



Methods for detailed desktop, field and laboratory characterisation of Acid Sulfate Soils in Managed Wetlands



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Executive summary

The aim of this document is to provide the 'basic rationale and describe a set of standardised methods for conducting detailed desktop, field and laboratory assessments of Acid Sulfate Soils (ASS) in Managed Wetlands in the South Australia River Murray Wetlands Region (SARMWR), between Wellington and the South Australian/Victorian border. The field and laboratory ASS assessment is conducted as a two-phase series of investigations involving:

- (i) Phase 1 to determine whether or not ASS materials are present (or absent) for the wetland area, provide characterisation of the properties and subtypes of ASS present, and to provide for the collection of sterile samples for potential DNA extraction; and
- (ii) Phase 2 to determine the nature and severity and the specific risks associated with the ASS materials.

Phase 2 assessment will be conducted on only those ASS materials identified during Phase 1, which are determined to be a priority concern. The methods described in this document have been adapted and updated from the Murray–Darling Basin Authority (2010) protocol document by incorporating contemporary ASS methods and classification systems to better fit the unique environmental settings of managed wetlands in the SARMWR. This revised ASS assessment document consists of office appraisals using Google Earth images, field sampling, field characterisation, laboratory analysis, data interpretation and reporting protocols.

This document is designed to be used as a working document and will be adapted as new information becomes available. The ultimate objective of the ASS assessment is to incorporate acid sulfate soils management options as part of wetland management plans.

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1 Purpose

This document describes the methods for conducting detailed desktop, field and laboratory assessments of Acid Sulfate Soils (ASS) in Managed Wetlands in the South Australia River Murray Wetlands Region (SARMWR Figure 1-1). The ASS assessment is conducted firstly as a desktop investigation and secondly as a two-phase series of detailed investigations involving: (i) Phase 1 to determine whether or not ASS materials are present (or absent) for the wetland area, and provide characterisation of the properties and subtypes of ASS present, (ii) Phase 2 on only those ASS materials identified during Phase 1, which are determined to be a priority concern, and if they are, they will then undergo further investigations to determine their nature and severity and the specific risks associated with the ASS materials. The methods have been adapted and updated from the Murray–Darling Basin Authority (2010) protocol document by incorporating contemporary ASS methods and classification systems to better fit the unique environmental settings of managed wetlands in the SARMWR. The revised ASS assessment document consists of office appraisals using Google Earth images, field sampling, field characterisation, laboratory analysis, data interpretation and reporting.

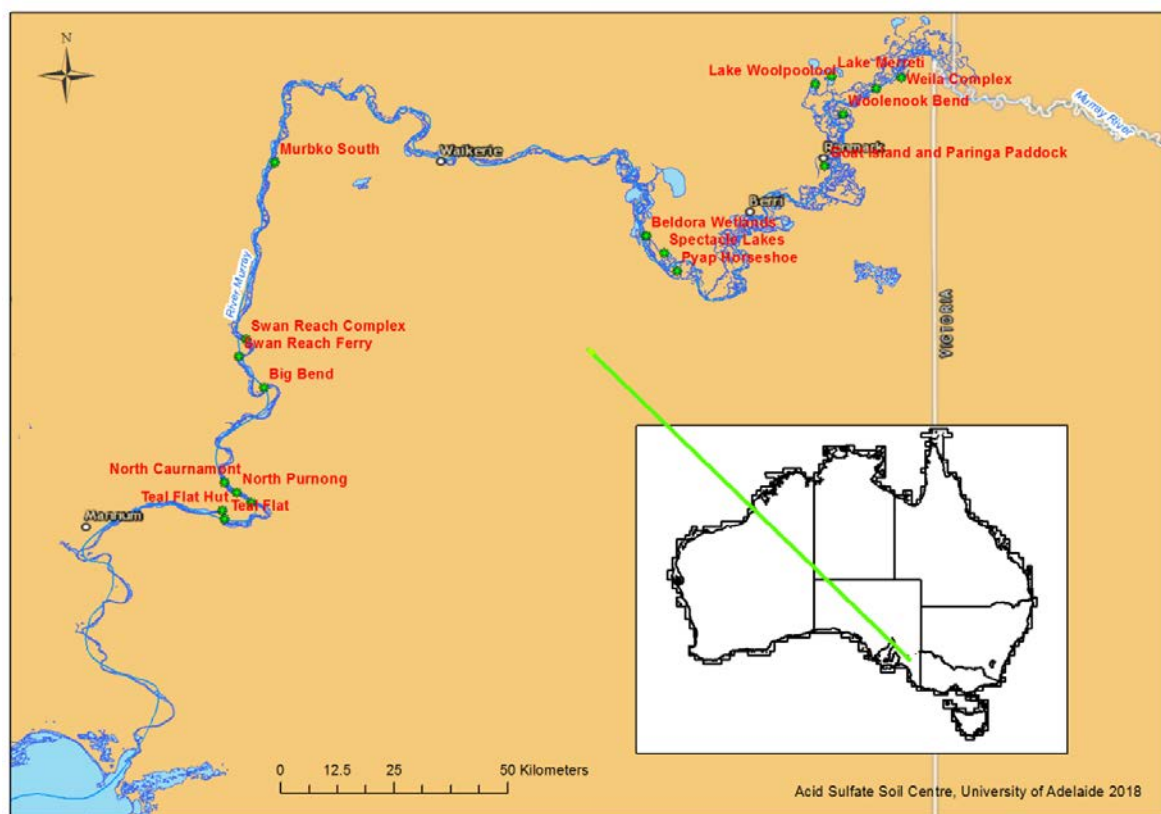


Figure 1-1. Map of the South Australia River Murray Wetlands Region (SARMWR) showing 16 priority RRP wetlands (Phase 1b and 2) to be considered in this assessment.

The South Australia River Murray Wetlands Region (SARMWR) has been faced severe challenges over the past decade from the effects the extreme period of the Millennium Drought from 2007 to 2010, which resulted in the lowest River Murray levels (1.75 m decline from average) in over 90 years of records. The purpose of this report is to provide standardised methods to undertake desktop, field and laboratory investigations to assess the impacts and management of acid sulfate soils in 16 managed Riverine Recovery Program (RRP) wetlands between Wellington and the South Australian/Victorian border (Figure 1-1 and Table 1-1). The specific objectives of this investigation will be to: (i) establish the degree of risk that Acid Sulfate Soils pose to environmental values and water quality in the RRP Wetlands; (ii) confirm that the knowledge and assumptions made in RRP Wetland Management Plans (WMP's) reflect contemporary science; (iii) ensure that appropriate management and mitigation actions are in place; and investigate the influence of wet-dry management regimes on soil microbial communities and processes. Investigation outcomes will inform and support ongoing wetland management and will be reflected in various WMP's as part of their review cycle.

Table 1-1 List of 16 Priority Phase 1B and 2 Priority Wetlands to receive ASS assessment including their management type, current status and RRP construction schedule. The green shaded sites have been previously surveyed and will receive desktop review only, other sites will receive detailed survey as outlined below.

#	Wetland Site	Management Plan	RRP Phase	Management Type	Current Status (Wet / Dry)	Area (Ha)	Proposed Construction Start	Indicative Completion	Construction commenced as of 1/4/18
1	Murtho - Weila	MURTHO PARK/WIELA WETLAND COMPLEX MANAGEMENT PLAN DRAFT, Sept 2007	2	Flow through with a small area of pumping	Some deeper sections are wet. Higher elevations within the wetland are currently dry.	40.50	Mon 5/02/18	Thu 31/05/18	Yes
2	Lake Merreti	Lake Merreti Management Plan	1B	Drying - Wetting. Pumped edges.	Wet	381.30	Constructed	Constructed	Constructed
3	Lake Woolpoolool	Lake Woolpoolool Management Plan 2014	1B	Drying - Wetting. Pumped edges.	Wet	295.20	Constructed	Constructed	Constructed
4	Woolenook Bend Complex	Woolenook Bend, 2014, Wetland Management Plan	2	Flow through	Wet sections. Higher elevations are mostly dry.	57.40	23/03/2018	21/08/2018	No
5	Goat Island & Paringa Paddock	Paringa Paddock / Goat Island Wetland Management Plan 2014	2	Wetting-drying & flow through	Dry.	62.20	Thu 31/05/18	Thu 27/09/18	No
6	Pyap Horseshoe North Section	Pyap Horseshoe Wetland Management Plan, Final report: July 2014	2	Drying – wetting and some extensive creek reconnection to enable flow through.	wet	172.60	Mon 5/2/18	Fri 31/8/18	Yes
7	Spectacle Lakes, Beldora North and South	Beldora - Spectacle Lakes, Wetland Management Plan, Version 1.4	1B	Drying - Wetting		287.80	Constructed	Constructed	Constructed
8	Murbko South	Murbko South Lagoon, Wetland Management Plan	1B	Drying - Wetting	Wet	129.70	Constructed	Constructed	Constructed
9	Sugar Shack Complex (Swan Reach Complex)	Wetland 10 Sugar Shack Pangki, Wetland Management Plan, 2012 Update	2	Drying - Wetting	Wet	29.80	Mon 5/2/18	Tues 24/7/18	Yes
10	Silverlea (Swan Reach Ferry)	Silver Lea Wetland Management Plan, December 2013	2	Drying - Wetting	Wet	68.00	Mon 28/5/18	Fri 19/10/18	No. Contractor has been given partial site possession.
11	Big Bend	Big Bend Wetland Management Plan, Final Report: July 2014	2	Drying - Wetting	Wet	35.22	Mon 5/2/18	Wed 30/5/18	Yes
12	North Curnamont	North Curnamont, Wetland Management Plan, January 2014	2	Drying - Wetting	Wet	73.20	Tue 20/3/18	Tues 10/7/18	No. Contractor has been given partial site possession.
13	North Purnong	Riverine Recovery, North Purnong Wetland Management Plan, February 2013	1B	Drying - Wetting	Wet	94.50	Constructed 1B	Constructed 1B	Constructed 1B
14	Curnamont	Curnamont Wetland Management Plan, 1/12/2013	2	Drying - Wetting	Wet	90.30	N/A	N/A	N/A
15	Teal Flat	Teal Flat Wetland Management Plan, Final Report: July 2014	2	Drying - Wetting	Wet	82.00	Fri 24/11/17	Fri 12/10/18	No. Discussions continuing
16	Teal Flat Hut	Teal Flat Hut Wetland Management Plan, Final Report: July 2014	2	Drying - Wetting	Wet	20.18	Mon 28/5/18	Thu 18/10/18	No. Landholder discussion.

2 Background

The Riverine Recovery Program (RRP) seeks to achieve long-term improvements in the health of the riverine environment between the South Australian/Victorian border and Wellington, SA (Figure 1-1). In addition, the project aims to provide water savings of up to 15 GL, through improved adaptive wetland management, that will be transferred to the Commonwealth as entitlements for environmental purposes. The Wetlands Project Element of RRP is primarily focused on management of pool-connected wetlands (typically implementing a regime of drying and re-wetting otherwise permanent wetlands to mimic the natural annual variation in river level) and is implemented through a phased approach. RRP Wetlands Phase 2 includes investigations to improve wetland management outcomes. It is intended that these investigations will enable management of infrastructure to be refined, and complementary measures to be identified, for the optimisation of environmental benefit and minimisation of risk.

Acid sulfate soils are those soils containing iron sulfide minerals (e.g. Pons 1973; Fanning et al. 2017) that form naturally when sulfate in the water is converted to sulfide by bacteria. These soils may either contain sulfuric acid (sulfuric material), or have the potential to form sulfuric acid (sulfidic material), or cause de-oxygenation (monosulfidic material), or release contaminants when the sulfide minerals are exposed to air (oxygen). The nomenclature and definitions used for acid sulfate soil materials (Hypersulfidic, Hyposulfidic, Sulfuric and Monosulfidic) is as defined by the 2nd edition of the Australian Soil Classification (Isbell and National Committee on Soils and Terrain, 2016) (see Appendix 4). All soils will be classified in accordance with the Australian Acid Sulfate Soil Identification key (Fitzpatrick, 2013), which is designed for people who are not experts in soil classification systems, assisting them to easily identify five acid sulfate soil types (subaqueous, organic, cracking clay, sulfuric and hypersulfidic soils) and 18 sub-types based on the occurrence of sulfuric, hypersulfidic, hyposulfidic, or monosulfidic material, and clayey or sandy layers (see Appendix 5).

Almost all pool-connected wetlands in the South Australia River Murray Wetlands Region (SARMWR) have a wide range of Acid Sulfate Soil subtypes especially from continued lowering of water levels (e.g. Fitzpatrick et al. 2008a,b,c,d,e,f; 2009; 2011; Lamontagne et al. 2004; 2006; Shand et al. 2010a,b; 2008a,b; 2009; Simpson et al. 2008, 2010). Soils that fringe and are below the waterline (“subaqueous soils”) of The South Australia River Murray Wetlands Region (SARMWR) are loaded with hypersulfidic (pyritic) material. When exposed to air, the hypersulfidic material oxidises to produce sulfuric acid, and as this happens, the soils shift from being “hypersulfidic” to becoming “sulfuric” - the latter being characterised by an acidic pH of less than 4 (Isbell and National Committee on Soils & Terrain (2016). These acid sulfate soils (ASS) may pose a considerable localised and regional environmental hazard, including, potentially, mobilisation of heavy metals by acid digestion of clay minerals, ecological damage and water quality issues due to low pH (e.g. Simpson et al., 2008).

Prior to the Millennium Drought from 2007 to 2010, which resulted in the lowest River Murray levels (1.75 m decline from average) in over 90 years of records, Acid Sulfate Soils with hypersulfidic materials built up in wetlands, lakes and river channels due to the presence of sufficient Fe, SO₄, carbon and permanently reducing conditions (due to almost permanent inundation since river regulation). During the Millennium drought, declining water levels led to the exposure and oxidation of accumulated hypersulfidic materials and the formation of severely acidified sulfuric materials and soils in South Australia. Upon the break of the Millennium Drought the sulfuric soils were re-flooded. However, the experience that sulfuric soils with extensive retained acidity (jarosites) has persisted for a decade or longer in the Lower River Murray Irrigation Area (Fitzpatrick et al. 2017a,b; Mosely et al. 2017a) highlights the need to understand the extent and occurrence of managed wetlands in the SARMWR with

hypersulfidic and sulfuric soils. In summary, the current extent and occurrence of wetlands with hypersulfidic and sulfuric soils is relatively unknown.

The Riverine Recovery Programs wetland management practice is based on significant research dealing with ASS assessments in lower Murray wetlands. These assessments identified risks, proposed management of risks and detailed ASS responses to wetting drying cycles. Additional support for RRP wetland management activities was based on findings from CSIRO's and Acid Sulfate Soil Centre (ASSC) successive soil sampling and investigations at Banrock Station (Fitzpatrick et al. 2016) following RRP's Phase 1. Fitzpatrick et al. (2016) reported that soil sampling at four of five Banrock Station wetland sites has found that over the six year wet-dry cycles, previously hyper-sulfuric soils have been transformed to hypo-sulfuric soils with a reduced acidification risk.

There is also a need to update the existing Murray–Darling Basin Authority (2010, 2009) acid sulfate soil protocol document using contemporary ASS methods and classification systems in order to develop more robust methods on how to conduct ASS investigations for the assessment of acid sulfate soils in managed wetlands in the SARMWR so as to avoid potentially negative environmental impacts (e.g. the irreversible formation of deep sulfuric clayey soils and related poor water quality).

In summary, the purpose of this document is to describe standardised methods for conducting desktop and detailed field and laboratory assessments of Acid Sulfate Soils (ASS) in Managed Wetlands in the South Australia River Murray Wetlands Region (SARMWR Figure 1-1). The detailed ASS assessment will be conducted as a two-phase process (Phase 1 and Phase 2), by adapting and updating the Murray–Darling Basin Authority (2010) protocol document using contemporary ASS methods and classification systems (Isbell and National Committee on Soils and Terrain, 2016) to better fit the unique environmental settings of constructed or managed wetlands in the SARMWR. The revised ASS assessment consists of office appraisals using Google Earth images, field sampling, field characterisation, laboratory analysis, data interpretation and reporting.

