity sources in soil materials as measured by the ANC methods.

Water extractable sulfate (1:5 soil:water suspension)
A 1:5 soil:water extract is prepared using 5g oven dried (80^oC) soil following the procedures described in Rayment and Higginson (1992). After shaking end-over-end for 4 hours, the suspensions are subject to 10 minutes centrifugation at 4000 rpm. The supernatant is filtered (0.45 μm) and sulfate concentration determined by turbidimetric analysis using a HACH spectrophotometer (or suitable alternative analytical technique for sulfate). Soluble sulfate content is expressed on a dry mass basis. Sulfate contents >10 mg L^{-1} in water of inland water bodies such as wetlands and rivers give a strong indication that the soil materials underlying those water bodies are able to sulfidise (Sullivan *et al*. 2002a, Baldwin *et al*. 2007, Sullivan *et al*. 2008a) forming monosulfidic black oozes (MBOs) or sulfidic sediments. In dry soils where there are no overlying water bodies, it is considered that water soluble sulfate contents of greater than or equal to 100 mg kg^{-1} in the surface soil layers (i.e. soil layers in the top 20 cm of the soil profile) would be able to create similar sulfate contents in overlying water bodies as a result of inundation. Therefore this soil sulfate content of greater than or equal to 100

mg kg^{-1} in surface soil layers has been selected to indicate whether or not surface soil materials from dry wetlands should be examined in the Phase 2 of the detailed assessment for the capacity of these soil materials to form monosulfidic soil materials upon inundation using the approach of Sullivan *et al*. (2008a).

1.5. Classification of soil materials

Recently, the Acid Sulfate Soils Working Group of the International Union of Soil Sciences agreed to adopt in principle the following new descriptive terminology and classification definitions of acid sulfate soil materials proposed by Sullivan *et al*. (2008b) at the 6th International Acid Sulfate Soil and Acid Rock Drainage Conference in September 2008 in Guangzhou, China. This new classification system for acid sulfate soil materials has also been recently (October 2008) adopted by the Scientific Reference Panel of the Murray-Darling Basin Acid Sulfate Soils Risk Assessment Project for use in the detailed assessment of acid sulfate soil in the Murray-Darling Basin.

The criteria to define the soil materials are as follows:

1) **Sulfuric materials** - soil materials currently defined as sulfuric by the Australian Soil Classification (Isbell 1996). Essentially, these are soil materials with a pHw < 4 as a result of sulfide oxidation.

2) ***Sulfidic materials** – soil materials containing detectable sulfide minerals (defined as containing ≥ 0.01% sulfidic S). The intent is for this term to be used in a descriptive context (e.g. sulfidic soil material or sulfidic sediment) and to align with general definitions applied by other scientific disciplines such as geology and ecology (e.g. sulfidic sediment). The method with the lowest detection limit is the Cr-reducible sulfide method, which currently has a detection limit of 0.01%; other methods (e.g. X-ray diffraction, visual identification, Raman spectroscopy or infra red spectroscopy) can also be used to identify sulfidic materials.
   **This term differs from previously published definitions in various soil classifications (e.g. Isbell 1996).*

3) **Hypersulfidic material** – Hypersulfidic material is a sulfidic material that (i) has a field pH of 4 or more and (ii) is identified by experiencing a substantial* drop in pH to 4 or less (1:1 by weight in water, or in a minimum of water to permit measurement) when a 2–10 mm thick layer is incubated aerobically at field capacity. The duration of the incubation is either:
   a. until the soil pH changes by at least 0.5 pH unit to below 4; or
   b. until a stable** pH is reached after at least 8 weeks of incubation.

   **A substantial drop in pH arising from incubation is regarded as an overall decrease of at least 0.5 pH unit.*
   ***A stable pH is assumed to have been reached after at least 8 weeks of incubation when either the decrease in pH is < 0.1 pH unit over at least a 14 day period, or the pH begins to increase.*

4) **Hyposulfidic material** – Hyposulfidic material is a sulfidic material that (i) has a field pH of 4 or more and (ii) does not experience a substantial* drop in pH to 4 or less (1:1 by weight in water, or in a minimum of water to permit measurement) when a 2–10 mm thick layer is incubated aerobically at field capacity. The duration of the incubation is until a stable** pH is reached after at least 8 weeks of incubation.
   **A substantial drop in pH arising from incubation is regarded as an overall decrease of at least 0.5 pH unit.*
   ***A stable pH is assumed to have been reached after at least 8 weeks of incubation when either the decrease in pH is < 0.1 pH unit over at least a 14 day period, or the pH begins to increase.*

5) **Monosulfidic materials** – soil materials with an acid volatile sulfide content of 0.01% S or more.

In addition the Scientific Reference Panel of the Murray-Darling Basin Acid Sulfate Soils Risk Assessment Project agreed to identify the other acidic soil materials arising from the detailed assessment of wetland soils in the Murray-Darling Basin even though these materials may not be the result of acid sulfate soil processes (e.g. the acidity developed during ageing may be the result of Fe^{2+} hydrolysis, which may or may not be associated with acid sulfate soil processes). Also the acidity present in field soils may be due to the accumulation of acidic organic matter and/or the leaching of bases. Of course, these acidic soil materials may also pose a risk to the environment and would be identified during the present course of the Phase 1 detailed assessment.

The definition of these *other acidic soil materials* for the detailed assessment of acid sulfate soils in the Murray-Darling Basin is as follows:

1) **Other acidic soil materials** – either:
   a. non-sulfidic soil materials that acidify by at least a 0.5 pH_W unit to a pH_W of < 5.5 during moist aerobic incubation; or
   b. soil materials with a $pH_W \geq 4$ but < 5.5 in the field.

2) **Other soil materials** – soils that do not have acid sulfate soil (or other acidic) characteristics.

2. METHODS AND MATERIALS

2.1. Narran Lake Nature Reserve site characteristics

Locations sampled in this study were uniformly flat with either a lack of vegetation cover or more typically a thick vegetation cover of sedges and grasses (e.g. Figure 2-4). The textures of the soil materials sampled ranged from clay loam through to light-medium and heavy clays (Appendix 2). Monosulfidic black oozes (MBO) did not occur at any sites at the time of sampling.

Many of the sites were waterlogged and sampling transects were established to traverse the lake edge transition. The recent rise in water levels was evident along the eastern side of Narran Lake. The soils outside the lakes were very dry.

A map giving the location of each of the sites sampled, the typical landscape and soil profile is shown below in Figures 2-1 – 2-4.

Figure 2-1 Map showing the areas assessed in the northern part of the Narran Lake Nature Reserve (Sites RSNL 1-11).

Figure 2-2 Typical landscape (Site RSNL 5) and grey clay (Site RSNL 2) in the Narran Lake Nature Reserve.

Figure 2-3 Map showing the areas assessed at the Kia Ora – Narran Lake sites in the southern part of the Narran Lake Nature Reserve (Sites RSNL 12-19).