The rationale for the two-phase approach was developed in light of not knowing in advance how many sites in wetlands will contain acid sulfate soil materials. To address this issue, the Phase 1 assessment will be conducted to conclusively identify the presence or absence of the various types of ASS materials in each wetland. The Phase 2 investigations will only commence when the results of the Phase 1 investigations have been completed and the need for further and more specific detailed risk assessment is determined, in order to reliably identify the nature and severity of the environmental risks posed by ASS materials present and allow identification of ASS management options. The specific objectives of this investigation will be to: (i) establish the degree of risk that Acid Sulfate Soils (ASS) pose to environmental values and water quality at RRP Wetlands in the SARMWR; (ii) confirm that the knowledge and assumptions made in RRP Wetland Management Plans (WMP's) reflect contemporary science; (iii) ensure that appropriate management and mitigation actions are in place; and investigate the influence of wet-dry management regimes on soil microbial communities and processes. Investigation outcomes will inform and support ongoing wetland management and will be reflected in various WMP's as part of their review cycle.

3 Desktop investigations

We will compile field, laboratory, and photographic data from all previous Acid Sulfate Soils investigations conducted by ASSC, CSIRO and others over the past 10 years relevant to the 16 RRP Priority (Phase 2 and 1B) wetlands provided by the Department for Environment and Water (DEW). Our preliminary assessment is that 8 out of the 16 RRP Priority wetlands have been previously surveyed by members of the Acid Sulfate Soil Centre (University of Adelaide and CSIRO). This comprises the green shaded wetlands (eight in total) listed in Table 1-1. Some other sites (e.g. Lakes Merreti, Woolenook Bend and Woolpoolool – see Thomas et al. 2011) have had limited sampling. The final list and sampling locations will be confirmed once further desktop assessment of previous information has occurred.

We will collate and review the Acid Sulfate Soils hazard priority ranking for each RRP wetland, site and sample. We will collate (in a simple tabular format) relevant management and contextual data that will aid in the interpretation of data produced in later stages of this project. Risk ratings will include type of ASS material, ASS soil sub-types, associated hazards, likelihood, consequences and level of risk in accordance with methods outlined in MDBA (2011; Fitzpatrick et al. 2011).

NB: The assumption is that the hazards in these 9 previously surveyed wetlands have not changed substantially since they were surveyed or at the least have not increased. This is considered a reasonable assumption if conditions affecting pyrite formation and/or oxidation have not changed.

4 Detailed acid sulfate soil assessments using two phases

The detailed assessment of ASS in managed wetlands of the SARMWR involves comprehensive analyses 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.

Eight wetlands (green shaded ones in Table 1-1) will receive detailed assessment, comprising RRP 1B and 2 priority wetlands that have not been surveyed previously.

We adapted the Murray-Darling Basin Authority (2010) acid sulfate soil protocols, which requires the following two-phase procedure.

Phase 1 investigations determine whether or not acid sulfate soil materials are present (or absent) for the study area, and provide characterisation of the properties and types of acid sulfate soil materials.

Phase 1 activities include:

- site and transect selection via office appraisals using Google Earth images,
- site and transect selection in the field
- site and profile description
- sample collection and storage
- collection of samples for potential microbial DNA extraction
- laboratory analysis (of soil and water)
- identification of acid sulfate soil materials
- identification of acid sulfate soil Types and Subtypes
- prioritisation and selection of Phase 2 samples
- interpretation and reporting

Phase 2 investigations will only be conducted if the acid sulfate soil materials from Phase 1 are determined to be a priority concern for the study area and, based on Phase 1 recommendations, samples will undergo further investigations to determine their nature and severity and the specific risks associated with the acid sulfate soil materials.

Phase 2 activities include:

- laboratory analysis (of soil)
- risk assessment
- interpretation and reporting, including discussion on broad acid sulfate soil management options.

The soil samples to be analysed for Phase 2 will have been collected as part of the Phase 1 field assessment and then put into storage. Based on the Phase 1 report recommendations the client will identify samples and the analyses to be conducted on each of the samples for Phase 2.

The mandatory data requirements, their objectives for obtaining the results, and methods are summarised for Phase 1 assessment in Tables 3–1 and 3-2, and for Phase 2 laboratory assessment in Appendix 6. Details of the approach and tests are discussed in the following sections. Phase 1 involves field work, collection of soil and

water samples, laboratory analysis, interpretation and reporting of data. Phase 2 involves laboratory analysis (only on samples that meet the selection criteria) and the interpretation and reporting of results.

A review of the existing Murray-Darling Basin Authority (2010) Acid Sulfate Soil Field Guide with accompanying field logging sheets identified significant gaps between the ASS property-recording options for managed wetlands typically found in the SARMWR. The key gaps in this respect included the following aspects as the MDBA Field Guide did not adequately cater for:

- An office assessment of wetlands to assist in the selection of transects and sites by using: (i) high resolution google earth images or aerial maps (current and historic images), (ii) bathymetry and (iii) localities of inlet-outlet water control infrastructures (i.e. gates to control flow and circulation of water into wetlands; and release of water from wetlands).
- The wider spectrum of ASS conditions [e.g. high instances of jarosite, and with that, very low pH (~ 2.5)] by using the new definitions of acid sulfate soil materials in the 2nd Edition of the Australian Soil Classification (Isbell and National Committee on Soils and Terrain, 2016).
- Multi-temporal surveying by defining an improved protocol for site selection when water levels change between survey intervals.

As a consequence, the decision was made to modify and update the Murray-Darling Basin Authority (2010) ASS assessment protocols to be more compatible with constructed wetland conditions in SARMWR. The data would also be uploaded to the ASS database, and made available to the Australian Soil Resource Information System (ASRIS).

Table 3-1 Phase 1 data requirements - list of methods for field data collection.

Data and Analysis	Objective	Method
<i>Field Data</i>		
Site number	uniquely identifies the site	Unique alpha numeric code (e.g. DXF2-01): D – project name; XF2 pond ID
Site location (Zone, easting, northing coordinates)	accurately places the sample site within the study area	Global positioning system (GPS) + or – 1 meters, locate to the WGS 84 Z 54S Grid.
Depth of water or depth to water table below soil surface	Current status of water level relative to the soil surface	Tape measure (National Committee on Soil and Terrain 2009)
Site description	Places the sample site within the landscape and surrounding environment, to enable extrapolation of the profile information and to estimate the proportion that it represents in study area	Refer for guidance to National Committee on Soil and Terrain (2009).
Landscape surface features (Appendix 2): Salt efflorescences, iron precipitates in drains, ponds and wetland soil surface, gilgai, shrinkage cracks, lime/gypsum	For characterisation and classification of acid sulfate soil impacted landscapes. Surface features, such as strong brown coloured schwertmannite-rich precipitates and salt efflorescences provides an important "visual environmental" indicator of combined acid drainage and acid sulfate soil issues in wetlands.	National Committee on Soil and Terrain (2009); Schoeneberger <i>et al.</i> (2002) – for redoximorphic features; Fitzpatrick <i>et al.</i> 2017b.
Sample depth (upper and lower)	Estimating the layer thickness and position in the profile of the soil sample	Tape measure (National Committee on Soil and Terrain 2009)
Soil profile Morphology Description (Appendix 2): field texture, consistence, structure, moisture status, and other diagnostic features if present, such as mottling (redoximorphic features), odour, organic material, shell fragments, minerals such as jarosite, crystals, coarse fragments), effective root depth.	For characterisation and classification of the soil. To facilitate understanding of soil variability and transfer of quantitative data between profiles and layers that appear similar through this qualitative description	National Committee on Soil and Terrain (2009); Schoeneberger <i>et al.</i> (2002) – for redoximorphic features
Photographs – soil profile, soil (or water) surface, surrounding landscape (at a minimum on the 4 opposite points of the compass), and any other features of interest, including chip-tray samples	Provides a visual record of the sampled site and location. Sufficient quality for reports. Soil profile photographs must have a scale marker on left side	Photographs saved as JPG format. See above sample number protocol for photographs required and file naming convention
Field soil pH	Measures the current status of the soil acidity or alkalinity	Field pH meter or Merck pH strips
Soil sample 500 g in one plastic bag	For storage and used if Phase 2 laboratory analysis is required	Stored refrigerated at 4 °C
Sterile soil sample 10-15 g in sample bag and tubes	For storage and used in DNA extraction and analysis if required	Refrigerated and frozen at <-20 °C

Data and Analysis	Objective	Method
Soil sample in 2 separate 70 ml plastic jars with screw top lid	Jar 1: Phase 1 laboratory analysis for acid base accounting parameters Jar 2: Phase 1 pH _w , pH _{peroxide} , water extractable sulfate (surface soil sample only) and specific electrical conductance, and then dried for storage and used if Phase 2 XRD and XRF analysis is required	Stored refrigerated at 4 °C
Soil sample in 2 separate chip-trays	Tray 1: Long term archive storage Tray 2: Ageing test to determine pH _{incubation}	
Water sample (if present) in two 125 mL polyethylene bottles, sample filtered through 0.45 µm membrane filters	Bottle 1: For laboratory analysis of Phase 1 major and trace cation analyses Bottle 2: For laboratory analysis of major and minor anion analyses	Stored refrigerated at 4 °C
Monosulfide sample (if present) 70 ml plastic jar with screw top lid	For Phase 1 analysis. Please note that the residual sample must be retained frozen for Phase 2 analysis of elemental sulfur	Frozen immediately for storage
Monosulfide sample (if present) 500 ml plastic jar with screw top lid	For Phase 2 analysis	Frozen immediately for storage

Table 3-2. Phase 1 and 2 data requirements - list of laboratory methods

Data and Analysis	Objective	Method
Phase 1		
pH _{water} (pH _W)	Measures the current sampled status of the soil acidity or alkalinity	pH meter; 1:1 soil:water (Rayment and Higgins on 1992)
pH _{peroxide} (pH _{OX})	Measures the potential end oxidized status of the soil pH	pH meter; Method 4E1 (Rayment and Higgins on 1992)
pH _{incubation} (pH _{Inc})	Represents a scenario for soil sample on exposure to air (oxygen) for a specified period of time	Fitzpatrick <i>et al.</i> 2010
Electrical conductivity	Measure of the soil salt content	(Rayment and Higgins on 1992)
Soil texture	Assessment of texture to assist with interpretation of acid base accounting results	Hand texture determination placed into 3 classes – coarse, medium, fine
Phase 2		
pH _{KCl}	pH value. Provides trigger value (pH _{KCl} >6.5) for deciding to test for acid neutralising capacity. Part of acid base accounting suite.	pH meter. Method 23A (Ahern <i>et al.</i> 2004)
Chromium reducible sulfur (SCR)	Identifies presence of sulfides. For acid base accounting suite.	Method 23B (Ahern <i>et al.</i> 2004)
Titrateable actual acidity (TAA)	Identifies soil acidity. For acid base accounting suite.	Method 23F (Ahern <i>et al.</i> 2004)
Acid neutralising capacity (ANC) (where pH _{KCl} >6.5)	Identifies neutralising capacity of soil. For acid base accounting suite.	Method 19A2 (Ahern <i>et al.</i> 2004)
Retained acidity (RA)	Identifies stored soil acidity. For acid base accounting suite.	Method 20J (Ahern <i>et al.</i> 2004)
Net acidity (NA)	Identifies the soil acidity (or alkalinity). Calculated in acid base accounting method & liming rate supplied.	Calculated (Ahern <i>et al.</i> 2004)
Acid volatile sulfur (AVS)	Identifies indicative presence of metastable iron monosulfide minerals	Method 22A (Ahern <i>et al.</i> 2004)
Metal mobilisation	Risk of metal release following rewetting	Adapted from Simpson <i>et al.</i> (2010)

4.1 Phase 1 - Site and transect selection using Google Earth images

For each managed wetland obtain: (i) high resolution Google Earth images or aerial photographs of current and historic periods of floodplain paddocks, drains, back swamps, riparian zone wetlands or ponded areas adjacent to the River Murray that are likely to have a problem (e.g. Figure 4-1), (ii) bathymetry of wetland and (iii) localities of inlet-outlet water control infrastructures (i.e. gates to control flow and circulation of water into wetlands; and release of water from wetlands). This information will be used to select several paths or transects across the wetland to represent a hydro-toposequence across the wetland. These transects will usually be from east to west or west to east (towards the river). Avoid transects that are not representative (for example, along fence lines or roadways).

Mark transects and sampling points on the Google Earth image or aerial photograph as shown in Figure 4-1 (i.e. yellow lines/points).



Figure 4-1. Example of sampling transects and points marked on an aerial photograph. Source: Author.

4.2 Site and transect selection in the field

Go onto the wetland to those areas marked on the aerial photograph (Figure 4-1).

A transect approach is to be used to place sites logically within different zones of the wetland. As shown in Figure 4-2 (wetland containing water) and Figure 4-3 (dry wetland), sites are to be placed along the transect at different landscape positions. Accordingly the ASS assessment is based on sampling along a “hydrosequence” at each of the selected transect areas. A hydrosequence is a transect of soils that transition across wet and dry soil conditions, typically running from an upper, drier beach to lower, open water. Transects are usually selected in consultation, and their selection is generally governed by the geographic spread of existing sites, areas of special interest, and local familiarity by the wetland managers.

- Site 1, in ankle-depth water;
- Site 2, just above the shoreline, and
- Site 3, approximately mid-way between the shoreline and the pre-drought high water mark.

This provides the opportunity to identify the range of soil materials that may occur in a wet wetland (e.g Figure 4-4) and dry wetland (Figure 4-5). The transect approach allows a conceptual hydro-toposequence cross-section to be developed that relates the soil information with landscape position and features. It can then be extrapolated spatially across the study area to generate a map of areas or proportions of the wetland that may contain different soil material types (e.g. Figures 4-4 and 4-5).

The study aims to characterise ASS materials, however the general transect approach to site selection may occasionally miss a potential hazard area. Therefore it is appropriate to locate an ad hoc site in the area of interest if it is determined that the ASS materials will impact significantly on the wetland, for example a probable acid sulfate soil location that may be small in area, but is of concern because it is low lying and would be one of the first areas to be inundated with water.

Careful planning and expert judgement is required to meet objectives with the limited number of profiles to be sampled and analysed.

4.2.1 Guidelines for Site Selection

The following points should be considered as guidelines for site selection:

- The number of sites placed in a study area will depend on the size of the study area, as indicated in Table 4-1. Based on our initial assessment of wetlands areas, a total of approximately 400 samples were proposed to be collected from the 8 wetlands.
- A transect approach is to be used to locate sites within a wetland. An example of transects and placement of sites is presented in Figures 4-2 and 4-3.
- Prior to the transects being placed, the wetland as a whole should be observed to determine the likely landscape or geomorphic zones that occur. For example, if wetlands are in a drying phase and therefore the water level decreases and contracts to the lower parts of the wetland. This happens over a period of time and the retreating water level leaves behind a drying soil environment across a range of geomorphic landscapes within the wetland. In a hypothetical wetland this forms a concentric pattern like 'onion rings' around the centre or lowest part. There is a somewhat gradational change in soils, from the dried soils on the periphery to transitional moist to wet soils, and then those that are covered with water at the

centre. This pattern identifies a sequence related to the hydrology and topography as shown in Figure 4-4.

- The study areas are generally lower than the surrounding landscape, either as a wetland, river, stream, lake, estuary, or receding shoreline. The transects and sample sites should be topographically related in short traverses that extend from the step-up high edge of the shore/bank (where generally reeds are growing and marks the old high water-level shoreline) to the lowest point (in dry wetlands) or to the deepest water depth (where water is present) at which it is practical to sample (e.g. see Figure 4-5).

Table 4–1. Study area size and suggested number of sites. Where toposequence transects are employed, a reduction in the number of sites per ha may be justified.

Study area size (ha)	Number of sampled sites
<5	2
5 – 20	4
20 –100	8
100 – 500	12
>500	20

- Other wetland features may identify zones that should be taken into consideration when selecting different landscapes within the wetland that require sampling. These include:
 - soil surface condition (for example, cracks, in-filled cracks, no cracks, sandy, firm, sealed)
 - vegetation pattern (no-vegetation, reeds, weeds, trees)
 - location and number of water entry and exit points and the distribution of the inlet/outlet channel features throughout the wetland
 - soil surface topography
 - presence of surface gels, algae or organic matter on the soil surface underwater
 - water depth (as an extension of the toposequence).
- Once potential zones of interest have been identified in a wetland, one or more transects may be located depending on the study area size and variability.
- Sites for sampling are then placed along the transect and located within each of the zones that the transect crosses. In this way the site sample data can be associated with the topographic position in the wetland and other associated wetland features that determined the zone. This will assist with providing an understanding of where ASS materials occur in the landscape and extrapolating from the site to similar areas.
- The site locations and the number of sites placed along the transect traverses will be determined by the senior soil surveyor or person equivalently skilled. If necessary other ad hoc sites can be placed in the study area to capture particular sites of interest.
- Soil surveyor (or equivalent) experience should be used to guide the selection of site locations and should take into account the following:
 - Safe access and working area, and ease of access to a sampling site location (farm tracks, gates, proximity to public roads and permission from landholders).

- Visually observed variability (vegetation habitat changes, soil surface condition changes, water on the surface, topography changes) and observed variability on remotely sensed image maps and other mapped information.
- Information about the area supplied by the landholder and relevant State/Territory staff.
Data from the earlier wetland assessment sampling event, if conducted.
- All sites are to be accurately geo-referenced and notes made as to the rationale behind the transect position and site locations, including a cross-section sketch showing the transect and features.

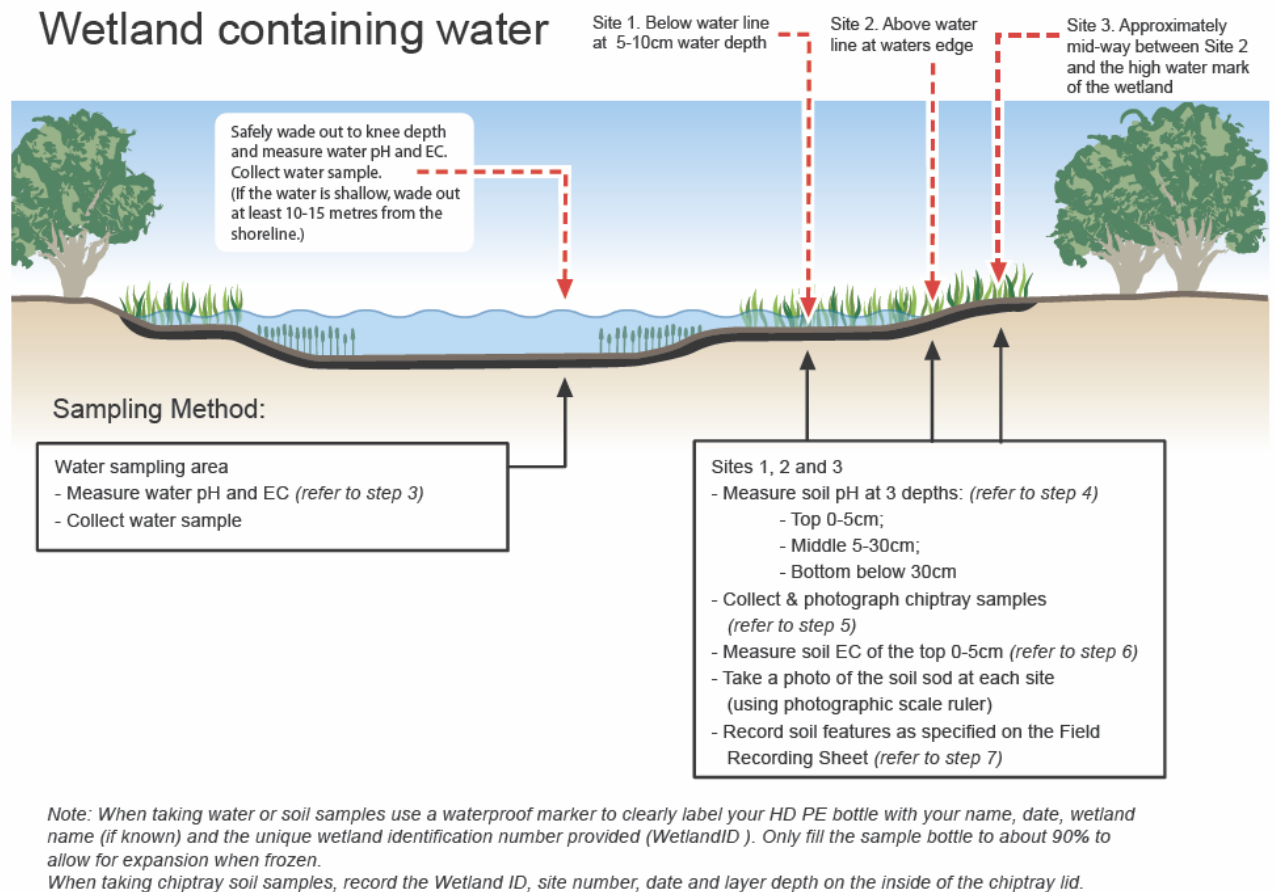


Figure 4-2. Generalised schematic cross-section diagram displaying the sampling locations for wet wetlands in the rapid assessment method (Modified from MDBA 2009).

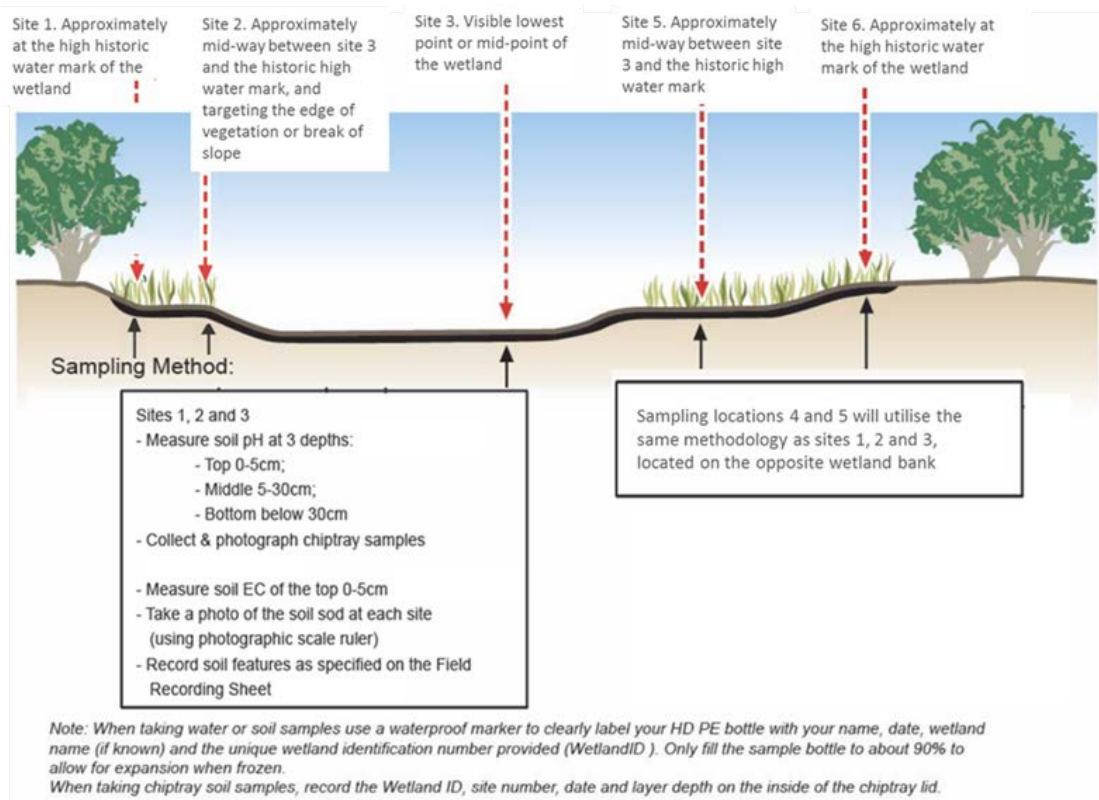


Figure 4-3. Generalised schematic cross-section diagram displaying the sampling locations for dry wetlands in the rapid assessment method (Modified from MDBA 2009).

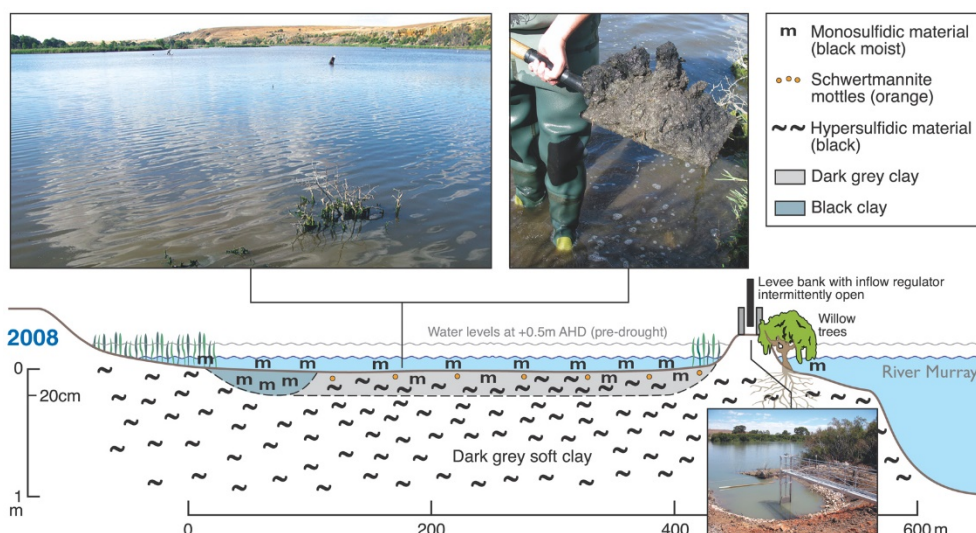


Figure 4–4. Example of a transect approach to placement of sites in the different zones in a wet wetland, which then allows a conceptual hydro-toposequence to be developed, providing information to then extrapolate the results spatially (Fitzpatrick unpublished).

Managed wetland - drying cycle (September 2013)

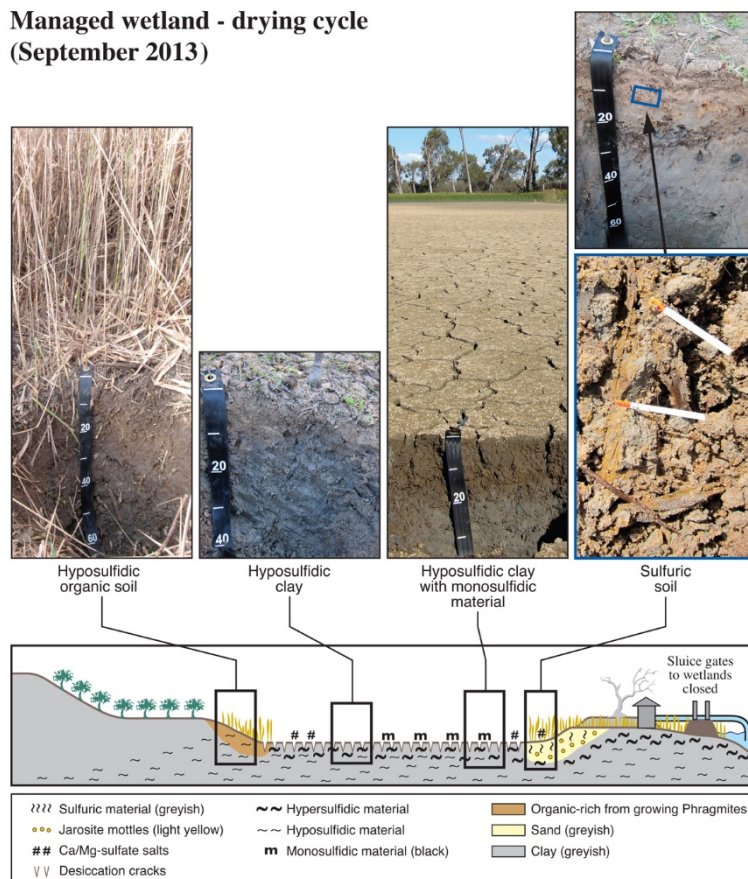


Figure 4–5. Example of a transect approach to placement of sites in the different zones in a dry wetland at Banrock showing the type of soil information that is captured that then allows a conceptual hydro-toposequence to be developed, providing information to then extrapolate the results spatially (Fitzpatrick et al. 2016).

4.3 Site and Profile Description

Site and soil descriptions are made to: (i) accurately locate the sample site within the study area, (ii) place the site within the landscape and surrounding environment, (iii) characterise the soil for classification and (iv) facilitate the understanding of soil variability between sites and soil layers. To do this a list of parameters and methods are provided in Appendix 2 and Table 3–1; this is the required dataset of field information that is to be collected at each site. Field data shall be collected on paper field sheets and checklists and/or on electronic field laptops or tablets using data capture platforms such as 'eDIRT' (e.g. <http://edirt.environment.nsw.gov.au>).

4.3.1 Guidelines for Site and Profile Description

The following points should be considered as guidelines for site and profile description:

- This survey is targeting the identification of ASS, therefore appropriate occupational health and safety should be observed, including the use of personal protective equipment.
- Parameters to be measured, method of measurement and the categories to use are listed in Appendix 2 and Table 3–1. They are based on the 'Australian soil and land survey field handbook, 3rd edition' (National Committee on Soil and Terrain 2009).
- Photograph requirements at each site and the file name convention that is to be used is provided in Murray-Darling Basin Authority (2010; Appendix 2).
- At dry site locations (no surface water) soil pits are to be dug to approximately 0.6 m deep for obtaining good photographs and soil samples, and then with a gouge auger (or similar tool) obtain soil samples below the base of the pit down to 1 m or to auger refusal.
- Where soils are below water (i.e. subaqueous soils), soil samples are to be obtained by wading and using a shovel to grab the upper 20 cm, and then a gouge auger (or similar tool) to approximately 90 cm depth or to auger refusal.
- Where deep water occurs (either beyond wading depth or unsafe to walk on) a grab sample of the subaqueous soil surface (about 10–20 cm of soil) should be collected if possible, by using a boat to get to the site location.
- Irrespective of the sampling method to extract soil material, soils are to be routinely sampled in defined depth intervals of 0–5 cm, 5–10 cm, 10–20 cm, 20–40 cm, and 40–90 cm. However, where there exists within these sample depth ranges an obvious and visually distinct or textually distinct layer change, or an identifiable redox boundary, then the layer should not be mixed across the change but be sampled separately.
- Descriptive layer depth range and sampling depth range for each layer are to be the same so that the description matches the soil sample collected.
- Where water occurs, either as a surface water body, in surface cracks or as pore water collecting in the bottom of a pit, if there is sufficient water depth a measurement of the water quality using a calibrated electrode probe is to be made.

Key soil features in each wetland are identified on a Field Recording Checklist (Table 4-2). The field assessment should proceed by following Steps 1 to 5 set out below:

1. Obtain **Field Recording Checklist/Table** (see Table 4-2, which carries references to relevant appendices in this handbook) to record results noted in the field.
2. Commence **field inspections** at Site 1 along a typical transect at a point of concern and continue where you see changes occur.
2. Mark this and subsequent points on an aerial photo and on Field Recording Checklist/Table.
4. **Auger** to rigid clay layers. (A gouge auger is ideal for this, as it drives easily into clayey swamp soils and provides a visual, complete and intact soil profile.)
5. Record the **soil profile features** on the field recording checklist. (See below.)