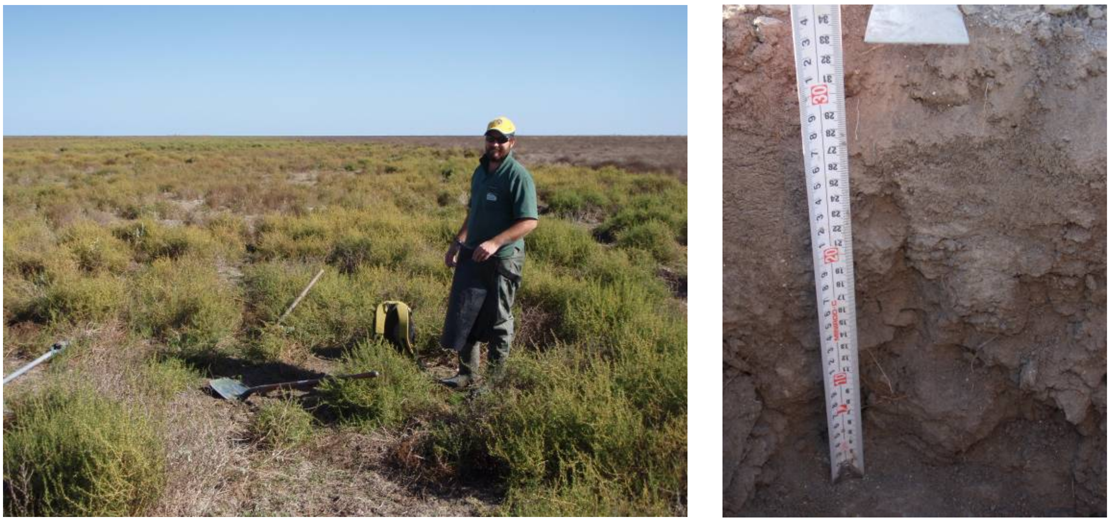

Figure 2-4 Typical landscape (Site RSNL 17) and soil profile (Site RSMM 18) at the Kia Ora – Narran Lake sites in the Narran Lake Nature Reserve. Soil profile was very powdery on surface underneath crust, course gravel (<5%) on surface with a blocky structure >10cm.

2.2. Field sampling of soils and waters

Field sampling of the Narran Lake Nature Reserve was undertaken between 30th June and 3rd July 2008. A total of 97 soil layers were collected and analysed from 19 representative soil profiles within the Narran Lake Nature Reserve to assess the current and potential environmental hazard due to the presence of acid sulfate soils.

Representative soil profiles were collected from several locations within the Narran Lake Nature Reserve (Figure 1-4). Many of the sites were waterlogged and sampling transects were established to traverse the lake edge transition.

Soil samples were collected from at least 5 sampling depths (to a maximum depth of 90 cm) using a range of implements (i.e. spades and augers). Samples were packed into plastic bags in which retained air was minimised. All soil samples were maintained at ≤ 4^{o}C prior to analysis.

Site and profile descriptions including global positioning system (GPS) coordinates are presented in Appendix 1. The soil texture and Munsell colour of each sampled soil layer is presented in Appendix 2. Digital photographs were also taken to document each site and soil profile characteristics. Photographs for a selection of representative sites can be found in Section 2.1.

Surface water quality data was collected from 8 locations in the Narran Lake Nature Reserve. Groundwater data was collected from 5 sites. No groundwater data was collected from the remaining sites as groundwater was not observed during soil pit excavation.

Surface water pH, specific electrical conductivity (SEC), dissolved oxygen (DO) and redox potential (Eh) were determined in the field using calibrated electrodes linked to a TPS 90-FLMV multi-parameter meter. Turbidity was measured using a calibrated TPS WP88 Turbidity meter.

Surface water samples were collected in 1L polypropylene containers. Filtered (0.45 μm) and unfiltered surface water samples were collected at each location. All filtered samples were acidified with a couple of drops of concentrated nitric acid (HNO_3). Samples were stored at < 4^{o}C and sent to CSIRO for analysis.

2.3. Laboratory soil analysis methods

All soil samples were oven-dried at 80^oC prior to analysis. Any coarse material (> 2 mm) present was removed by sieving, and then samples were ring mill ground.

Several parameters were examined to determine whether acid sulfate soil materials were likely to be present, or if there was a potential for acid sulfate soil materials to form. The parameters measured in this study included pH (pH_W, pH_{FOX} and pH_{KCl}), titratable actual acidity (TAA), water soluble sulfate and chromium reducible sulfur (S_{CR}).

The existing acidity of each soil layer (pH_W) was assessed by measuring the pH in a saturated paste (1:1 soil:water mixture). The pH_{FOX} was determined following oxidation with 30 % hydrogen peroxide (H_2O_2) (Method Code 23Bf) (Ahern *et al.* 2004). The KCl extractable pH (pH_{KCl}) was measured in a 1:40 1.0 M KCl extract (Method Code 23A), and the titratable actual acidity (TAA) (i.e. sum of soluble and exchangeable acidity) was determined by titration of the KCl extract to pH 6.5 (Method Code 23F) (Ahern *et al.* 2004). TAA is a measure of the actual acidity in soil materials.

Water soluble sulfate (1:5 soil:water extract) was prepared following the procedures described in Rayment and Higginson (1992), and analysed by ICP-OES (Inductively Coupled Plasma - Optical Emission Spectrometry). The pyritic sulfur content was quantified using the chromium reduction analysis method of Burton *et al.* (2008b).

Standard quality assurance (QA) procedures were followed including the monitoring of blanks, duplicates and standards in each batch.

2.4. Laboratory water analysis

The water quality parameters measured by CSIRO included (i) pH, EC, alkalinity, (ii) dissolved organic carbon, (iii) major anions/nutrients (Cl, Br, F, NO_2, NO_3, PO_4, SO_4, NH_4, total N & P, B, S), (iv) major cations (Na, K, Ca, Mg), and (v) trace metals (Al, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Se, Ti, Zn). EC, pH, alkalinity, nutrient (N and P) and major ion analyses were undertaken on unfiltered samples (centrifuged and no visible suspended solids present). Dissolved metals were analysed on filtered samples.

2.5. Criteria for ranking soil materials for inclusion in Phase 2 of the detailed assessment process

The Scientific Reference Panel of the Murray-Darling Basin Acid Sulfate Soils Risk Assessment Project agreed to recommend that soil materials be assigned the following priorities to undertake the Phase 2 detailed assessment:

High Priority

1) All sulfuric materials.
2) All hypersulfidic materials (as recognised by either 1) incubation of sulfidic materials or 2) a positive net acidity result with a Fineness Factor of 1.5 being used).
3) All hyposulfidic materials with S_{CR} contents ≥ 0.10% S.
4) All surface soil materials (i.e. within 0-20 cm) with water (1:5 soil:water) contents ≥ 100 mg SO_4 kg^{-1}.
5) All monosulfidic materials.

Moderate Priority

All hyposulfidic materials with S_{CR} contents < 0.10% S.

No Further Assessment

1) Other acidic soil materials.
2) All other soil materials.

It is important to note, while the criteria identifying samples for Phase 2 analysis is clearly defined, samples only go through to Phase 2 when consideration is given to the wetland as a whole.

3. RESULTS

3.1. Summary of Narran Lake Nature Reserve field and laboratory results

3.1.1. Soil pH testing (pH_W, pH_{FOX} and pH_{KCl})

The pH_W, pH_{FOX} and pH_{KCl} data for the Narran Lake Nature Reserve sites examined is presented in Table 7-2 (Appendix 2) and summarised in Table 3-1. The pH_W values ranged between 6.26 and 8.86, with the majority of the samples having a pH_W > 7.0. None of the soils in the Narran Lake Nature Reserve would be classified as being sulfuric materials as all soils had a pH_W > 4.