How to record the soil profile features

On the field recording checklist (Table 4-2), record the surface features, including gilgai and cracks when soil is dry (Appendix 2). Record the depth (mm) of main soil layers from the soil surface to where there is a change in

- **soil consistence** (Appendix 2: Table A2-4)
- **soil colour** (Appendix 2: Table A2-3) — Grey, Black, Brown, Red, Yellow or Mottled greyish to bluish colours
- **structure** (Appendix 2: Figure A2-1) — slickensides, peds or massive
- **texture** (Appendix 1: Tables A2-1 and A2-2) — heavy clay; medium clay; light clay; sandy clay; sandy clay loam; loam or sand (the test of soil texture is critical and applicable to each layer)
- **amount of roots** (Appendix 2: Table A2-5).

Table 4-2. Field recording checklist/table

Date: **Site number:** **Distance from start of route:**

1. Surface features (see Appendix 2)

Hard Rock or Large Calcrete fragments

Hard rock/calcrete to restrict cultivation	NO	YES
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Gilgai (mounds or depressions on soil surface)

Zero or none (Z)	Low gilgai (L)	High gilgai (H)	

L = low gilgai (vertical interval of <300 mm)

H = high gilgai (vertical interval of >300 mm and commonly >800 mm)

Cracks when soil is dry

Zero or none (Z)	Fine	Medium	Coarse	Very coarse	Extremely coarse
Width (mm)	<5	5-10	10-20	20-50	>50

Soil Surface Condition

Salt crystals on soil surface	NO	YES
Trampled extensively under dry conditions by hoofed animals	NO	YES
Orange-brown precipitates on soil surfaces or drains	NO	YES
Soil dispersing and/or no vegetation present	NO	YES

Erosion

Zero or none (Z)	Rill (R)	Gully (G)	Notes:

Vegetation (classify according to headings below)

Zero or none (Z)	Salt tolerant grasses <i>Samphire?</i>	Healthy pasture	Healthy crop	Reeds <i>Phragmites?</i>	Notes:

2. Soil Profile features (see Appendix 2)

Site a1	Depth mm	Colour	Structure	Texture	Consistence	Profile sketch (optional)
a1.1	0-10 (surface)					
a1.2	10-100					
a1.3	100-500					
a1.4	500-1000					
a1.5	1000-1500					

Colour:

Grey (gr), Black (bl), Brown (br), Red (r), Yellow (y), Mottled greyish to bluish colours (mot).

Structure:

Slickensides (ss) Abundance		Peds = p	Massive = m
Few	<10% of the profile face	<10% of the profile face	m = no ss or p
Many	>10% of the profile face	>10% of the profile face	m = no ss or p

e.g. ss (2) = >10% slickensides present

Texture:

HC = heavy clay; MC = medium clay; LC = light clay; CL = sandy clay;
SCL = sandy clay loam; L = loam; S = sand.

Consistence classes:

Dry	Loose	Soft	Firm	Very hard	Rigid
Moist	Loose	Friable	Firm	Very firm)	Rigid

Root abundance:

Estimate approximately the number of <2 mm diameter roots in each layer in areas 100 mm square on a cleaned exposure face and classify per 100 mm x 100 mm area as:
abundant = >200, common = 10-200; few = <10 roots per 100 mm x 100 mm.

3. Supplementary Testing (see Appendix 3 and 4)

Collect in a labelled bag or plastic chip-tray approximately two cups of soil.

Measure pH, Electrical conductivity (EC; salinity 1:5 soil:water ratio), dispersion test (sodicity) on collected samples back in the house or shed or laboratory and record the data in Table 4-3.

Table 4-3. Soil pH, EC and dispersion tests

Site a1	Depth mm	pH	Salinity (EC)	Sodicity (dispersion test)
a1.1	1-10 (surface)			
a1.2	10-100			
a1.3	100-500			
a1.4	500-1000			
a1.5	1000-1500			

Repeat above approximately every 30 m along each transect.

Mark each subsequent point on the plastic overlay.

Start new Field Recording Sheet for each transect.

4.4 Sample Collection and Storage

Soil and water samples are required for laboratory analysis that will provide quantitative data on the sample characteristics. The samples are being collected for a range of analyses related to testing of a wide range of ASS materials, and therefore a number of samples from each layer are required. A list of parameters describing the types and number of samples to be collected from each layer is provided in Table 3–1.

4.4.1 Guidelines for Soil Sample Collection

The following points should be considered as guidelines for soil sample collection:

- This investigation is targeting the identification of ASS, therefore appropriate occupational health and safety should be observed, including the use of personal protective equipment.
- All samples shall be collected in such a way to avoid cross-contamination of the sample – requiring careful extraction of the sample, clean sampling tools and clean sample containers.
- Soil sample collection at each site is by layer identified covering the entire depth increment that corresponds with the described layer.
- Soil samples should be labelled according to the convention outlined in Figure 3–3 to ensure clear identification of the wetland, site and layer from which the sample was collected.
- Soil samples are placed in plastic chip-trays (Figure 3–2; Fitzpatrick et al. 2010), and in a plastic bag that is then sub-sampled into plastic jars. Multiple soil samples are required to be taken from each layer and are to include:
 - One bulk soil sample (typically about 500 g), is placed in a pre-labelled, thick, sealable plastic bag and mixed up. To be kept and used if Phase 2 laboratory analysis is required.
 - Two sub-samples from the bag are placed in two 70 ml screw-top plastic jars, with care taken to exclude air by filling the jars to the maximum level to limit sulfur oxidation during transit and storage.
 - One jar for acid base accounting parameters.
 - The second jar for pH_w , $\text{pH}_{\text{peroxide}}$, water extractable sulfate (surface soil sample only) and specific electrical conductance measurements. The remainder for drying at 80 °C to be kept and used if Phase 2 XRD (powder X-ray diffraction) and XRF (X-ray fluorescence spectrometry) analysis are required.
 - Two sub-samples from the layers are placed in two separate chip-trays.
 - One is used to display morphologically representative aggregates for each of the sampled layers (compartments filled to $\frac{3}{4}$ full with preferably undisturbed clods/samples) for later visual reference (e.g. during report writing and then placed in the CSIRO Land and Water soil archive).
 - The second chip-tray is used for the acid sulfate soil incubation test ($\text{pH}_{\text{incubation}}$) in the laboratory (compartments filled to $\frac{1}{3}$ full with disturbed crushed samples and moistened with distilled or deionised water).

- Each compartment is to be adjacently labelled (on the inside of the lid) with the layer sample ID, and on the outside of the chip-tray labelled with survey locations and collection date (see Figure A3-1).
- If monosulfidic material is present:
 - fill one 70 ml screw-top plastic jar and freeze immediately for Phase 1 AVS analysis.
 - collect an additional minimum volume of 500 ml into airtight jars to be kept frozen for Phase 2 analyses.
- Sub-samples for microbial DNA analyses will be collected following agreed protocols (APPENDIX 8).
- Occasionally, samples of salt efflorescences and coatings are observed in the field (e.g. Appendix 2) and they should be carefully collected into the chip-tray for mineralogical analysis.
- Visible shell and fragments greater than 2 mm should be removed from the sample.
- Air should be excluded as far as possible from all the jarred and bagged samples to minimise oxidation before laboratory analysis. Double bagging of samples is recommended.
- Jarred and bagged samples should be kept cold, at least below ambient temperature, in insulated containers (i.e. stored in a cool-box or Esky) when in the field and transferred to a fridge at 4 °C as soon as possible after sampling.
- All sample bags and containers are to be clearly marked with wetland, site and layer identification, sample depth and the date of sample collection. They should be marked with permanent marker (or stick-on labels) and preferably in two places. The markings should be waterproof and capable of withstanding oven drying at 85°C.

4.4.2 Guidelines for Sample Handling and Storage

The following points should be considered as guidelines for sample handling and storage:

- All sample bags and containers must be clearly marked with the wetland ID, site and layer identification, sample depth and date of sample collection. They must be marked with permanent marker (or stick-on bar code labels) and preferably in two places. The markings should be waterproof and capable of withstanding oven drying at 85°C.
- Soil and water samples to be placed into clean containers or plastic bags.
- Exclude as much air as possible from jarred and bagged samples.
- Samples transported to the laboratory should be kept cold in insulated containers (i.e. stored in a cool-box or Esky).
- All sample bags and containers will be clean on the outside to minimise contamination during transportation and on receipt at the laboratory.
- Transfer of samples to the laboratory should be conducted as quickly as practical, and before a maximum of 10 days has elapsed.
- A sample delivery list (chain of custody form) should be emailed to the laboratory and also provided in hardcopy with the sample shipment.
- The maximum time available between sample collection and laboratory analysis is considered the holding time. If the analysis is not conducted within this holding time

frame there is a risk that the results will not be a true reflection of the material when collected. Note that the length of holding time varies depending on the parameter to be analysed and the method of storage prior to analysis. The allowable holding time will be specified by the laboratory and these timeframes should be followed.

4.5 Laboratory Analysis (Phase 1)

Laboratory analysis for Phase 1 provides quantitative data that can be used to assess the type of ASS material present (sulfuric, hypersulfidic, hyposulfidic, monosulfidic or other as defined in Appendix 4) and the acid base accounting measurements to determine net acidity level.

4.5.1 Soil

Three sets of laboratory analysis have been identified to be conducted on soil samples collected for Phase 1 laboratory testing (Table 3–2). These measures and the objective for conducting them are listed here:

- Soil pH_w , $pH_{incubation}$, and $pH_{peroxide}$. These measures are used to determine the current status of the soil acidity (pH_w), the type of acid sulfate soil material present as defined in Section 1.4 that are based on the soil pH_w value (to identify sulfuric materials) or change in pH on ageing ($pH_{incubation}$ to identify hypersulfidic or hyposulfidic materials). $pH_{peroxide}$ identifies a potential end pH after oxidation and if it declines to 2.5 or less then it can be assumed that soil acidity problems will emerge when the soil or sediment is exposed to air. Based on assessment of the pH data on the approximately 400 samples collected, samples will be selected for acid-base accounting as detailed below (*note: as per proposal an estimated 100 samples will be selected for this*). Measuring soil pH_w is a standard test. Measuring $pH_{incubation}$ is the standard method used in the Australian Soil Classification (Isbell 1996). The method using chip trays has been provided in Appendix 4. Measuring $pH_{peroxide}$ is a standard test (see Appendix 4).
- Electrical conductivity (EC) analysis via the method of Rayment and Higginson (1992).
- Texture via hand texture test

4.5.2 Water quality

Water pH, temperature, specific electrical conductivity (SEC), dissolved oxygen (DO), and turbidity will be determined in the field using calibrated electrodes linked to a YSI Pro DSS Multiparameter System. Alkalinity of surface water will also be determined in the field by acid titration using a HACH kit.

If low pH (<6.5) conditions are observed additional samples will be collected for metal and acidity analysis.

4.6 Identification of Acid Sulfate Soil Materials

Classifying soil materials and soil profiles provides a means to communicate and integrate data that describes the key features of the soil.

Field and laboratory data results are to be used to allocate soil samples to an acid sulfate soil material class according to the criteria specified in Appendix 4.

Each sampled soil profile may have one or more classified acid sulfate soil materials that occur at different depths down the profile. To provide an overall description for the sampled soil profile, an assessment of these classified soil layers is made by using the Australian Acid Sulfate Soil Identification Key presented in Appendix 5.

Step 1

From information recorded on the Field Recording sheets (Tables 4-2 and 4-3), allocate to each layer (a1.1, a1.2, etc.) the 'Key soil/water features and acid sulfate materials' (Table 4-4), using the question and answer format shown in Table 4-5 to the following 7 points relating to occurrences or interpretations of

1. surface water levels — for example, subaqueous, hydrosol, unsaturated soils
2. soil colour mottling
3. slickensides (smooth/polished surfaces on soil)
4. texture
5. pH value
6. saline, sodic or salt efflorescences present and specify type — for example, Gyp (= Gypsum)
7. 'Types of acid sulfate soil materials' (see Appendix 4).

Table 4-4. Key soil/water features and acid sulfate materials of layers

Soil/water features and materials	Code	Definitions
Subaqueous condition/soils	W	Surface water levels, 2.5 m below the surface water level
Hydric condition/soils	Hyd	Surface water levels, 0.50 m above the surface water level
Unsaturated condition/soils	Uns	Drained soils with water level below 0.50 m
Salt efflorescences	Ef	Fluffy salt accumulations (e.g. gypsum and halite)
Gypsum/Halite crusts	Gyp	See Glossary (Appendix 9)
Calcareous materials	Ct	See Glossary (Appendix 9)
Shells	Sh	Hard, protective outer layer created by an animal that lives in the sea or inland environments
Organic rich material/soil	Or	See Glossary (Appendix 9)
Clays	Cy	See Table A2-2
Sands	Sa	See Table A2-2
Loams	Lo	See Table A2-2
Sulfuric material/soil	Su	See Appendix 4
Hypersulfidic material/soil	He	See Appendix 4
Hyposulfidic material/soil	Ho	See Appendix 4
Monosulfidic wet	Mow	See Appendix 4, Table A4-1 with n-Value greater than 1
Monosulfidic material dry	Mod	See Appendix 4, with n-Value with n-Value between 1 and 0.7
Reddish Fe-rich precipitates/gels	Rp	Reddish-yellow Fe-rich precipitates/gels (schwertmannite-rich)
Saline soils	Sal	See Appendix 3, Table A3-1
Sodic soils	Sod	See Appendix 3, Table A3-1

Table 4-5. Key soil features and acid sulfate materials for each soil layer

Site a1	Depth mm	Surface Water levels W/Hyd? or drained Uns?	¹ Do mottled greyish to bluish colours occur?	² Do slicken- sides occur?	What is the soil texture?	³ pH	⁴ Saline or sodic? Or Ef?		Acid sulfate soil materials (Appendix 3 and key Soil/water Features)
a1.1	0-10	Uns	NO	NO	Loamy	>4	Gyp		Non, Lo
a1.2	10-100	Hyd	NO	NO	Loamy	<4	saline		Su, Cy
a1.3	100- 500	Hyd	NO	YES	Clayey	<4	saline		Su, Cy
a1.4	500- 1000	Hyd	YES	YES	Clayey	>4	saline		He, Cy
a1.5	1000- 1500	Hyd	YES	YES	Clayey	>4	saline		He, Cy

¹ Is surface water 2.5 m below the surface water level?	¹ Do mottled greyish to bluish colours occur in the soil profile?	² Do slickensides occur?	³ Measure pH	⁴ Measure electrical conductivity
If yes, then soil is subaqueous	If yes, then soil is wet	If yes, then soil is a cracking clay	If EC is <4.0, then soil is sulfuric	If EC is >0.7 dS/m, then soil is saline

Step 2

The information recorded in Table 4-5 for the ‘Key soil features and acid sulfate materials of **layers**’ is used to classify the **soil subtype for each soil profile** (or sampling site — for example, a1) in accordance with the following procedure, as applied to the ‘Soil identification key’ (see Tables A4-1 and A4-2 in Appendix 4). This is based on the presence of the dominant acid sulfate soil material present, with the highest hazard ASS material keying out first, as follows:

1. Sulfuric material keys out first.
2. Hypersulfidic material keys out second.
3. Hyposulfidic material keys out third.
4. Monosulfidic material keys out forth.
5. Last, all **other soils** (non-acid sulfate soil subtypes — for example, Unsaturated or Hydric soils).

As explained in Appendix 4 the classification of ASS materials (i.e. sulfuric, hypersulfidic, hyposulfidic or monosulfidic) is based mainly on the initial pH (pH at time zero) and after incubation for at least 16 weeks.

A soil profile that classifies as a ‘**sulfuric soil**’ requires sulfuric material (i.e. pH <4 at time zero incubation) to be identified in a layer or horizon, which is at least 10 cm thick within 150 cm of the soil surface (Appendix 5).

A soil profile that classifies as a ‘**hypersulfidic soil**’ requires hypersulfidic material (i.e. decrease in pH to pH 4 or less after incubation for at least 16 weeks) to be identified in a layer or horizon, which is at least 10 cm thick within 150 cm of the soil surface (Appendix 5).

Finally, a soil profile that classifies as a ‘**hyposulfidic soil**’ requires hyposulfidic material (i.e. decrease in pH to >pH 4 after incubation for at least 16 weeks) to be

identified in a layer or horizon, which is at least 10 cm thick within 150 cm of the soil surface (Appendix 5).