The pH_{FOX} values ranged between 3.09 and 8.80. The majority of the soils showed a pH drop after treatment with peroxide, with a maximum decrease of 3.9 pH units. The pH_{FOX} results also indicate the surface soils at 4 of the sites in the Narran Lake Nature Reserve may have the potential to acidify to pH < 4 as a result of sulfide oxidation. However, the S_{CR} data shows none of these layers contain detectable sulfide (i.e. S_{CR} ≥ 0.01% S). While such decreases in pH after treatment with peroxide are often used to indicate the presence of sulfide minerals in coastal acid sulfate soil materials, the S_{CR} data from these studies suggest that pH decreases in inland acid sulfate soil materials after peroxide has been added are often due to non-acid sulfate soil factors such as the oxidation of organic matter.

Table 3-1 Summary soil data for pH testing and sulfur suite.

Parameter	Units	Minimum	Median	Maximum	n[1]
pH_W[2]		6.26	8.06	8.86	97
pH_{FOX}[3]		3.09	7.48	8.80	97
pH_{KCl}[4]		5.10	7.88	9.39	97
TAA[5]	mole H^+/tonne	0.00	4.86	18.20	97
SO_4[6]	mg SO_4 kg^{-1}	9	23	308	97
S_{CR}[7]	Wt. %S	<0.01	<0.01	<0.01	97
ANC* [8]	$\%CaCO_3$	n.a.	n.a.	n.a.	0
Net Acidity[9]	mole H^+/tonne	0	4.9	18.2	26

[1] n: number of samples. [2] pH_W: pH in saturated paste with water. [3] pH_{FOX}: pH after treatment with 30% H_2O_2. [4] pH_{KCl}: pH of 1:40 1 M KCl extract. [5] TAA: Titratable Actual Acidity. [6] Soluble sulfate: in 1:5 soil:water extract. [7] S_{CR}: Chromium Reducible Sulfur. [8] ANC: Acid Neutralising Capacity: by definition, where pH_{KCl} < 6.5 ANC = 0. [9] Net Acidity here does not include allowance for Retained Acidity.

3.1.2. Chromium Reducible Sulfur (S_{CR})

The S_{CR} data for the Narran Lake Nature Reserve sites examined is presented in Table 7-2 (Appendix 2) and summarised in Table 3-1. Sulfidic soil materials (i.e. $S_{CR} \geq 0.01\%$ S) were absent from all sampling sites, with all materials having a sulfide content of < 0.01% S.

3.1.3. Acid Neutralising Capacity

The ANC was not determined as no sulfidic soil materials were present in the Narran Lake Nature Reserve.

3.1.4. Net Acidity

The net acidity thresholds used to characterise the acid sulfate soil materials in this assessment include low net acidity (< 19 mole H^+/tonne), moderate net acidity (19-100 mole H^+/tonne) and high net acidity (> 100 mole H^+/tonne). There is no acidification hazard from acid sulfate soil disturbance as no sulfidic soil materials were present in the Narran Lake Nature Reserve.

3.1.5. Water soluble SO_4

The water soluble SO_4 data for the Narran Lake Nature Reserve sites examined is presented in Table 7-2 (Appendix 2) and summarised in Table 3-1. The water soluble SO_4 content in the soils in the Narran Lake Nature Reserve ranged between 9 and 308 mg kg^{-1}. The water soluble SO_4 contents in the surface soil materials did not exceed the trigger value of 100 mg kg^{-1} at any locations suggesting that monosulfidic materials are unlikely to form after inundation of these wetlands. Only Site RSNL 2 and RSNL 3 had soil layers with a water soluble SO_4 content exceeding the trigger value of > 100 mg kg^{-1}. Sites RSNL 2 and RSNL 3 showed an increase water soluble SO_4 content with depth (Figure 3-1), although a decrease with depth was usually observed (Figure 3-2).

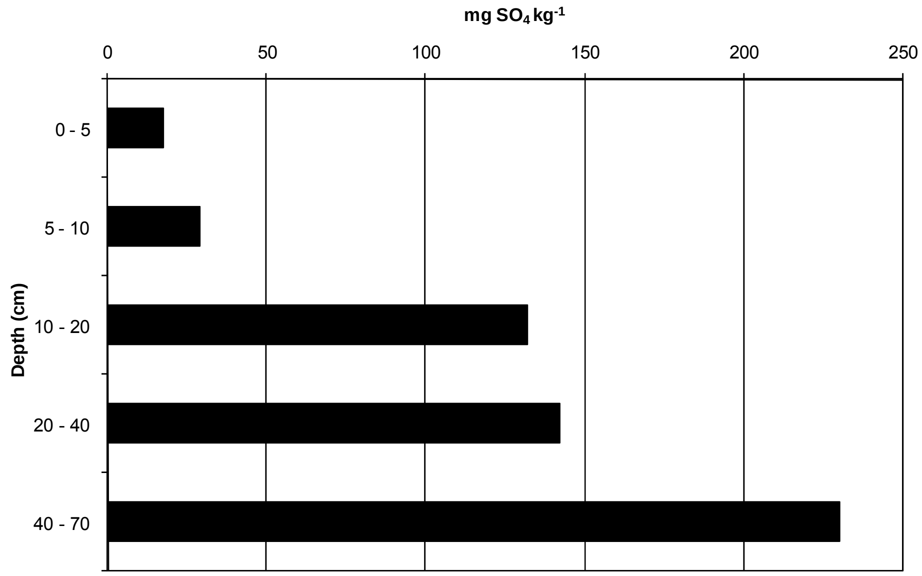

Figure 3-1 Variation in water soluble SO_4 (mg SO_4 kg^{-1}) with depth at site RSNL 2.

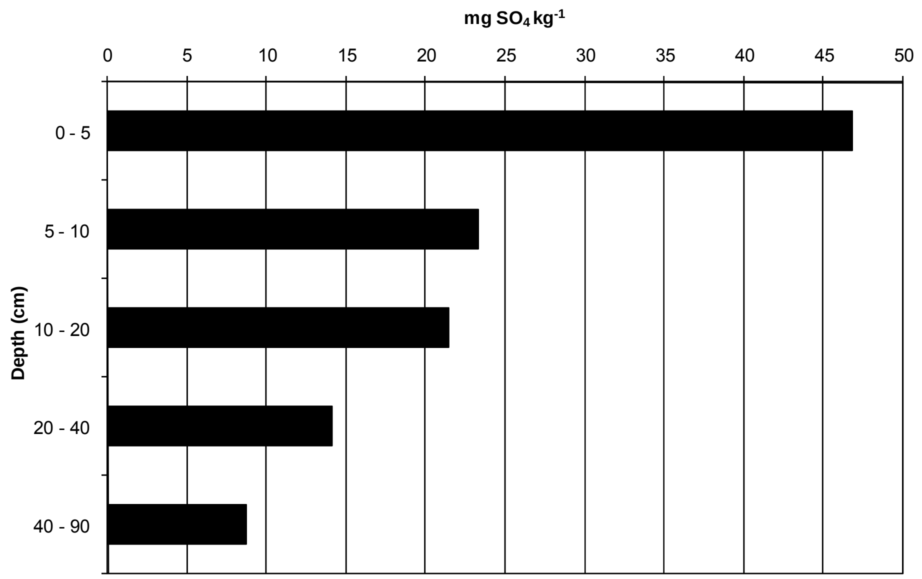

Figure 3-2 Variation in water soluble SO_4 (mg SO_4 kg^{-1}) with depth at site RSNL 10.