Step 3

Finally, additional key information recorded in Table 4-6 for the key soil features and acid sulfate materials of layers is also used to highlight presence of other dominant soil features present, with the highest hazard soil feature keying out first, as follows:

- clays, loams and sands
- salt efflorescences
- gypsum/Halite crusts
- saline
- sodic.

Table 4-6. Acid sulfate soil subtypes/other soils with additional key soil features for each soil profile

Profile No	Profile classification (Appendix 5: Table A5-2)
A-A': a1	Sulfuric subaqueous clay soil with reddish Fe-rich precipitates
A-A': a2	Sulfuric cracking clay soil with hydric and salt efflorescences
A-A': a3	Sulfuric cracking clay soil with hydric and salt efflorescences
A-A': a3	Sulfuric cracking clay soil with hydric, salt efflorescences and calcareous segregations
B-B': b1	Waterlogged soil with hydric and gypsum crusts
B-B': b2	Other soils (Unsaturated red sandy sodic soils)

Confidence level of soil classification

In some specific areas, it may not be possible to fully classify soils because of lack of access to properties (for example, areas with a low ability to support a load or with low bearing capacity, i.e. areas that have an n-Value (Table A3-1 in Appendix 3) that is >1, no road or track access). For this reason, the following levels of confidence are used to classify soil landscapes:

1. *high confidence* — when a high quantity of detailed soil profile observations are made of areas or map units via soil pit, auger or road cutting investigations
2. *moderate confidence* — when only reconnaissance observations are made of areas or map units through few detailed soil profile observations via pits, auger or road cutting investigations — but mostly via visual observations made either by walking across landscapes (for example, selected transects) or by looking through the windows of a moving vehicle with satisfactory road access and road cuttings
3. *fair to provisional confidence* — when soil landscape classification is based on a knowledge of *similar* soils in similar environments (for example, knowledge extrapolation based on soil or geological maps documented during the office assessment), especially where no road or property access was available during field investigations.

4.7 Determining Priorities for Phase 2 Laboratory Analysis and Assessment

Phase 2 detailed laboratory analyses will be conducted on a subset of samples collected from the Phase 1 investigations. Selection of samples will generally depend on identifying those wetlands where the Phase 1 results are of concern so that an improved understanding of their characteristics can be determined to assist with making planning and management decisions. To assist with making the selection, a set of criteria have been established to rank the soil materials.

The Scientific Reference Panel of the Murray–Darling Basin Acid Sulfate Soil Risk Assessment Project agreed to recommend that soil materials be assigned based on the set of criteria for the following priorities for Phase 2 detailed assessment:

High Priority

- 1) All sulfuric materials.
- 2) All hypersulfidic materials, as recognised by either
 - a. incubation of sulfidic materials or $\text{pH}_{\text{peroxide}} < 2.5$ (high priority) or < 4.0 (moderate priority)
 - b. a positive net acidity result (with a Fineness Factor of 1.5 being used).
- 3) All hyposulfidic materials with SCR contents $\geq 0.10\% \text{S}$.
- 4) All wetlands with surface waters with $\text{pH} < 6.5$
- 5) Observations and/or measurements indicating presence of monosulfidic materials.

Moderate Priority

- 1) All hyposulfidic materials with SCR contents $< 0.10\% \text{S}$.

No further assessment

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

Priority samples exceeding thresholds for Phase 2 analysis will likely occur throughout the depth of the soil profile. Samples that are recommended to undergo Phase 2 laboratory analysis will firstly be those that occur on the surface layer, as this is the soil most likely to have initial contact with water. Recommendations for other samples (not necessarily all samples) within the soil profile for Phase 2 analysis should also be made and justified to assist the client in authorisation for Phase 2 analysis to be conducted. Examples of justification could include deep cracks exposing the deeper soil layers to oxidation and then water, representative of a large proportion of the study area, or provide continuity to understand behaviour of a key soil profile.

Following Phase 1 analyses, a table listing all samples analysed for the study area, their priority for Phase 2 analysis based on the above criteria, selection and justification for Phase 2 analysis will be provided to the client. For budgeting purposes up to 100 samples have been allowed for to undergo more detailed analysis.

4.8 Phase 1 - Interpretation and Reporting

Phase 1 of the detailed assessment will not report on the risks associated with acid sulfate soil materials, and will only determine the presence, extent, nature (chemistry) and frequency of observed hazards (e.g. 'Hypersulfidic materials were observed in 32 of 38 (84%) sites').

The report requirements for Phase 1 should include the following report sections and information where relevant as listed in Table 4-7.

Table 4-7. Phase 1 report structure and information requirements

Report section	Information to be included
Executive Summary	<ul style="list-style-type: none">• Project background and purpose of study• Objectives of the study• Summary of field and laboratory results, including presence/absence and type of acid sulfate soils, their extent and assessment of hazard• Summary of conclusions and recommendations
Introduction	<ul style="list-style-type: none">• Project background and purpose of study• Objectives of the study• Background information and summary of previous work• Wetland overview including general description of study area: location, topography, shape, hydrology, soil, vegetation, infrastructure, surroundings• Definitions of acid sulfate soil materials
Field and Laboratory Methods	<ul style="list-style-type: none">• Field sampling of soils and water (referencing this protocol document and describing any variations)• Rationale for site location selection and density of sites• Rationale for number of samples selected and distribution• Description of the equipment and the method used to obtain samples• Laboratory soil analysis methods (referencing this protocol document and describing any variations)• Laboratory water analysis methods (referencing this protocol document and describing any variations)
Quality Assurance and Quality Control (QA/QC)	<ul style="list-style-type: none">• Field QA/QC report• Laboratory QA/QC report• Evaluation of all QA/QC information
Results and Discussion	<ul style="list-style-type: none">• Study area location and setting description• Map showing sample site locations (preferably image map with grid)• Summary and assessment of soil field and laboratory results including:<ul style="list-style-type: none">- Soil pH- CRS

Report section	Information to be included
	<ul style="list-style-type: none"> o ANC o Net Acidity • Soil field and laboratory data presented in tables and as summary graphs for pH (pH_w, pH_{incubation}, pH_{peroxide}) and Net Acidity • Summary and assessment of water field and laboratory results • Soil identification according to Soil Identification Key (Appendix 3) • Interpretation and discussion on distribution, extent and proportion of acid sulfate soil materials in the study area (including cross-sections like that presented in Figure 3–1, and maps where appropriate)
Hazard Assessment	<ul style="list-style-type: none"> • Basis for hazard assessment • Criteria used in the hazard assessment (from Section 3.6) • Assessment of soil and water data • Discussion of assessment and impact • Discussion of assumptions
Selection of Phase 2 Samples	<ul style="list-style-type: none"> • Basis for selection • Recommendations and justification for selection/non-selection of samples for Phase 2 analysis (tabled)
Conclusions and Recommendations	<ul style="list-style-type: none"> • Summary of key findings and outcomes • Assumptions used and uncertainties • Recommendations for Phase 2 analysis • Recommendations for monitoring and further work
References	<ul style="list-style-type: none"> • List of all references included throughout the report
Appendices	<ul style="list-style-type: none"> • Site and sample descriptions • Field and laboratory soil analytical data • Field and laboratory water analytical data • Classification of soil materials according to the Soil Identification Key (Appendix 3)
Database	<ul style="list-style-type: none"> • Electronic database, in Microsoft Excel ® format, of all field and laboratory data including quality control and quality assurance measurements using the supplied standard data collection template
Photographic library	<ul style="list-style-type: none"> • Digital, in JPEG format, of all field site and soil photographs, labelled according to the guidelines in Appendix 2.

5 Phase 2 - Laboratory Analysis and Assessment

Phase 2 investigations will only be conducted if the acid sulfate soil materials from Phase 1 are determined to be a priority concern for the study area and, based on Phase 1 recommendations, samples will undergo further investigations to determine their nature and severity and the specific risks associated with the acid sulfate soil materials.

Phase 2 activities include:

- Further laboratory analysis (of soil)
- Risk assessment
- Interpretation and reporting, including discussion on broad acid sulfate soil management options.

The soil samples to be analysed for Phase 2 will have been collected as part of the Phase 1 field assessment and then put into storage. Based on the Phase 1 report recommendations the client will identify samples and the analyses to be conducted on each of the samples for Phase 2.

5.1 Laboratory Analysis

The list of potential Phase 2 analyses is presented in Table 3-1 and Appendix 6. These tests are only conducted on samples that meet the Phase 2 priority criteria as defined in Section 4.7.

Samples that meet the criteria are then screened further as follows:

- Chromium reducible sulfur, titratable actual acidity, retained acidity, pH_{KCl} and acid neutralising capacity analyses are used in acid base accounting. These measures are 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. The standard acid based accounting applicable to acid sulfate soils is described in Ahern *et al.* (2004) and summarised in Appendix 6. (*prioritised for at least 100 samples*)
- Analysis for Acid Volatile Sulfide when monosulfidic soil materials are visibly present via the method of Hsieh *et al.* (2002) using a modified apparatus (Burton *et al.* 2006). (*prioritised for at least 100 samples*)
- Total carbon and nitrogen analyses will be conducted on selected samples to help provide information on wetland productivity and factors influencing microbial processes including pyrite formation. (*prioritised for at least 100 samples*)
- X-ray diffraction analysis tests will be conducted on a very limited number of samples (*at least 14*) to determine the nature of the mineral or crystals identified in the sample. Usually these samples are associated with sulfuric layers to determine the presence and type of acid mineral presence.
- Rapid metal release and contaminant and metalloid dynamics tests will be conducted on selected samples (*at least 28*) that meet the criteria

5.2 Hazard and risk ratings for acidity, deoxygenation and odour

5.2.1 Hazard evaluation

This section comprises investigations and interpretations that are primarily focussed on determining the relative hazards associated with the presence of ASS materials and more importantly with the various ASS subtypes.

Acid sulfate soil materials when disturbed can lead to the following hazards:

- a. Acidification;
- b. Deoxygenation/malodours (i.e. presence of monosulfidic material)
- c. Contaminant mobilisation.

It is acknowledged that there are other hazards associated with acid sulfate soil materials such as the production of odours, noxious gases and dust. These hazards may be identified and acknowledged in reports dealing with the detailed assessment of acid sulfate soil materials.

The field and laboratory analyses carried out using current standard Acid Sulfate Soil protocols for sampling, field characterisation, laboratory analysis and data presentation help determine whether ASS materials present a potential hazard to wetlands and whether further investigation is required to elucidate risk. Information emanating from the data and interpretations will therefore:

- a. Report on the presence, nature and extent of observed ASS materials.
- b. Advise on potential **hazards** posed by ASS soil materials where possible.
- c. Make recommendations on the requirement for further analyses including the number of samples to be analysed.

5.2.2 Defining and Assessing Risk

Risk is a measure of both the consequences of a hazard occurring, and the likelihood of its occurrence (Murray–Darling Basin Authority 2010). The Likelihood will be related to the ongoing and future management of pool levels and drying / wetting events experienced by the wetland, in addition to the potential for physical disturbance. Consequence is the impact of the acid sulfate soil materials being expressed, and primarily takes into account environmental and water quality impacts. Level of consequence will be determined in consultation with environmental managers for each identified hazard in a specific wetland using a standardised Table 5-1.

Table 5-1. Standardised table used to determine the consequence of a hazard occurring.

Descriptor	Definition
Extreme	Irreversible damage to wetland values and/or adjacent waters; localised species extinction; permanent loss of water supplies
Major	Long-term damage to wetland values and/or adjacent waters; significant impacts on listed species; significant impacts on water supplies
Moderate	Short-term damage to wetland values and/or adjacent waters; short-term impacts on species
Minor	Localised short-term damage to wetland values and/or adjacent waters; temporary loss of water supplies
Insignificant	Negligible impact on wetland values and/or adjacent waters; no detectable impacts on species

Likelihood is the probability of disturbance of the acid sulfate soil material and requires understanding of both the nature and severity of the acid sulfate soil materials (e.g. extent, net acid generating potential, etc) as well as contributing factors influencing the risk (e.g. disturbance of acid sulfate soil materials, wetland management regime).

Level of likelihood will be determined separately for each hazard type. This is due to the variability of contributing factors for each hazard. Likelihood should be determined by assessing the probability of disturbance of the acid sulfate soil materials (Table 5-2). Examples of disturbance include:

- re-wetting of acid sulfate soil materials after they have oxidised;
- acid sulfate soil materials that are currently inundated and that may be oxidised; or
- acid sulfate soil materials that are currently inundated and that may be dispersed by flushing (e.g. scouring flows).

Table 5-2. Likelihood ratings for the disturbance scenario.

Descriptor	Definition
Almost certain	Disturbance is expected to occur in most circumstances
Likely	Disturbance will probably occur in most circumstances
Possible	Disturbance might occur at some time
Unlikely	Disturbance could occur at some time
Rare	Disturbance may occur only in exceptional circumstances

Risks are ranked using a standardised risk assessment matrix in Table 5-3 which is the product of the estimates of the likelihood of disturbance of the acid sulfate soil materials and the consequences to wetland values and/or adjacent waters (Tables 5-1 and 5-2). This must also take into account the scientific assessment of the nature and extent of the acid sulfate soil materials present at the site as confirmed through the field and laboratory analyses through detailed ASS analyses.

According to Murray–Darling Basin Authority 2010, acid sulfate soil scientists conducting detailed assessments cannot reasonably determine the level of consequence or likelihood at a given wetland without understanding the historic and ongoing water management regime. Input from relevant wetland managers will therefore be critical. As such, assessment of risk must be made in consultation with

the wetland environmental managers. This is to ensure that acid sulfate soil scientists have an understanding of the wetland values and context of wetland management for the site.

Table 5-3. Risk assessment matrix (Standards Australia/Standards New Zealand, 2004).

Likelihood category	Consequences category				
	Extreme	Major	Moderate	Minor	Insignificant
Almost Certain	Very High	Very High	High	High	Medium
Likely	Very High	High	High	Medium	Medium
Possible	High	High	High	Medium	Low
Unlikely	High	Medium	Medium	Low	Low
Rare	High	Medium	Medium	Low	Low

Legend: It is suggested that, sites with

- Very High: Very High Risk - immediate action recommended;
- High: High Risk - senior management attention needed;
- Medium: Moderate Risk - management action may be recommended.
Agency responsible must be specified;
- Low: Low Risk - manage by routine procedures (should be monitored regularly to determine whether the hazard is increasing).

5.2.3 Reporting on Risk

Reports of assessments will establish the level of risk associated with each identified hazard at a wetland using the framework outlined here and in consultation with relevant wetland managers. In order to assist wetland managers in decision-making, the level of risk outlined in final reports should be accompanied by an explanation of the major contributing factors to the risk level (e.g. water management regimes, water chemistry, wetland values etc).

Acidification hazard categories

The wetland acidification hazard ratings can be subdivided into the following three acidification categories:

- High acidification rating (red colour) indicates that sulfuric (dominant) or hypersulfidic soil materials were present near the soil surface.
- Medium acidification rating (amber colour) indicates that hypersulfidic or hyposulfidic soil materials were present, usually in the subsoil and in about 50% of the polygon.
- Low rating (green colour) indicates that hyposulfidic materials (dominant) were present near the soil surface.

Red is associated with the highest soil hazard rating class, **amber** with moderate soil hazard rating class, and **green** with the lowest soil hazard rating class.

'The Red-Amber-Green system, also known as the 'RAG' or 'traffic light' system is a convenient method to facilitate easy visualisation in a manner that will be easily interpreted and identified on soil maps and in reports.

Wetland sections with high (i.e. red) acidification rating should be monitored regularly, and have management plans in place to activate if triggers are reached, as they are

more likely to increase in acidification hazard. Wetlands with lower ratings are less likely to be of concern and would require less monitoring.

Soil deoxygenation/malodour hazard categories

The wetland deoxygenation/malodour hazard ratings can be subdivided into the following three deoxygenation/malodour categories:

- High rating (red colour) indicates that high amounts of monosulfidic materials (wet) were present at or near the surface (i.e. is exposed and not covered by a crust or topsoil)
- Medium rating (amber colour) indicates that monosulfidic materials (wet) were present.
- Low rating (green colour) indicates that no monosulfidic materials (wet) materials (dominant) were present near the surface.

Sodicity hazard

Sodic soils are characterized by low permeability and thus restricted water flow because the clay and organic fractions of these soils are dispersed.

All the ASS soils described classify as “moderately saline soils” (Table 5-4) and comprise “flocculated clays” (i.e. fluffy or loosely aggregated clay particles). Consequently, these saline topsoils and surface layers with salt efflorescences are prone to wind erosion. However, if these saline soils with relatively freely draining topsoils are not treated with “calcium-based soil amendments” they will likely transform to “sodic soils” over time due to leaching with rain water (i.e. low levels of salinity). This will occur because of the leaching of the high levels of soluble salts and the formation of sodic soils with resultant low levels of total salt and high levels of exchangeable sodium (Na).

Sodic soils develop very poor structure and drainage over time because sodium ions on clay particles cause the soil particles to deflocculate, or disperse. Sodic soils are hard and cloddy when dry and tend to crust. Water intake is usually poor with sodic soils, especially those high in silt and clay. Poor plant growth and germination are also common. Applying especially gypsum (highly soluble salt) and lime to clayey sodic soils with poor drainage will likely be most beneficial.

Table 5-4. Salinity hazard as defined by the electrical conductance of a saturation extract (EC_{se}) and 1:5 soil:water extract (i.e. soil is extracted with distilled water)¹.

Salinity hazard	EC _{se} dS/m	Effects on plant yield	1:5 Soil/Water Extract (dS/m)				
			Loamy sand	Loam	Sandy clay loam	Light clay	Heavy clay
Non-saline	<2	Negligible effect	<0.15	<0.17	<0.25	<0.30	<0.4
Slightly saline	2-4	Very sensitive plants affected	0.16-0.30	0.18-0.35	0.26-0.45	0.31-0.60	0.41-0.80
Moderately saline	4-8	Many plants affected	0.31-0.60	0.36-0.75	0.46-0.90	0.61-1.15	0.81-1.60
Very saline	8-16	Salt tolerant plants unaffected	0.61-1.20	0.76-1.45	0.91-1.75	1.16-2.30	1.60-3.20
Highly saline	>16	Salt tolerant plants affected	>1.20	>1.45	>1.75	>2.30	>3.20

¹EC 1:5 - the electrical conductance of a 1:5 soil:water extract (i.e. soil is extracted with distilled water), normally expressed in units of Siemens (S) or deciSiemens (dS) per meter at 25°C. While the EC1:5 method is quick and simple it does not take into account the effects of soil texture. It is therefore inappropriate to compare the EC1:5 readings from two soil types with different textures. It is possible to approximately relate the conductivity of a 1:5 soil-water extract (EC1:5) to that of the saturation extract (EC_{se}) and predict likely effects on plant growth. The above criteria are used for assessing soil salinity hazard and yield reductions for plants of varying salt tolerance, EC_{se} is saturated paste electrical conductivity (after Richards, 1954) and EC1:5 is the corresponding calculated electrical conductivity of a 1:5 soil:water extract for various soil textures.

5.3 Phase 2 - Interpretation and Reporting

Subject to the recommendation for Phase 2 investigations and the conducting of this work, the Phase 2 report will be appended to the Phase 1 report as Part 2. After internal and client review the entire report (Milestone 5) will be prepared as the Final Report for the study area and RRP Wetland Handbook (Milestone 6).

The report requirements for Phase 2 (this will be appended to the Phase 1 report as Part 2) should include the following report sections and provide the following information where relevant as listed in Table 5-5.

Table 5-5. Phase 2 report structure and information requirements

Report section	Information to be included
Executive Summary	<ul style="list-style-type: none"> • Objectives of the Phase 2 investigations • Summary of laboratory results • Summary of risk assessment, including specific risks associated with acidification, metal mobilisation, and de-oxygenation • Summary of conclusions and recommendations
Introduction	<ul style="list-style-type: none"> • Provide linkage and history with Phase 1 work • Samples to be analysed • Rationale for the samples selected for Phase 2 analysis
Laboratory Methods	<ul style="list-style-type: none"> • Laboratory soil analysis methods (referencing this protocol document and describe any variations)
Quality Assurance and Quality Control (QA/QC)	<ul style="list-style-type: none"> • Laboratory QA/QC report • Evaluation of all QA/QC information
Results and Discussion	<ul style="list-style-type: none"> • Summary and assessment of soil laboratory results • Summary soil field and laboratory data presented in tables • Interpretation and discussion of results and relating to soil materials and distribution in the study area
Risk Assessment	<ul style="list-style-type: none"> • Basis for risk assessment including framework and criteria used • Assessment of risks associated with each identified hazard (acidification, contaminant mobilisation, and de-oxygenation) • Level of risk and explanation of the major contributing factors • Discussion of assumptions
Broad Acid Sulfate Soil Management Options	<ul style="list-style-type: none"> • Identify areas of concern relating to the specific risks • Describe broad management options and their advantages and disadvantages • Discuss assumptions, limitations, and further information required
Conclusions and Recommendations	<ul style="list-style-type: none"> • Summary of key findings and outcomes • Assumptions used and uncertainties • Recommendations for monitoring and further work • Recommendations for management
Appendix	<ul style="list-style-type: none"> • Tables of laboratory soil analytical data
Database	<ul style="list-style-type: none"> • Electronic database, in Microsoft Excel ® format, of all laboratory data including quality control and quality assurance measurements using the supplied standard data collection template.

6 Detailed field sampling schedule

A provisional sampling schedule for detailed field and laboratory acid sulfate soil assessment is shown in Table 6-1. This will be revised as required.

Table 6-1. Provisional sampling schedule for detailed field and laboratory acid sulfate soil assessment

Wetland Site	Silverlea (Swan Reach Ferry)	Return to Adelaide	Murtho - Weila	Lake Merreti	Lake Woolpoolool	Return to Adelaide	Sugar Shack Complex (Swan Reach Complex)	Return to Adelaide	Woolenook Bend Complex	Pyap Horseshoe North Section	Return to Adelaide	Spectacle Lakes, Beldora North and South	Return to Adelaide
Area (Ha)*	68.00	Sample processing	40.50	381.30	295.20	Sample processing	29.80	Sample processing	57.40	172.60	Sample processing	287.80	Sample processing
No. of Transects Proposed (5 sites per transect)	2		4	2	2		6		2	2		6	
No of GS sites Proposed	3		3	1	1		3		4	5		3	
No. of sites to be Sampled	13		26	13	13		33		16	15		33	
No. of samples collected for Phase 1 (4 samples per site)	40		90	40	40		120		50	50		120	
Field Work Proposed Start date	Mon 21/05/18	Tues 22/05/2018	Sun 27/05/18	Wed 30/05/18	Thu 31/05/18	Fri/1/06/18	Tues 5/06/18	Fri 8/06/18	Sun 24/06/18	Wed 27/06/18	Fri 29/06/18	Tues 3/07/18	Fri 6/07/18
Indicative Completion date	Tues 22/05/2018		Wed 30/05/18	Thu 31/05/18	Fri 1/06/18		Fri 8/06/18		Wed 27/06/18	Fri 29/06/18		Fri 6/07/18	

* "Wetland area" designates the area (Ha) of the main waterbodies located within the wetland complex and does not include the flood plain area as a whole. Therefore, the number of soil sampling sites nominated to characterise a wetland complex is not necessarily proportional to the "Wetland area" listed above.

7 Work Health and Safety (WHS)

The University of Adelaide has risk management policies for field trips that involves staff, students and visitors. A field work form including a risk assessment is undertaken prior to the trip.

The field work form is sent to ees.fieldsafety@adelaide.edu.au by the traveller at least 2 working days prior to departure and must include a CC: to the trip supervisor. All staff or students with a fieldwork component should have a current senior first aid certificate. The trip supervisor assumes the WHS responsibility for the trip. For the purposes of this protocol, the trip supervisor is the staff member embarking on the trip. All participants of the field activity must be informed of the identified hazards and control measures prior to the commencement of the activity. The effectiveness of the control measures must be reviewed after the field activity and improved where considered necessary prior to a repeat of that activity.

Field Activity Risk is determined by the level of experience and nature of the work, general categories of risk are:

- *Low - field days, talks, population counts, standard\routine measurements, field mapping\survey work etc.*
- *Medium - student daytrips, heavy machinery, spraying, animal handling, heavy lifting, tree climbing, large group size, etc.*
- *High - radioactive source readings, inexperience, snake handling, etc.*

No staff members may work alone in activities involving boating. Additional induction and training procedures are required for boating activities.

The University of Adelaide has dedicated WHS officers who oversee the risk management approach, including in the laboratories that will be used for the sample analyses. All laboratory staff undergo inductions for chemical and laboratory safety.

8 Contingency Plan

A contingency plan has been formulated for the project based on identified project risks (Table 8-1).

Table 8-1. Contingency Plan

Risk to project	Risk level	Contingency Plan
Team member becomes sick or leaves employment	Low	Back-up team members are trained and inducted to assist or manage field work. If required the works will be postponed until field staff are fit for service
High flow prevents sampling	Low	<p>Aim to complete sampling before typical winter-spring higher flow period</p> <p>Sampling in wetlands should still be possible (e.g. use longer auger extension) unless high flows pose safety concerns. A combination of sampling techniques are able to be employed, which allow for sampling in water of depths in excess of 4 m</p> <p>If not possible, discuss with DEW and wait for flows to recede</p>
Construction activity prevents sampling	Low	<p>Obtain construction schedule</p> <p>Plan sampling transects away from area of direct construction (e.g. regulator inlets)</p> <p>Sampling is mainly undertaken on the water so should not be disrupted.</p>
Field data integrity and back-ups compromised	Low	<p>All field notes will be written in waterproof note books. A photo log will be maintained of pages in the field notes, using a waterproof camera / phone. All photos will be uploaded to the Cloud (Adelaide University "Box" file server) daily.</p> <p>Field recorded data will be input to Excel spreadsheets nightly, saved and backed up to (Adelaide University "Box" file server).</p> <p>Field data will be reviewed by Adelaide based staff for integrity and completeness. Field methods and sampling location characteristics, monitoring results and progress (and WHS issues) will be communicated with Adelaide based staff / project leaders for progressive feedback and communication with DEW staff</p> <p>The Sampling and Analytical Plan (this Methods document) will remain an open document to allow adaptation through all stages of the project</p> <p>If required, re-sampling of sites will be undertaken</p>

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References

- Ahern CR, McEnea AE, Sullivan LA (2004). Acid sulfate soils laboratory methods guidelines. In 'Queensland Acid Sulfate Soils Manual 2004'. Department of Natural Resources, Mines and Energy, Indooroopilly, Queensland, Australia.
- ANZECC and ARMCANZ (2000). Australian and New Zealand guidelines for fresh and marine water quality: Volume 1 - The guidelines. <http://www.environment.gov.au/water/publications/quality/nwqms-guidelines-4-vol1.html>
- Burton ED, Bush RT, Sullivan LA (2006). Acid-volatile sulfide oxidation in coastal flood plain drains: Iron-sulfur cycling and effects on water quality. *Environmental Science and Technology* 40: 1217-1222.
- Dent, D. (1986). Acid sulfate soils: A baseline for research and development. ILRI Publication No. 39, pp. 31-32. Wageningen, The Netherlands, International Institute for Land Reclamation and Improvement.
- Dear SE, Moore NG, Dobos SK, Watling KM, Ahern CR (2002). Soil management guidelines. In 'Queensland Acid Sulfate Soil Technical Manual.' Department of Natural Resources and Mines, Indooroopilly, Queensland, Australia.
- Donnelly, LJ and Harrison, M. (2013). Geomorphological and geoforensic interpretation of maps, aerial imagery, conditions of diggability and the colour-coded RAG prioritization system in searches for criminal burials. *Geological Society, London, Special Publications*, 384:173-194 doi:10.1144/SP384.10.
- Fanning, Delvin, Rabenhorst, Martin and Fitzpatrick Robert (2017) Historical developments in the understanding of acid sulfate soils. *Geoderma*. 308, 191-206. <http://dx.doi.org/10.1016/j.geoderma.2017.07.006>
- Fitzpatrick R.W. (2013). Demands on Soil Classification and Soil Survey Strategies: Special-purpose soil classification systems for local practical use. In: S.A Shahid, F.K. Taha and M.A. Abdelfattah (eds.), *Developments in Soil Classification, Land Use Planning and Policy Implications: Innovative Thinking of Soil Inventory for Land Use Planning and Management of Land Resources*, Springer Science+Business Media Dordrecht. pp. 51-83. DOI 10.1007/978-94-007-5332-7_2
- Fitzpatrick, R.W, Baker, A.K.M, Shand, P., Merry, R.H, Grealish, G and Mosley, L.M (2012). A modern soil-landscape characterization approach to reconstructing and predicting pedogenic pathways of inland Acid Sulfate Soils. In: P. Osterholm, M Yli-Halla and P. Eden (Editors). *Proceedings of 7th International Acid Sulfate Soil Conference*, 26-30 August 2012, Vaasa, Finland. Geological Survey of Finland, Guide 56. pp 47-50. http://arkisto.gtk.fi/op/op56/op_056.pdf [8MB]
- Fitzpatrick, RW, Grealish, G, Chappell, A Marvanek, S. and Shand P (2010). Spatial variability of subaqueous and terrestrial Acid Sulfate Soils and their properties, for the Lower Lakes, South Australia. CSIRO Sustainable Agriculture National Research Flagship Client Report R-689-1-15 122 pp. <http://www.clw.csiro.au/publications/science/2010/SAF-Lower-Lakes-SA-sulfate-soils.pdf>
<https://doi.org/10.4225/08/5852da2932c66>
- Fitzpatrick, RW, Hicks W, Merry RH, Thomas M, and Shand P (2011). Changes in acid sulfate soils and organic carbon following revegetation and episodic rewetting at Waltowa and Browns Beach trial sites in Lake Albert. CSIRO: Sustainable Agriculture Research Flagship Client Report R-325-8-7., 250 pp.
- Fitzpatrick, R.; Marvanek, S; Powell, B Grealish, G. (2010) Atlas of Australian Acid Sulfate Soils: Recent developments and future priorities. In: RJ Gilkes and N Prakongkep (Editors). *Proceedings of the 19th World Congress of Soil Science; Soil Solutions for a Changing World*; ISBN 987-0-646-53783-2; Published on DVD; <http://www.iuss.org>; Symposium WG 3.1 Processes in acid sulfate soil materials; 2010 Aug 1–6, Brisbane, Australia; IUSS; 2010, pp 24-27.
- Fitzpatrick RW, Marvanek S, Shand P, Merry RH, Thomas M & Raven M (2008a) Acid Sulfate Soil Maps of the River Murray below Blanchetown (Lock 1) and Lakes Alexandrina and Albert when water levels were at pre-drought and current drought conditions. CSIRO Land and Water Science Report 12/08. CSIRO, Adelaide. 16 pp. http://www.clw.csiro.au/publications/science/2008/sr12-08_withmaps.pdf.
- Fitzpatrick R.W, S.P. Marvanek, P. Shand, R.H. Merry, M. Thomas and Raven MD (2008) Acid Sulfate Soil Maps of the River Murray below Blanchetown (Lock 1) and Lakes Alexandrina and Albert when water levels were at pre-drought and current drought conditions. CSIRO Land and Water Science Report 12/08. CSIRO, Adelaide, 10 p There are 2 versions of the report – one without maps as appendix and one with maps: http://www.clw.csiro.au/publications/science/2008/sr12-08_withmaps.pdf
http://www.clw.csiro.au/publications/science/2008/sr12-08_nomaps.pdf