3.1.6. Titratable actual acidity (TAA)

The TAA data for the Narran Lake Nature Reserve sites examined is presented in Table 7-2 (Appendix 2) and summarised in Table 3-1. The TAA ranged between 0 and 18 mole H^+/tonne, with the majority of soil layers having a TAA < 10 mole H^+/tonne. There was no TAA in 12 of the 19 soil profiles as all layers had a pH_{KCl} of ≥ 6.5.

3.2. Hydrochemistry

Surface water quality data was collected from 8 sites within the Narran Lake Nature Reserve (Sites RSNL 2, 4, 7, 8, 11, 12, 15, and 16). Groundwater quality data was collected from 5 sites (Sites RSNL 8, 9, 12, 15, and 16). No groundwater data was collected at the remaining 14 sites as groundwater was not observed during soil pit excavation.

A summary of the surface water and groundwater characteristics measured in the field are presented in Table 3-2 and 3-3. The results of the laboratory analyses are presented in Appendix 3.

The field pH of the surface waters ranged between 6.8 and 10.1 (Table 3-2) with 4 sites exceeding the most relevant ANZECC/ARMCANZ (2000) trigger value for aquatic ecosystems of 8.0. The water data indicates that the surface water has not been affected by acidification. The surface water had low sulfate concentrations ranging between < 0.05 and 6.14 mg L^{-1}.

Table 3-2 Summary of surface water hydrochemical characteristics (field).

	pH	**SEC** µS cm^{-1}	**DO** % sat.	**Eh** mV	**Turbidity** NTU	**Alkalinity** (mg L^{-1} as HCO_3)
Minimum	6.84	229.7	59.7	158	1.7	n.a.
Median	8.20	383.0	92.8	303	253	n.a.
Maximum	10.12	459.0	162.5	376	2577	n.a.
n[1]	8	8	8	8	6	0

[1] n: number of samples

The field pH of the groundwater ranged between 7.4 and 7.7 indicating that the groundwater has not been affected by acidification (Table 3-3). The groundwater also had low sulfate concentrations ranging between < 0.05 and 3.60 mg L^{-1} (Table 7-6, Appendix 3).

Table 3-3 Summary of groundwater hydrochemical characteristics (field).

	pH	**SEC** µS cm^{-1}	**DO** % sat.	**Eh** mV	**Turbidity** NTU	**Alkalinity** (mg L^{-1} as HCO_3)
Minimum	7.40	575	17.7	142	n.a.[2]	n.a.
Median	7.60	722	33.4	241	n.a.[2]	n.a.
Maximum	7.72	811	79.0	283	n.a.[2]	n.a.
n[1]	5	5	5	5	0	0

[1] n: number of samples [2] n.a.: Turbidity was measured only for surface water samples

4. HAZARD ASSESSMENT

4.1. Interpretation of soil and water data

Sulfuric and sulfidic soil materials were not encountered in any of the sampling sites (Table 4-1). The data indicates that acidification as a result of sulfide oxidation is unlikely to present a major hazard to these wetlands.

The water soluble sulfate contents for none of the surficial soil materials sampled exceeded the trigger value of 100 mg kg^{-1} indicating that the formation of monosulfidic materials upon rewetting of these wetlands is unlikely (Table 4-1).

The water data indicates that the surface water and groundwater has not been affected by acidification.

Table 4-1 Type and prevalence of acid sulfate soil materials.

Type of actual or potential acid sulfate soil material	Number of sampling sites containing sulfuric or sulfidic materials (Total sites = 19)	Proportion of total sampling sites (%)
Sulfuric	0	0
Hypersulfidic	0	0
Hyposulfidic (S_{CR} ≥ 0.10%)	0	0
Monosulfidic (observed)	0	0
Monosulfidic (potential)	0	0
Hyposulfidic (S_{CR} < 0.10%)	0	0
Other acidic (pH_w &/or pH_{age}) 4 – 5.5	0	0
Other soil materials	19	100

5. CONCLUSIONS

This report provides the results of Phase 1 of a two-phased detailed assessment procedure to determine the hazards posed by acid sulfate soil materials in the Narran Lake Nature Reserve Ramsar wetlands. This Phase 1 report is aimed solely at determining whether or not acid sulfate soil materials are present in the Narran Lake Nature Reserve.

Sulfuric or sulfidic materials were not observed at the sites sampled in these wetlands. The data indicates that acidification as a result of sulfide oxidation is unlikely to present a major hazard to these wetlands.

The water soluble sulfate contents in the surficial soil materials did not exceed the trigger value of 100 mg kg^{-1} at any locations indicating that the formation of monosulfidic materials upon rewetting of these wetlands is unlikely.

The water data indicates that the surface water and groundwater has not been affected by acidification.

Based on the priority ranking criteria adopted by the Scientific Reference Panel of the Murray-Darling Basin Acid Sulfate Soils Risk Assessment Project no further assessment is recommended at the Narran Lake Nature Reserve Ramsar wetlands. As such, the Scientific Reference Panel of the Murray-Darling Basin Acid Sulfate Soils Risk Assessment Project agreed that Phase 2 detailed assessment of acid sulfate soil materials was not required for the Narran Lake Nature Reserve Ramsar wetlands.

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7. APPENDICES

APPENDIX 1. Site and sample descriptions

Table 7-1 Narran Lake Nature Reserve site and sample descriptions.

Profile	Date	Location	GPS Co-ords *Zone*	*East.*	*North.*	Location Remarks	Profile remarks
RSNL1	30/6/08	Narran Lake N.R.	55	544524	6713005	Drainage line between claypan/salt lake and back lake. Above main track. 95% groundcover of herbs grass and nardoo.	Fine sand in top layers. Carbonate nodules >40cm.
RSNL2	1/7/08	Narran Lake N.R.	55	536280	6713455	Narran River below bridge. Halfway up bank, 4m from waters edge. No veg cover. Surface water taken.	Grey cracking clays with some sands in between cracks. Dug to 70cm.
RSNL3	1/7/08	Narran Lake N.R.	55	536148	6713425	Profile 150m to the W in open River cooba and Lignum floodplain. 90% ground cover of dead herbs and leaf litter.	Semi angular pebbles on surface. Gravel throughout profile.
RSNL4	1/7/08	Narran Lake N.R.	55	542512	6714241	Profile dug in middle of pool within lignum of long arm approx. 150m west of tank and windmill, 20m south of old fence line. Pool covered in water weed. Water very clear. Surface water sample taken	Gouge auger dug to 75cm.
RSNL5	1/7/08	Narran Lake N.R.	55	542330	6714280	Grassy clearing within open lignum. 100m NW of NL4. 95% groundcover of herbs and grasses.	Moist grey clays. Very sticky.
RSNL6	1/7/08	Narran Lake N.R.	55	542112	6714316	Similar to NL5 however lignum more clumped and groundcover taller (20cm).	Black soils lightening with depth. Carbonate nodules throughout profile.
RSNL7	1/7/08	Narran Lake N.R.	55	544407	6712877	Mud covered by azolla within a closed community of lignum within Back Lake. Pit dug 1m from waters edge. Surface water sample taken.	
RSNL8	1/7/08	Narran Lake N.R.	55	545491	6711381	NE edge of 'salt lake'. Low bank jutting into water ~20cm above water level. 20% groundcover of sedges. Surface and groundwater samples taken.	Sandy surface. Different Layers sampled: 8.3 – 0-9cm: Yellow sand; 8.4 – 9-22cm: grey sandy clays; 8.5 – 22-40cm: Dark grey sand; 8.6 – 40-90: yellow sandy clay.