<https://doi.org/10.4225/08/585eb8711b192>

- Fitzpatrick R.W. and R.H. Merry (1999). Pedogenic Carbonate Pools and Climate Change in Australia. p.105-119. In: R. Lal, J.M. Kimble, H. Eswaran and B.A. Stewart (eds.). "Global Climate Change and Pedogenic Carbonates". CRC Press Lewis Publishers. Boca Raton, FL. Proceedings of the International Workshop on Global Climate Change and Pedogenic Carbonates. Tunis, Tunisia. 13-17 October, 1997.
- Fitzpatrick RW, Merry RH, Raven MD & Shand P (2008b) Acid Sulfate Soil Materials and Salt Efflorescences in Subaqueous and Wetland Soil Environments at Tareena Billabong and Salt Creek, NSW: Properties, Risks and Management. In Inland Acid Sulfate Soil Systems Across Australia (Eds Rob Fitzpatrick and Paul Shand. pp 281–293. CRC LEME Open File Report No. 249. (Thematic Volume) CRC LEME, Perth, Australia.
- Fitzpatrick RW, Merry RH, Thomas, BP, and Simpson P (2012). Assessment of Acid Sulfate Soil materials (Phase 2): Riverland Wetland Complex. CSIRO Water for a Healthy Country Flagship Client Report. 77pp (Appendix 3: 21 pages).
- Fitzpatrick RW, Mosley LM., and Cook FJ. (2017a). Understanding and managing irrigated acid sulfate and salt-affected soils: A handbook for the Lower Murray Reclaimed Irrigation Area. Acid Sulfate Soils Centre. Report ASSC_186. 97 pp. University of Adelaide Press. DOI: <https://doi.org/10.20851/murray-soils>
- Fitzpatrick, RW, Mosley LM, Raven MD and Shand P (2017b) Schwertmannite formation and properties in acidic drain environments following exposure and oxidation of acid sulfate soils in irrigation areas during extreme drought. *Geoderma*. 308, 235-251. <http://dx.doi.org/10.1016/j.geoderma.2017.08.012>
- Fitzpatrick R.W., R., Powell, B. and Marvanek, S. (2008c). Atlas of Australian Acid Sulfate Soils. In Inland Acid Sulfate Soil Systems Across Australia (Eds. R.W. Fitzpatrick and P Shand). pp 75-89. CRC LEME Open File Report No. 249. (Thematic Volume) CRC LEME, Perth, Australia.
- Fitzpatrick R and P Shand (2008). Inland Acid Sulfate Soils: Overview and conceptual models. In Inland Acid Sulfate Soil Systems Across Australia (Eds. Rob Fitzpatrick and Paul Shand). pp 6-74. CRC LEME Open File Report No. 249 (Thematic Volume) CRC LEME, Perth, Australia.
- Fitzpatrick R.W, P Shand R.H. Merry and M.D. Raven (2008d) Acid sulfate soil materials and salt efflorescences in subaqueous and wetland soil environments at Lake Bonney, SA: Properties, risks and management. Consultancy Report for South Australian Murray-Darling Basin Natural Resources Management Board. CSIRO, Adelaide, 130. pp
- Fitzpatrick, RW, P. Shand, M. Thomas, R.H. Merry, M.D. Raven, S.L Simpson (2008e) Acid sulfate soils in subaqueous, waterlogged and drained soil environments of nine wetlands below Blanchetown (Lock 1), South Australia: properties, genesis, risks and management. CSIRO Land and Water Science Report 42/08. CSIRO, Adelaide, 122. pp. <http://www.clw.csiro.au/publications/science/2008/sr42-08.pdf>
- Fitzpatrick, RW, P. Shand, R.H Merry; B. Thomas, S. Marvanek, N. Creeper, M. Thomas, M.D. Raven, S.L. Simpson, S. McClure and N. Jayalath (2008f) Acid sulfate soils in the Coorong, Lake Alexandrina and Lake Albert: properties, distribution, genesis, risks and management of subaqueous, waterlogged and drained soil environments. CSIRO Land and Water Science Report 52/08. CSIRO, Adelaide, 177. pp. <http://www.clw.csiro.au/publications/science/2008/sr52-08.pdf>
- Fitzpatrick RW, Shand P, Merry RH (2009). Acid Sulfate Soils. In 'Natural History of the Riverland and Murraylands'. (Ed. JT Jennings) pp. 65-111. (Royal Society of South Australia (Inc.) Adelaide, South Australia).
- Fitzpatrick, RW, Shand, P. and Hicks, W. (2011). Technical Guidelines for Assessment and Management of Inland Freshwater Areas impacted by Acid Sulfate Soils. CSIRO Land and Water Science Report, 05/11. 171 pp. [Published Version](https://publications.csiro.au/rpr/download?pid=csiro:EP15480&dsid=DS3) (pdf) (17.56MB)
<https://publications.csiro.au/rpr/download?pid=csiro:EP15480&dsid=DS3>
<https://doi.org/10.5072/83/5849a13e94e13>
- Fitzpatrick, RW. Shand, P, Grealish G, Thomas, M, McClure, S, Merry RH, Raven R and Baker A (2011). Acid Sulfate Soil investigations of vertical and lateral changes with time in five managed wetlands between Lock 1 and Wellington. CSIRO Land and Water Science Report, 03/10. 189 pp.
- Fitzpatrick RW, Shand P, Marvanek S, Merry RH, Thomas M, Simpson SL, Raven MD, McClure S (2008d) Acid sulfate soils in subaqueous, waterlogged and drained soil environments in Lake Albert, Lake Alexandrina and River Murray below Blanchetown (Lock 1): properties, distribution, genesis, risks and management. Prepared for Department of Environment and Heritage, SA. CSIRO Land and Water Science Report 46/08. CSIRO, Adelaide.

- Fitzpatrick, RW, Shand P and Mosley LM (2017c). Acid sulfate soil evolution models and pedogenic pathways during drought and reflooding cycles in irrigated areas and adjacent natural wetlands. *Geoderma*. 308, 270-290. <http://dx.doi.org/10.1016/j.geoderma.2017.08.016>
- Fitzpatrick, RW, Shand P, Merry RH, Marschner P, Jayalath N, Grocke S and Mosley LM (2016) Acid Sulfate Soil Assessment and Monitoring of the Banrock Station wetland. Acid Sulfate Soils Report No ASSC_035 (V13); 93 pp.
<https://www.adelaide.edu.au/directory/robert.fitzpatrick?dsn=directory.file:field=data.id=36917;m=view>
- Fitzpatrick RW, Thomas, BP, Simpson, S Shand, P and R.H Merry (2012) Assessment of Acid Sulfate Soil materials (Phase 2): Banrock Station Wetland Complex. CSIRO Water for a Healthy Country Flagship Client Report, 48 pp (Appendix 3: 21 pages).
- Isbell, R.F., National Committee on Soils and Terrain (2016). The Australian Soil Classification. Second Edition. CSIRO Publishing, Clayton, Victoria, Australia.
- Lamontagne S, Hicks WS, Fitzpatrick RW, Rogers S (2004) Survey and description of sulfidic materials in wetlands of the Lower River Murray floodplains: Implications for floodplain salinity management. Technical Report 28/04. CSIRO Land and Water. Adelaide, Australia.
- Lamontagne S, Hicks WS, Fitzpatrick RW, Rogers S (2006) Sulfidic materials in dryland river wetlands. *Marine and Freshwater Research* 57, 775–788.
- McDonald RC, Isbell RF, Speight JG, Walker J, Hopkins MS (1990). 'Australian soil and land survey field handbook.' (Inkata Press, Melbourne).
- McDonald, R and Isbell, RF. (2009). Soil profile. In National Committee on Soil and Terrain (2009), Australian soil and land survey field handbook (3rd ed.). CSIRO Publishing, Melbourne.
- Mosley L., Barnett L., Cugley J., Bush R., Fitzpatrick R., Hicks W., Hipsey M., Pape S., Seaman R., Shand P., Sullivan L. and Taylor J. (2010) Acid sulfate soils research program summary report. Prepared by the Lower Lakes Acid Sulfate Soils Research Committee for the South Australia Department of Environment and Natural Resources, Adelaide. 45 pp.
http://www.environment.sa.gov.au/Conservation/Rivers_Wetlands/Coorong_Lower_Lakes_Murray_Mouth/The_environment/Acid_sulfate_soils/Acid_Sulfate_Soils_Research_Program_reports
- Mosley LM, Palmer D, Mettam P, Cummings CR and Leyden E (2013). Lower Murray Reclaimed Irrigation Area (LMRIA) Acid Drainage Project. Final Summary Report. ISBN 978-1-921495-30-4, 36pp.
- Mosley LM, Fitzpatrick R, and Groenenberg B-J (2014). A biogeochemical model for assessing and managing acid sulfate soils in the Lower Murray region of South Australia. Environment Protection Authority technical report. Available at:
http://www.epa.sa.gov.au/xstd_files/Water/Report/lmria_acid_biogeochemical.pdf
- Mosley, L.M., Palmer, D., Leyden, E., Cook, F., Zammit, B., Shand, P., Baker, A., Fitzpatrick, R.W., (2014). Acidification of floodplains due to river level decline during drought. *Journal of Contaminant Hydrology* 161, 10-23.
- Mosley LM, Willson P, Hamilton B, Butler G, Seaman R (2015). The capacity of biochar made from common reeds to neutralise pH and remove dissolved metals in acid drainage. *Environmental Science and Pollution Research* 22, 15113-15122.
- Mosley LM, Daly R, Palmer D, Yeates P, Dallimore C, Biswas T, Simpson SL (2015). Predictive modelling of pH and dissolved metal concentrations and speciation following mixing of acid drainage with river water. *Applied Geochemistry* 59, 1–10.
- Mosley, LM, Biswas T, Cook F., Marschner P, Palmer D, Shand P, Yuan C, and Fitzpatrick RW (2017a) Prolonged recovery of acid sulfate soils with sulfuric materials following severe drought: causes and implications. *Geoderma*. 308, 312-320. <http://dx.doi.org/10.1016/j.geoderma.2017.03.019>
- Mosley, Luke M., Freeman Cook and Rob Fitzpatrick (2017b) Remediation of soil salinity and sodicity in Lower Murray irrigation areas; comparison and modelling of different treatments. *Soil Research*. 55(5), 670–681 <http://dx.doi.org/10.1071/SR16272>
- Murray-Darling Basin Authority. (2009). Acid sulfate soils field guide Field guide for the identification of wetlands at risk of acid sulfate soils in the Murray–Darling Basin.
- Murray-Darling Basin Authority. (2010). Detailed assessment of acid sulfate soils in the Murray-Darling Basin: Protocols for sampling, field characterisation, laboratory analysis and data presentation. Murray-Darling Basin Authority Publication 57/10. SBN 978-1-921557-67-5. 58 pp.
<https://www.mdba.gov.au/publications/report/detailed-assessment-acid-sulfate-soils-murray%E2%80%9393darling-basin>

- Murray-Darling Basin Authority. (2011). Acid Sulfate Soils in the Murray Darling Basin. MDBA Publication No. 147/11. Available at: <https://www.mdba.gov.au/sites/default/files/pubs/Acid-sulfate-soils-in-the-MDB.pdf>
- Pons, L.J. (1973). Outline of the genesis, characteristics, classification and improvement of acid sulphate soils. In H Dost (Ed.), Proceedings of the 1972 (Wageningen, Netherlands) International Acid Sulphate Soils Symposium, Volume 1 (pp. 3-27). International Land Reclamation Institute Publication 18. Wageningen, Netherlands.
- Pons, LJ and Zonneveld, IS. (1965). Soil ripening and soil classification: Initial soil formation in alluvial deposits and classification of the resulting soils. Inst. Land Reclam. and Impr. Pub. 13, Wageningen, The Netherlands. 128pp.
- Rayment GE, Higginson FR (1992). 'Australian laboratory handbook of soil and water chemical methods.' Melbourne, Inkata Press.
- Rayment G.E., Lyons D.J. (2010). Soil chemical methods - Australasia CSIRO Publishing: Collingwood.
- Schoeneberger, PJ, Wysocki, DA, Benham, EC, Broderson, WD and Soil Survey Staff. (2012). Field book for describing and sampling soils, Version 3.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE, USA.
- Shand P, Grocke S, Kirby J & Baker AK (2012) The characterisation of metal and metalloid contaminants in re-flooded Acid Sulfate Soils of Lake Alexandrina, South Australia. Water for a Healthy Country Flagship Report series ISSN: 1835-095X 58pp.
- Shand P, Fitzpatrick RW, Thomas M, Merry RH, Grocke S, Thomas B, Creeper N, Hollis B, Marsland K, Fogg M, Turner R & Goode J (2010a) Mobilisation of metals and acidity during reflooding of a wetland containing acid sulfate soils. In, P. Birkle & I.S. Torres-Alvarado (eds.), Water-Rock Interaction 13, CRC Press Balkema, London, 303-306.
- Shand P, Merry R, Grocke S, Thomas M, Fitzpatrick RW, Thomas B, Baker A & Creeper N (2010b) Water and soil quality impacts during reflooding of Nelwart Lagoon, South Australia. CSIRO: Water for a Healthy Country National Research Flagship.
- Shand P, Merry RH, and Fitzpatrick, RW (2008a) Acid sulfate soil assessment of wetlands associated with Lock 8 and Lock 9 weir pools. Prepared for Murray-Darling Basin Board. CSIRO Land and Water Science Report 40/08. CSIRO, Adelaide, 88 pp. <http://www.clw.csiro.au/publications/science/2008/sr40-08.pdf>
- Shand, P, Merry RH, and Fitzpatrick, RW (2008b), Acid sulfate soil assessment of wetlands associated with Lock 8 and Lock 9 weir pools. CSIRO Land and Water Science Report 40/08. CSIRO, Adelaide, 88 pp. <http://www.clw.csiro.au/publications/science/2008/sr40-08.pdf>
- Stauber J, A Chariton, M Binet, M Adams, SL Simpson, G Batley, M Durr, K Bentley, RW Fitzpatrick and P Shand (2008) Water quality screening risk assessment of Acid Sulfate Soil Impacts in the Lower Murray, SA. CSIRO Land and Water Science Report 45/08. CSIRO, Adelaide, 133 pp. <http://www.clw.csiro.au/publications/science/2008/sr45-08.pdf>
- Shand, P, Merry RH, Thomas Brett P, Thomas M, and Fitzpatrick RW (2009). Acid sulfate soil assessment of the Pike River system. CSIRO Land and Water Science Report 28/09 83 pp. <http://www.clw.csiro.au/publications/science/2009/sr28-09.pdf>
- Shand, P, Merry, RH, Fitzpatrick, RW and Thomas, M. (2009). Acid sulfate soil assessment of disconnected wetlands between Lock 1 and Lock 5, River Murray, South Australia. Client Report. CSIRO: Water for a Healthy Country National Research Flagship. 197 pp. <http://www.clw.csiro.au/publications/waterforahealthycountry/2009/wfhc-Murray-acid-sulfate-assessment.pdf>
- Shand P, Merry RH, Fitzpatrick RW & Thomas M (2009) Acid sulfate soil assessment of disconnected wetlands between Lock 1 and Lock 5, River Murray, South Australia. Client Report. CSIRO: Water for a Healthy Country National Research Flagship. 197 pp <http://www.clw.csiro.au/publications/waterforahealthycountry/2009/wfhc-Murray-acid-sulfate-assessment.pdf>
- Shand, P, Baker, AK, Grocke, S, Fitzpatrick, RW, Smith, L, Cozens, G & Fiebigler, C (2011) Assessment of Acid Sulfate Soil Materials (Phase 2): Morgan's Lagoon, South Australia. Prepared for Murray-Darling Basin Authority (MDBA) by CSIRO Water for a Healthy Country Flagship. [PDF 0.9 MB]