Table 7-1 (continued) Narran Lake Nature Reserve site and sample descriptions.

Profile	Date	Location	GPS Co-ords			Location Remarks	Profile remarks
			Zone	*East.*	*North.*		
RSNL9	2/7/08	Narran Lake N.R.	55	543402	6706719	Southern side of Clear lake on lignum-phragmites boundary towards southern boundary of NR. 95% cover of azolla and water weed on moist mud with no surface water. Groundwater sample taken.	Grey sticky mud. Groundwater from top 40cm of profile.
RSNL10	2/7/08	Narran Lake N.R.	55	543473	5708121	Towards Clear lake on boundary of lignum and phragmites (3m tall). 20% groundcover of young herbs, algae and phragmites pieces.	Rocks up to 20cm diameter on surface. Moist cracking mud. Large pebbles/cobbles through profile. Dark grey clay. >40cm two different colours with patches of light merging at depth.
RSNL11	2/7/08	Narran lake N.R.	55	543913	5708321	Exposed bank of lake. Exposed mud with <5% cover of cobbles. Surface water sample taken	More clayey than sandy
RSNL12	2/7/08	Kia Ora – Narran Lake.	55	535964	6698087	Out in middle of delta to the north of Narran Lake. Nardoo and QLD bean as well as other tall grasses to 1m. Profile dug next to pooled water. Surface and Ground water samples taken.	Grey sticky mud. Pit to 75cm.
RSNL13	2/7/08	Kia Ora – Narran Lake.	55	536037	6698151	100m NE of NL12. In dryer Nardoo grass gilgui. Hoof prints common. 70% nardoo cover in thin belt of 1m tall annual grass.	Dryer soil however still sticky grey clay.
RSNL14	2/7/08	Kia Ora – Narran Lake.	55	536166	6698222	120 NE of NL13. 50% cover of Nardoo and grasses.	Dry grey clay. Dug to 85cm.
RSNL15	3/7/08	Kia Ora – Narran Lake.	55	534719	6695716	Eastern side of Narran Lake. 100m into a zone of water killed dryland perennials. 85% cover of Nardoo and aquatic reeds. Some dead roly poly surrounding profile site. Surrounding pools of water <10cm deep and full of aquatic weeds. Surface and Ground water samples taken	

Table 7-1 (continued) Narran Lake Nature Reserve site and sample descriptions.

Profile	Date	Location	GPS Co-ords			Location Remarks	Profile remarks
			Zone	*East.*	*North.*		
RSNL16	3/7/08	Kia Ora – Narran Lake.	55	534656	6695790	100m east of NL15. 1m grass tussocks, with occasional dead roly poly. 85% groundcover of nardoo and stranded algae. Surface and Ground water samples taken	
RSNL17	3/7/08	Kia Ora – Narran Lake.	55	534778	6695636	100m SE of NL16. On boundary of dead and live roly poly marking extent of recent flooding. Sparse (5%) cover of herbs and grasses.	Dry cracking grey clays.
RSNL18	3/7/08	Kia Ora – Narran Lake.	55	538833	6693989	Southern side of inlet to the east of NL15-17. 95% cover of 70cm clumped prickly bushes. No understory.	Very powdery on surface underneath crust. Course gravel (<5%) on surface. Blocky structure >10cm.
RSNL19	3/7/08	Kia Ora – Narran Lake.	55	538736	6694096	150m NW of NL18 with very similar veg cover as NL18	Crust sampled here again. 5mm-10cm powdery, 10-90cm blocky.

APPENDIX 2. Field and laboratory analytical soil data

Table 7-2 Narran Lake Nature Reserve field and laboratory analytical soil data.

Site / Sample	Depth (cm)	Texture	Colour	Mottle % / Colour	pH_W	pH_{FOX}	pH_{FOX} reaction [1]	pH_{KCl}	TAA mole H^+/tonne	CRS %Scr	Sulfate (mg SO_4 /kg)
RSNL / 1.3	0 - 5	CLS	10YR 3/1		6.63	3.09	XX	5.79	6.83	<0.01	51.46
1.4	5 - 10	ZC	10YR 5/3		6.31	3.63	XX	5.40	14.11	<0.01	54.69
1.5	10 - 20	ZC	10YR 4/2		6.26	4.11	XX	5.10	18.20	<0.01	26.29
1.6	20 - 40	MC	2.5Y 3/1		6.93	5.29	XXX	5.66	7.28	<0.01	15.34
1.7	40 - 90	MC	2.5Y 3/1		8.23	7.58	XX	6.81	-	<0.01	12.80
RSNL / 2.3	0 - 5	MC	10YR 3/2		7.25	4.74	XXX	5.56	9.56	<0.01	17.48
2.4	5 - 10	MC	10YR 3/2		6.88	4.88	XXX	5.80	7.74	<0.01	29.11
2.5	10 - 20	MHC	10YR 3/2		6.98	5.37	XXXX	6.32	2.28	<0.01	131.91
2.6	20 - 40	MHC	10YR 3/2		7.78	7.57	XXX	6.90	-	<0.01	142.43
2.7	40 - 70	MHC	10YR 3/2		7.84	7.86	XXX	6.91	-	<0.01	230.30
RSNL / 3.3	0 - 5	MC	10YR 4/1		7.06	5.17	XXX	5.98	5.46	<0.01	16.96
3.4	5 - 10	MC	10YR 3/1		7.29	4.78	XXX	6.02	5.46	<0.01	30.55
3.5	10 - 20	MC	2.5Y 4/1		7.69	6.25	XXXX	6.29	2.28	<0.01	46.88
3.6	20 - 40	MC	10YR 4/1		7.67	6.61	XXX	6.30	2.28	<0.01	84.63
3.7	40 - 90	MC	10YR 4/1		7.22	6.97	XXX	6.26	1.82	<0.01	308.49
RSNL / 4.3	0 - 5	MC	2.5Y3/1		7.88	7.28	XXXX	8.48	-	<0.01	71.45
4.4	5 - 10	MC	2.5Y4/1		7.98	7.41	XXX	8.71	-	<0.01	32.04
4.5	10 - 20	MC	2.5Y4/1		7.73	7.48	XXXX	8.66	-	<0.01	21.80
4.6	20 - 40	MC	2.5Y3.5/1		7.72	7.70	XXX	8.83	-	<0.01	15.12
4.7	40 - 75	MC	2.5Y3/1		7.93	7.72	XXX	8.92	-	<0.01	21.13
RSNL / 5.3	0 - 5	MC	2.5Y4/1		7.64	6.92	XXXX	8.39	-	<0.01	64.21
5.4	5 - 10	MC	2.5Y4/1.5		7.96	7.21	XXX	8.10	-	<0.01	23.24
5.5	10 - 20	MC	5Y4/1.5		8.19	7.57	XXX	8.22	-	<0.01	15.63
5.6	20 - 40	MC	5Y4.5/1		8.25	7.75	X	8.32	-	<0.01	9.63
5.7	40 - 90	MC	5Y4/1		8.29	8.06	XX	8.41	-	<0.01	14.66
RSNL / 6.3	0 - 5	FSMC	10YR3/1		7.60	3.72	XX	6.54	-	<0.01	36.27
6.4	5 - 10	FSMC	10YR2/1		7.63	4.88	X	6.73	-	<0.01	17.19
6.5	10 - 20	LMC	10YR2/1		8.60	5.83	X	6.60	-	<0.01	11.81
6.6	20 - 40	MHC	2.5Y4/1		8.85	7.03	X	9.05	-	<0.01	15.03
6.7	40 - 90	MC	2.5Y5/1		8.29	8.13	X	9.39	-	<0.01	12.45
RSNL / 7.3	0 - 5	MC	10YR3/1		6.87	3.85	XXX	6.06	8.19	<0.01	44.76
7.4	5 - 10	MC	2.5Y2.5/1		6.70	4.29	XXX	5.89	9.48	<0.01	31.04
7.5	10 - 20	MC	2.5Y3/1		6.96	4.37	XXX	5.91	9.01	<0.01	23.12
7.6	20 - 40	MC	10YR3/1		6.90	4.41	XXX	5.98	7.11	<0.01	16.96
7.7	40 - 90	MC	10YR3/1		6.88	4.62	XXX	6.16	4.27	<0.01	14.00
RSNL / 8.3	0 - 5	FCS	2.5Y6/4		7.61	3.69	XX	6.05	3.79	<0.01	49.66
8.4	5 - 10	FSLC	2.5Y6/2		7.49	4.83	XXX	6.12	2.84	<0.01	30.57
8.5	10 - 20	FSLC	2.5Y5/2		7.98	6.50	XXX	6.07	13.75	<0.01	26.14
8.6	20 - 40	CLS	2.5Y5/1.5		8.06	6.31	X	6.48	1.90	<0.01	23.13
8.7	40 - 90	CLS	2.5Y5.5/2		8.25	7.92	X	7.99	-	<0.01	18.21
RSNL / 9.3	0 - 5	FSZMC	2.5Y3/1		7.24	4.36	XXX	6.43	2.84	<0.01	45.42
9.4	5 - 10	SMC	2.5Y4/1		7.35	4.79	XXXX	6.39	2.84	<0.01	32.26
9.5	10 - 20	MC	2.5Y3.5/1		7.49	5.60	XXX	6.51	-	<0.01	21.60
9.6	20 - 40	SMC	2.5Y3.5/1		8.47	6.62	X	7.73	-	<0.01	10.48
9.7	40 - 90	MC	2.5Y4/1		8.29	7.03	XX	7.84	-	<0.01	20.12
RSNL / 10.3	0 - 5	MC	2.5Y4/1		6.96	4.77	XXX	6.43	2.84	<0.01	46.82
10.4	5 - 10	MC	2.5Y3.5/1		6.87	5.24	XXX	6.35	2.84	<0.01	23.34
10.5	10 - 20	MC	10YR3/1		6.88	5.52	XXX	6.34	2.84	<0.01	21.46
10.6	20 - 40	MC	10YR3/1	15% 2.5Y6/1	8.18	6.54	XXX	6.60	-	<0.01	14.11
10.7	40 - 90	HC	2.5Y7/1	40% 2.5Y3/1	8.20	8.06	XXX	7.73	-	<0.01	8.73
RSNL / 11.3	0 - 5	MC	5Y4/1		7.80	7.40	XXXX	7.49	-	<0.01	32.38
11.4	5 - 10	MC	2.5Y4/1		7.85	7.67	XXX	7.76	-	<0.01	24.39
11.5	10 - 20	MC	5Y4/1		7.93	7.74	XXXX	7.83	-	<0.01	20.89
11.6	20 - 40	MC	2.5Y4/1		8.04	7.88	XXX	7.88	-	<0.01	19.22
11.7	40 - 90	MC	5Y4/1		8.06	8.17	XXX	7.93	-	<0.01	20.82
RSNL / 12.3	0 - 5	MC	2.5Y4/1		7.97	7.41	XXXX	7.77	-	<0.01	37.86
12.4	5 - 10	MHC	2.5Y3/1		8.12	7.17	XXXX	7.85	-	<0.01	26.37
12.5	10 - 20	MHC	2.5Y4/1		8.08	7.48	XXX	7.84	-	<0.01	22.84
12.6	20 - 40	MHC	2.5Y4/1		8.21	7.74	XXXX	7.93	-	<0.01	20.55
12.7	40 - 75	MC	2.5Y4/1		8.24	7.83	XXX	7.93	-	<0.01	17.63
RSNL / 13.3	0 - 5	MC	10YR5/1	1% 10YR6/8	7.48	5.14	XXXX	6.93	-	<0.01	49.96
13.4	5 - 10	MC	10YR4/1		7.87	6.57	XXXX	6.74	-	<0.01	35.66
13.5	10 - 20	MC	10YR4/1		8.26	7.34	XXXX	7.31	-	<0.01	30.94
13.6	20 - 40	MC	10YR4/1	1% 10YR6/8	8.83	7.84	XXXX	7.75	-	<0.01	21.90
13.7	40 - 90	MHC	10YR4/1		8.64	8.06	XXXX	7.84	-	<0.01	27.54
RSNL / 14.3	0 - 5	MC	10YR3.5/1		8.53	7.79	XXX	7.91	-	<0.01	22.04
14.4	5 - 10	MC	10YR3.5/1		8.71	7.70	XX	7.98	-	<0.01	20.69
14.5	10 - 20	LMC	5Y4/1		8.83	7.97	XXX	7.99	-	<0.01	14.99
14.6	20 - 40	MHC	5Y4/1		8.86	8.13	XXX	7.98	-	<0.01	15.07
14.7	40 - 85	MC	5Y4/1		8.79	8.36	XXX	8.02	-	<0.01	19.34

Table 7-2 (continued) Narran Lake Nature Reserve field and laboratory analytical soil data.

Site / Sample	Depth (cm)	Texture	Colour	Mottle % / Colour	pH_W	pH_{FOX}	pH_{FOX} reaction [1]	pH_{KCl}	TAA mole H^+/tonne	CRS %Scr	Sulfate (mg SO_4 /kg)
RSNL / 15.3	0 - 5	MC	2.5Y5/2		7.77	7.66	XXXX	7.97	-	<0.01	37.22
15.4	5 - 10	MC	2.5Y4/1		8.07	8.04	XXXX	8.05	-	<0.01	21.18
15.5	10 - 20	MC	2.5Y4/1		8.06	8.04	XXXX	8.05	-	<0.01	21.25
15.6	20 - 40	MC	2.5Y4/1		8.21	8.56	XXXX	8.14	-	<0.01	23.47
15.7	40 - 90	LMC	5Y5/1		8.31	8.31	XXXX	8.15	-	<0.01	20.56
RSNL / 16.3	0 - 5	MC	5Y5/1		8.18	7.74	XXXX	8.03	-	<0.01	28.70
16.4	5 - 10	MC	2.5Y6/1		8.25	7.87	XXXX	8.10	-	<0.01	27.98
16.5	10 - 20	MC	2.5Y5/1		8.40	8.40	XXXX	8.10	-	<0.01	19.70
16.6	20 - 40	MC	2.5Y5/1		8.38	8.37	XXXX	8.14	-	<0.01	22.60
16.7	40 - 90	LMC	2.5Y5/1		8.41	8.68	XXX	8.59	-	<0.01	25.05
RSNL / 17.3	0 - 5	LMC	10YR5/2		8.07	6.90	XXXX	8.14	-	<0.01	38.01
17.4	5 - 10	LMC	2.5Y5/1		8.24	7.04	XX	8.13	-	<0.01	32.73
17.5	10 - 20	MC	2.5Y5/2		8.35	7.34	XXX	8.15	-	<0.01	32.10
17.6	20 - 40	MC	10YR5/1		8.51	8.19	XXXX	8.18	-	<0.01	26.69
17.7	40 - 90	MC	10YR5/1		8.61	8.80	XXXX	8.23	-	<0.01	44.53
RSNL / 18.2	Crust	ZCL	2.5Y5/1		8.32	7.86	XXXX	8.08	-	<0.01	20.44
18.3	0 - 5	LC	2.5Y4/1		8.40	7.71	XXXX	8.11	-	<0.01	21.18
18.4	5 - 10	LC	2.5Y4/1		8.43	8.09	XXXX	8.12	-	<0.01	27.87
18.5	10 - 20	LMC	2.5Y4/1		8.48	8.28	XXXX	8.14	-	<0.01	31.14
18.6	20 - 40	MC	2.5Y4/1		8.39	8.65	XXXX	8.08	-	<0.01	82.92
18.7	40 - 90	MC	2.5Y4/1		8.61	8.78	XXXX	7.99	-	<0.01	28.19
RSNL / 19.2	Crust	ZCL	2.5Y5/1		8.05	8.08	XX	8.09	-	<0.01	
19.3	0 - 5	LC	2.5Y4/1		8.00	7.91	XX	8.15	-	<0.01	19.85
19.4	5 - 10	LC	2.5Y4/1		8.40	8.44	XXXX	8.17	-	<0.01	21.88
19.5	10 - 20	LMC	2.5Y4.5/1		8.52	8.37	XXXX	8.13	-	<0.01	19.64
19.6	20 - 40	MC	2.5Y4.5/1		8.55	8.75	XXX	8.19	-	<0.01	57.30
19.7	40 - 90	MC	2.5Y4.5/1		8.60	8.48	XXXX	8.29	-	<0.01	15.78

[1] Soil reaction rating scale for pH_{FOX} test: slight reaction (X), moderate reaction (XX), high reaction (XXX), and very vigorous reaction, gas evolution and heat generation commonly >80°C (XXXX) (Ahern *et al*. 2004).

APPENDIX 3. Field and laboratory hydrochemistry data

Table 7-3 Narran Lake Nature Reserve field surface water hydrochemistry data.

Site	Units	Site RSNL 2	Site RSNL 4	Site RSNL 7	Site RSNL 8	Site RSNL 11	Site RSNL 12	Site RSNL 15	Site RSNL 16	Minimum	Median	Maximum	Range	n
Water type		Surface	Surface	Surface	Surface	Surface	Surface	Surface	Surface					
pH		7.37	10.12	6.84	8.46	8.85	7.93	9.35	7.87	6.84	8.20	10.12	6.84 - 10.12	8
SEC	µS cm^{-1}	229.7	396.0	282.8	370.0	300.9	443.0	459.0	456.0	229.7	383.0	459.0	229.7 - 459.0	8
DO	% sat	69.6	130.4	59.7	126.9	98.7	63.6	162.5	86.9	59.7	92.8	162.5	59.7 - 162.5	8
Eh	mV	376	300	339	330	272	158	306	211	158	303	376	158 - 376	8
Turbidity	NTU	-	4	2	2577	154	352	453	-	1.7	252.8	2577	1.7 - 2577	6
Alkalinity	(mg L^{-1} as HCO_3)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	-	-
Temperature	^{o}C	9.5	10.7	14.5	13.5	9.7	17.9	13.4	11.0	9.5	12.2	17.9	9.5 - 17.9	8

Table 7‑4 Narran Lake Nature Reserve laboratory surface water analytical hydrochemistry data.

Parameter	Units	Site RSNL 2	Site RSNL 4	Site RSNL 7	Site RSNL 8	Site RSNL 11	Site RSNL 12	Site RSNL 15	Site RSNL 16	Minimum	Median	Maximum	Range	n
pH		7.52	9.57	7.97	8.14	8.26	8.51	8.13	8.09	7.52	8.14	9.57	7.52 - 9.57	8
E.C.	µS cm^{-1}	240	340	270	360	230	291	432	274	230	283	432	230 - 432	8
Alkalinity	meq/L	1.43	2.55	1.88	2.63	1.60	1.94	3.22	2.09	1.43	2.02	3.22	1.43 - 3.22	8
Ammonium (NH_4-N)	mg/L	0.675	0.055	0.099	0.185	0.023	0.207	0.079	0.015	0.015	0.089	0.675	0.015 - 0.675	8
Oxides of Nitrogen (NO_x-N)	mg/L	1.497	0.015	0.030	0.668	< 0.005	< 0.005	2.287	0.556	< 0.005	0.293	2.287	< 0.005 - 2.287	8
Nitrate (NO_3-N)	mg/L	1.411	0.015	0.030	0.611	< 0.005	< 0.005	2.279	0.556	< 0.005	0.293	2.280	< 0.005 - 2.280	8
Nitrite (NO_2-N)	mg/L	0.087	< 0.005	< 0.005	0.057	< 0.005	< 0.005	0.008	< 0.005	< 0.005	< 0.005	0.087	< 0.005 - 0.087	8
Phosphate (PO_4-P)	mg/L	0.203	0.022	0.012	1.831	0.072	0.011	0.012	0.004	0.004	0.017	1.831	0.004 - 1.831	8
Fluoride (F^-)	mg/L	0.12	0.07	0.09	0.29	0.14	0.14	0.06	0.06	0.06	0.11	0.29	0.06 - 0.29	8
Chloride (Cl^-)	mg/L	9.99	15.77	11.24	15.22	11.63	17.87	20.54	11.59	9.99	13.43	20.54	9.99 - 20.54	8
Bromide (Br^-)	mg/L	0.35	0.06	0.10	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.35	< 0.05 - 0.35	8
Sulfate (SO_4^{2-})	mg/L	6.14	< 0.05	< 0.05	3.59	3.27	3.38	< 0.05	< 0.05	< 0.05	< 0.05	6.14	< 0.05 - 6.14	8
Calcium (Ca)	mg/L	19.81	20.99	17.00	2.93	25.00	37.44	29.54	32.79	2.93	23.00	37.44	2.93 - 37.44	8
Potassium (K)	mg/L	8.32	13.99	7.20	3.31	7.87	12.74	12.48	14.65	3.31	10.40	14.65	3.31 - 14.65	8
Magnesium (Mg)	mg/L	8.09	14.56	6.75	2.75	7.12	12.71	15.07	14.21	2.75	10.40	15.07	2.75 - 15.07	8
Sodium (Na)	mg/L	20.16	29.36	23.98	82.72	21.17	28.61	47.18	36.57	20.16	28.98	82.72	20.16 - 82.72	8
Sulfur (S)	mg/L	2.56	0.09	0.30	1.75	0.80	1.81	0.81	0.74	0.09	0.80	2.56	0.09 - 2.56	8
Total Organic Carbon (NPOC)	mg/L	12.54	38.38	21.59	8.33	14.41	15.46	43.00	16.29	8.33	15.88	43.00	8.33 - 43.00	8
Total Nitrogen (TN)	mg/L	3.050	2.550	1.250	2.210	1.130	1.510	6.250	2.250	1.130	2.230	6.250	1.13 - 6.25	8
Aluminium (Al)	mg/L	6.850	0.066	0.050	6.082	0.074	0.099	0.081	0.021	0.021	0.077	6.850	0.021 - 6.850	8
Boron (B)	mg/L	0.055	0.084	0.019	0.299	0.056	0.047	0.089	0.066	0.019	0.061	0.299	0.019 - 0.299	8
Copper (Cu)	mg/L	0.010	0.006	< 0.005	0.014	0.007	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	0.014	< 0.005 - 0.014	8
Iron (Fe)	mg/L	7.448	0.071	0.058	4.627	0.068	0.083	0.121	0.025	0.025	0.077	7.448	0.025 - 7.448	8
Manganese (Mn)	mg/L	0.105	< 0.006	< 0.006	0.032	< 0.006	0.088	0.008	< 0.006	< 0.006	< 0.006	0.105	< 0.006 - 0.105	8
Phosphorus (P)	mg/L	0.350	0.090	0.040	1.304	0.142	0.053	0.061	< 0.03	0.040	0.076	1.304	0.040 - 1.304	8
Zinc (Zn)	mg/L	0.241	0.021	0.082	0.042	0.010	0.018	0.020	0.022	0.010	0.021	0.241	0.010 - 0.241	8
Molybdenum (Mo)	mg/L	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	8
Cobalt (Co)	mg/L	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	8
Nickel (Ni)	mg/L	0.011	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.011	< 0.01 - 0.011	8
Chromium (Cr)	mg/L	0.011	< 0.008	< 0.008	0.011	< 0.008	< 0.008	< 0.008	< 0.008	< 0.008	< 0.008	0.011	< 0.008 - 0.011	8
Cadmium (Cd)	mg/L	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	8
Lead (Pb)	mg/L	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	8
Selenium (Se)	mg/L	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	8
Titanium (Ti)	mg/L	0.005	< 0.002	< 0.002	0.011	< 0.002	< 0.002	0.002	< 0.002	< 0.002	< 0.002	0.011	< 0.002 - 0.011	8

Table 7-5 Narran Lake Nature Reserve field groundwater hydrochemistry data.

Site	Units	Site RSNL 8	Site RSNL 9	Site RSNL 12	Site RSNL 15	Site RSNL 16	Minimum	Median	Maximum	Range	n
Water type		Ground	Ground	Ground	Ground	Ground					5
pH		7.72	7.67	7.56	7.60	7.40	7.40	7.60	7.72	7.40 - 7.72	5
SEC	µS cm^{-1}	575	762	811	683	722	575	722	811	575 - 811	5
DO	% sat	17.7	33.4	79.0	32.9	37.3	17.7	33.4	79.0	17.7 - 79.0	5
Eh	mV	241	283	257	142	237	142	241	283	142 - 283	5
Turbidity	NTU	n.a.	n.a.	n.a.	n.a.	n.a.	-	-	-	-	-
Alkalinity	(mg L^{-1} as HCO_3)	n.a.	n.a.	n.a.	n.a.	n.a.	-	-	-	-	-
Temperature	°C	12.6	12.5	13.2	12.9	12.9	12.5	12.9	13.2	12.5 - 13.2	5

Table 7-6 Narran Lake Nature Reserve laboratory groundwater analytical hydrochemistry data.

Parameter	Units	Site RSNL 8	Site RSNL 9	Site RSNL 12	Site RSNL 15	Site RSNL 16	Minimum	Median	Maximum	Range	n
pH		8.38	8.24	8.29	8.30	8.27	8.24	8.29	8.38	8.24 - 8.38	5
E.C.	µS cm^{-1}	550	340	688	622	727	340	622	727	340 - 727	5
Alkalinity	meq/L	5.04	6.14	6.54	5.92	7.03	5.04	6.14	7.03	5.04 - 7.03	5
Ammonium (NH_4-N)	mg/L	0.016	0.203	0.027	0.129	0.062	0.016	0.062	0.203	0.016 - 0.203	5
Oxides of Nitrogen (NO_x-N)	mg/L	<0.005	0.081	<0.005	0.020	0.019	<0.005	0.019	0.081	<0.005 - 0.081	5
Nitrate (NO_3-N)	mg/L	<0.005	0.066	<0.005	0.020	0.019	<0.005	0.019	0.066	<0.005 - 0.066	5
Nitrite (NO_2-N)	mg/L	<0.005	0.015	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	5
Phosphate (PO_4-P)	mg/L	0.156	0.047	0.018	0.034	0.065	0.018	0.047	0.156	0.018 - 0.156	5
Fluoride (F^-)	mg/L	0.01	0.11	0.09	0.14	0.28	0.01	0.11	0.28	0.01 - 0.28	5
Chloride (Cl^-)	mg/L	12.68	11.37	14.75	15.02	16.35	11.37	14.75	16.35	11.37 - 16.35	5
Bromide (Br^-)	mg/L	0.06	0.20	<0.05	<0.05	<0.05	<0.05	<0.05	0.20	<0.05 - 0.20	5
Sulfate (SO_4^{2-})	mg/L	3.60	0.60	0.15	<0.05	<0.05	<0.05	0.15	3.60	<0.05 - 3.60	5
Calcium (Ca)	mg/L	20.65	82.03	77.69	54.21	40.29	20.65	54.21	82.03	20.65 - 82.03	5
Potassium (K)	mg/L	15.20	11.56	8.53	13.59	9.66	8.53	11.56	15.20	8.53 - 15.20	5
Magnesium (Mg)	mg/L	7.63	24.23	30.05	20.30	18.35	7.63	20.30	30.05	7.63 - 30.05	5
Sodium (Na)	mg/L	96.89	85.22	123.18	96.54	124.47	85.22	96.89	124.47	85.22 - 124.47	5
Sulfur (S)	mg/L	1.07	1.01	0.66	0.07	0.38	0.07	0.66	1.07	0.07 - 1.07	5
Total Organic Carbon (NPOC)	mg/L	8.13	13.61	11.16	16.40	15.62	8.13	13.61	16.40	8.13 - 16.40	5
Total Nitrogen (TN)	mg/L	0.68	1.520	0.71	2.32	1.99	0.68	1.52	2.32	0.68 - 2.32	5
Aluminium (Al)	mg/L	0.081	0.201	0.032	0.603	0.608	0.032	0.201	0.608	0.032 - 0.608	5
Boron (B)	mg/L	0.452	0.110	0.248	0.224	0.265	0.110	0.248	0.452	0.110 - 0.452	5
Copper (Cu)	mg/L	< 0.005	< 0.005	< 0.005	0.008	0.007	< 0.005	< 0.005	0.008	< 0.005 - 0.008	5
Iron (Fe)	mg/L	0.073	0.152	0.034	0.456	0.451	0.034	0.152	0.456	0.034 - 0.456	5
Manganese (Mn)	mg/L	0.011	0.024	0.027	0.010	0.020	0.010	0.020	0.027	0.010 - 0.027	5
Phosphorus (P)	mg/L	0.259	0.196	0.080	0.164	0.111	0.080	0.164	0.259	0.080 - 0.259	5
Zinc (Zn)	mg/L	0.015	0.015	0.017	0.011	0.023	0.011	0.015	0.023	0.011 - 0.023	5
Molybdenum (Mo)	mg/L	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	5
Cobalt (Co)	mg/L	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	5
Nickel (Ni)	mg/L	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	5
Chromium (Cr)	mg/L	< 0.008	< 0.008	< 0.008	< 0.008	< 0.008	< 0.008	< 0.008	< 0.008	< 0.008	5
Cadmium (Cd)	mg/L	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	5
Lead (Pb)	mg/L	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	0.000	< 0.03	< 0.03	< 0.03	5
Selenium (Se)	mg/L	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	5
Titanium (Ti)	mg/L	< 0.002	< 0.002	< 0.002	0.003	0.004	< 0.002	< 0.002	0.004	< 0.002 - 0.004	5

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