- [http://www.mdba.gov.au/files/bp-kid/1978_Assessment_of_acid_sulfate_soil_materials\(Phase2\)-MorgansLagoon,SouthAustralia.pdf](http://www.mdba.gov.au/files/bp-kid/1978_Assessment_of_acid_sulfate_soil_materials(Phase2)-MorgansLagoon,SouthAustralia.pdf)
- Shand, P, Baker, AK, Grocke, S, Fitzpatrick, RW, Smith, L, Cozens, G & Fiebiger, C (2011) Assessment of Acid Sulfate Soil Materials (Phase 2): Swan Reach Ferry wetland, South Australia. Prepared for Murray-Darling Basin Authority (MDBA) by CSIRO Water for a Healthy Country Flagship. [PDF 0.9 MB]
- [http://www.mdba.gov.au/files/bp-kid/1975_Assessment_of_acid_sulfate_soil_materials\(Phase2\)-SwanReachFerry_wetland,SouthAustralia.pdf](http://www.mdba.gov.au/files/bp-kid/1975_Assessment_of_acid_sulfate_soil_materials(Phase2)-SwanReachFerry_wetland,SouthAustralia.pdf)
- Shand, P, Baker, AK, Grocke, S, Fitzpatrick, RW, Smith, L, Cozens, G & Fiebiger, C (2011) Assessment of Acid Sulfate Soil Materials (Phase 2): Devon Downs South wetland, South Australia. Prepared for Murray-Darling Basin Authority (MDBA) by CSIRO Water for a Healthy Country Flagship. [PDF 0.9 MB]
- [http://www.mdba.gov.au/files/bp-kid/1974_Assessment_of_acid_sulfate_soil_materials\(Phase2\)-DevonDownsSouth,SouthAustralia.pdf](http://www.mdba.gov.au/files/bp-kid/1974_Assessment_of_acid_sulfate_soil_materials(Phase2)-DevonDownsSouth,SouthAustralia.pdf)
- Shand, P, Grocke, S, Baker, AK, Raven, M, Fitzpatrick, RW, Smith, L, Fiebiger, C, Cozens, G & Merry, RH (2011) Assessment of Acid Sulfate Soil Materials (Phase 2): Ukee Boat Club wetland, South Australia. Prepared for Murray-Darling Basin Authority (MDBA) by CSIRO Water for a Healthy Country Flagship. [PDF 1.5 MB]
- [http://www.mdba.gov.au/files/bp-kid/1968_Assessment_of_acid_sulfate_soil_materials\(Phase2\)-UkeeBoatClub_wetland,SouthAustralia.pdf](http://www.mdba.gov.au/files/bp-kid/1968_Assessment_of_acid_sulfate_soil_materials(Phase2)-UkeeBoatClub_wetland,SouthAustralia.pdf)
- Shand, P, Grocke, S, Baker, AK, Raven, M, Smith, L, Fitzpatrick, RW, Fiebiger, C & Cozens, G (2011) Assessment of Acid Sulfate Soil Materials (Phase 2): Swanport wetland, South Australia. Prepared for Murray-Darling Basin Authority (MDBA) by CSIRO Water for a Healthy Country Flagship. [PDF 1.5 MB]
- [http://www.mdba.gov.au/kid/files/1964_Assessment_of_acid_sulfate_soil_materials\(Phase2\)-Swanport_wetland,SouthAustralia.pdf](http://www.mdba.gov.au/kid/files/1964_Assessment_of_acid_sulfate_soil_materials(Phase2)-Swanport_wetland,SouthAustralia.pdf)
- Shand, P, Baker, AK, Grocke, S, Raven, M, Fitzpatrick, RW, Smith, L, Cozens, G & Fiebiger, C (2011) Assessment of Acid Sulfate Soil Materials (Phase 2): Riverglades wetland, South Australia. Prepared for Murray-Darling Basin Authority (MDBA) by CSIRO Water for a Healthy Country Flagship. [PDF 1.5 MB]
- [http://www.mdba.gov.au/kid/files/1963_Assessment_of_acid_sulfate_soil_materials\(Phase2\)-Riverglades_wetland,SouthAustralia.pdf](http://www.mdba.gov.au/kid/files/1963_Assessment_of_acid_sulfate_soil_materials(Phase2)-Riverglades_wetland,SouthAustralia.pdf)
- Shand, P, Grocke, S, Baker, AK, Smith, L, Fiebiger, C, Cozens, G & Fitzpatrick, RW (2011) Assessment of Acid Sulfate Soil Materials (Phase 2): Paiwalla wetland, South Australia. Prepared for Murray-Darling Basin Authority (MDBA) by CSIRO Water for a Healthy Country Flagship. [PDF 1.0 MB]
- [http://www.mdba.gov.au/kid/files/1962_Assessment_of_acid_sulfate_soil_materials\(Phase2\)-Paiwalla_wetland,SouthAustralia.pdf](http://www.mdba.gov.au/kid/files/1962_Assessment_of_acid_sulfate_soil_materials(Phase2)-Paiwalla_wetland,SouthAustralia.pdf)
- Shand, Grocke, S, P, Baker, AK, Raven, M, Fitzpatrick, RW, Smith, L, Fiebiger, C & Cozens, G (2011) Assessment of Acid Sulfate Soil Materials (Phase 2): Jury swamp, South Australia. Prepared for Murray-Darling Basin Authority (MDBA) by CSIRO Water for a Healthy Country Flagship. [PDF 2.0 MB]
- [http://www.mdba.gov.au/kid/files/1958_Assessment_of_acid_sulfate_soil_materials\(Phase2\)-JurySwamp,South%20Australia.PDF](http://www.mdba.gov.au/kid/files/1958_Assessment_of_acid_sulfate_soil_materials(Phase2)-JurySwamp,South%20Australia.PDF)
- Simpson, S.L., Fitzpatrick, R.W., Shand, P., Angel, B., Sparado, D.A. & Mosley, L. (2010) Climate-driven mobilisation of acid and metals from acid sulfate soils. *Marine and Freshwater Research*, 61, 129-138.
- Simpson S, B Angel, D. Spadara, R W Fitzpatrick, P Shand, R.H Merry and M Thomas (2008) Acid, Metal and Nutrient Mobilisation Following Rewetting of Acid Sulfate Soils in the Lower Murray. CSIRO Land and Water Science Report 27/08. CSIRO, Adelaide, 150. pp.
- <http://www.cdw.csiro.au/publications/science/2008/sr27-08.pdf>
- Thomas, BP, Merry RH, Creeper NL, Shand P, Marvanek S, Fitzpatrick RW, and Jayalath N (2011b). Assessment of Acid Sulfate Soil materials in Ramsar wetlands of the Murray-Darling Basin: Riverland. Prepared for Murray-Darling Basin Authority (MDBA) by CSIRO Water for a Healthy Country Flagship. [PDF 13.1 MB] <https://publications.csiro.au/rpr/download?pid=csiro:EP114566&dsid=DS1>

Appendix 1 Provisional list and maps of priority RRP Wetlands for detailed ASS field and laboratory assessment

Figure 1. Murtho Park

Figure 2. Lake Merreti

Figure 3. Lake Woolpoolool

Figure 4. Woolenook Bend Complex

Figure 5. Pyap Horseshoe North Section

Figure 6a. Spectacle Lakes - Beldora (North)

Figure 6b. Spectacle Lakes (South)

Figure 7. Sugar Shack Complex (Swan Reach Complex)

Figure 8. Silverlea (Swan Reach Ferry)



Figure 1, Appendix 1. Murtho Park – Provisional Acid Sulfate Soil sampling locations. A number of soil profiles will be located between the respective transect points displayed on the map, in accordance with the methodology described in this document. Transect locations will be finalised following a desk-top review, consultation with steak holders and field inspection of the wetland. Locations marked as “GS1” indicate a site of potential interest to visit during the field assessment.



Figure 2, Appendix 1. Lake Merreti – Provisional Acid Sulfate Soil sampling locations. A number of soil profiles will be located between the respective transect points displayed on the map, in accordance with the methodology described in this document. Transect locations will be finalised following a desk-top review, consultation with steak holders and field inspection of the wetland. Locations marked as “GS1” indicate a site of potential interest to visit during the field assessment.



Figure 3, Appendix 1. *Lake Woolpoolool* – Provisional Acid Sulfate Soil sampling locations. A number of soil profiles will be located between the respective transect points displayed on the map, in accordance with the methodology described in this document. Transect locations will be finalised following a desk-top review, consultation with steak holders and field inspection of the wetland. Locations marked as “GS1” indicate a site of potential interest to visit during the field assessment.

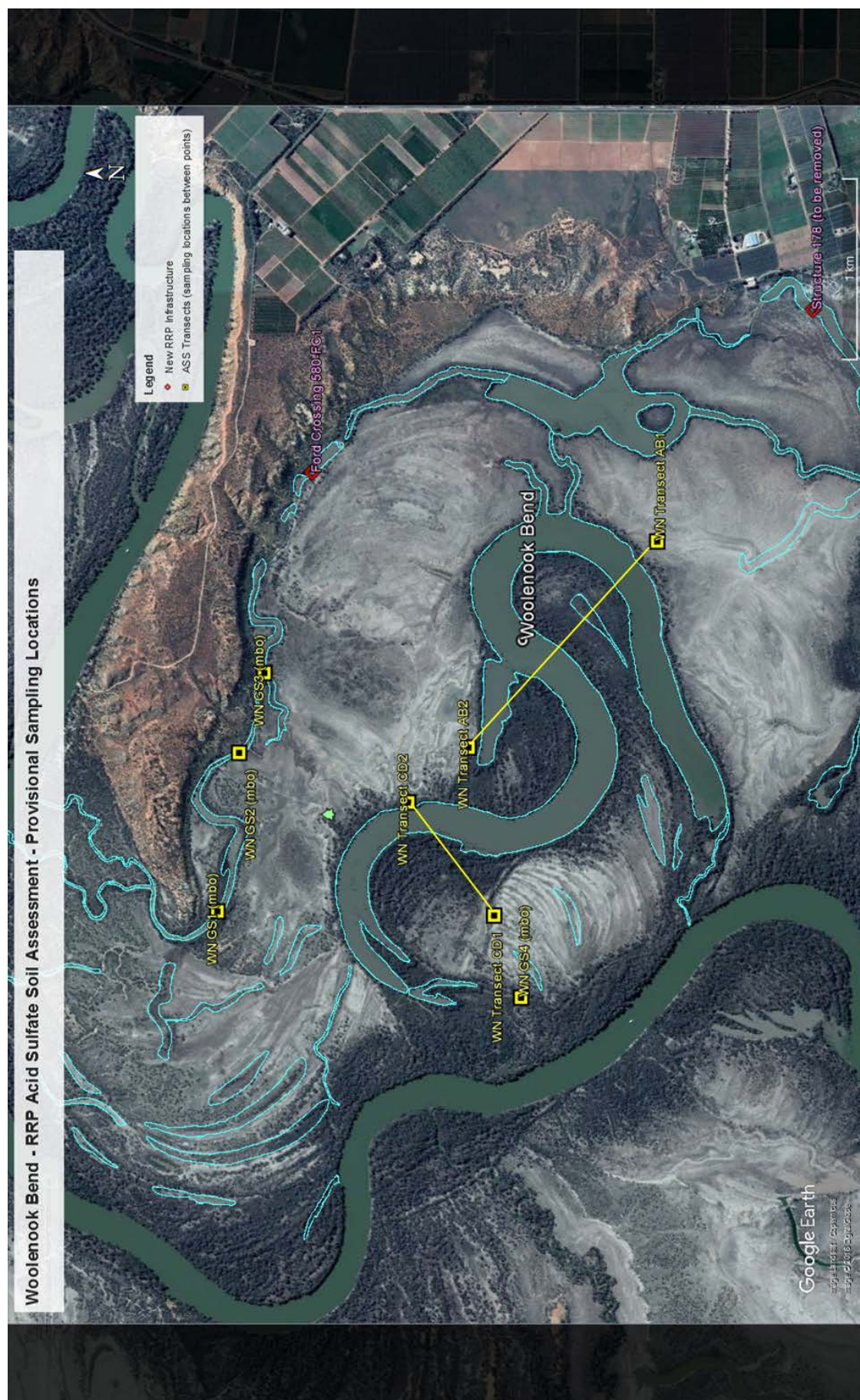


Figure 4, Appendix 1. Woolenook Bend – Provisional/Acid Sulfate Soil sampling locations. A number of soil profiles will be located between the respective transect points displayed on the map, in accordance with the methodology described in this document. Transect locations will be finalised following a desk-top review, consultation with steak holders and field inspection of the wetland. Locations marked as “GS1” indicate a site of potential interest to visit during the field assessment.

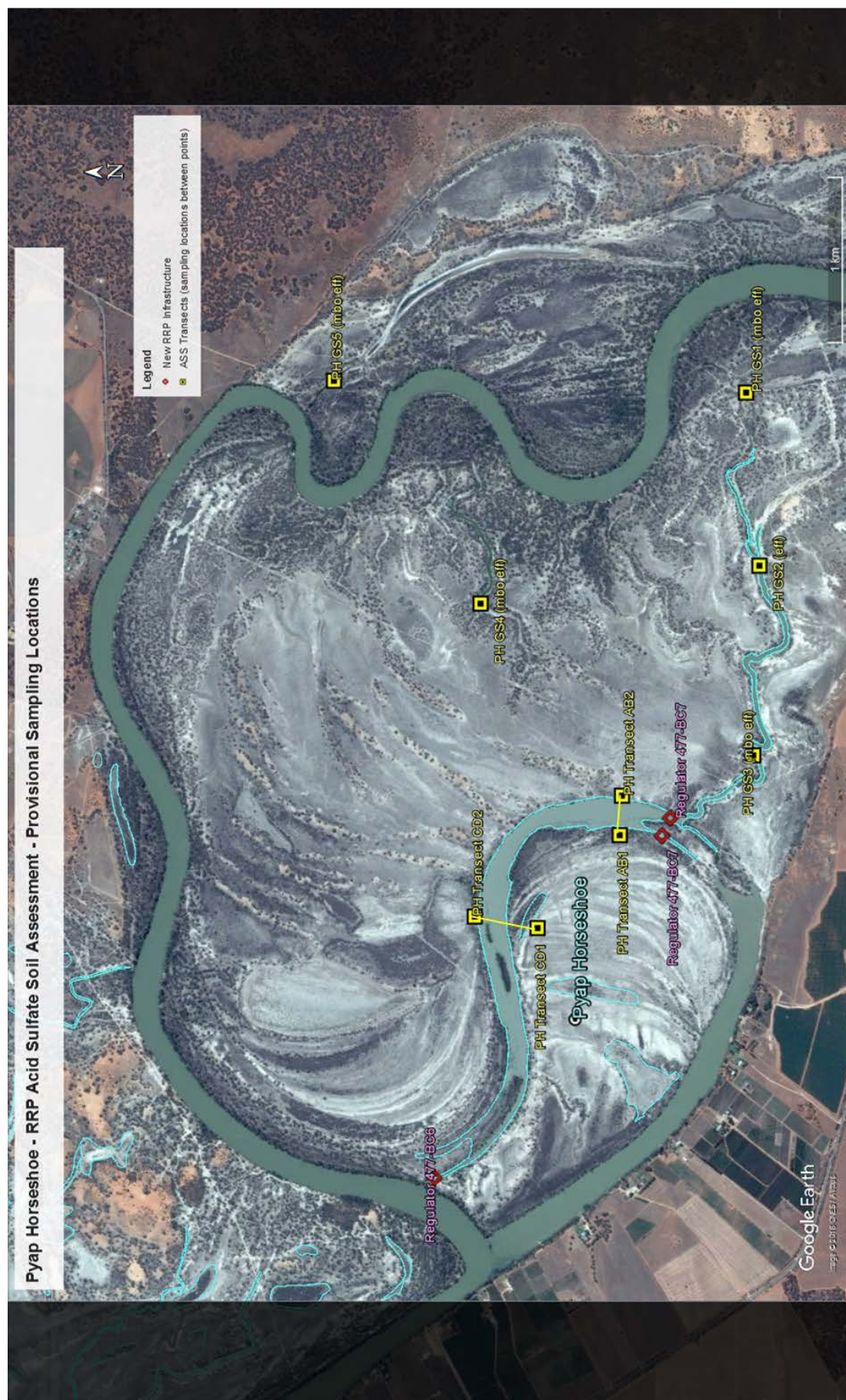


Figure 5, Appendix 1. Pyap Horseshoe – Provisional Acid Sulfate Soil sampling locations. A number of soil profiles will be located between the respective transect points displayed on the map, in accordance with the methodology described in this document. Transect locations will be finalised following a desk-top review, consultation with steak holders and field inspection of the wetland. Locations marked as “GS1” indicate a site of potential interest to visit during the field assessment.

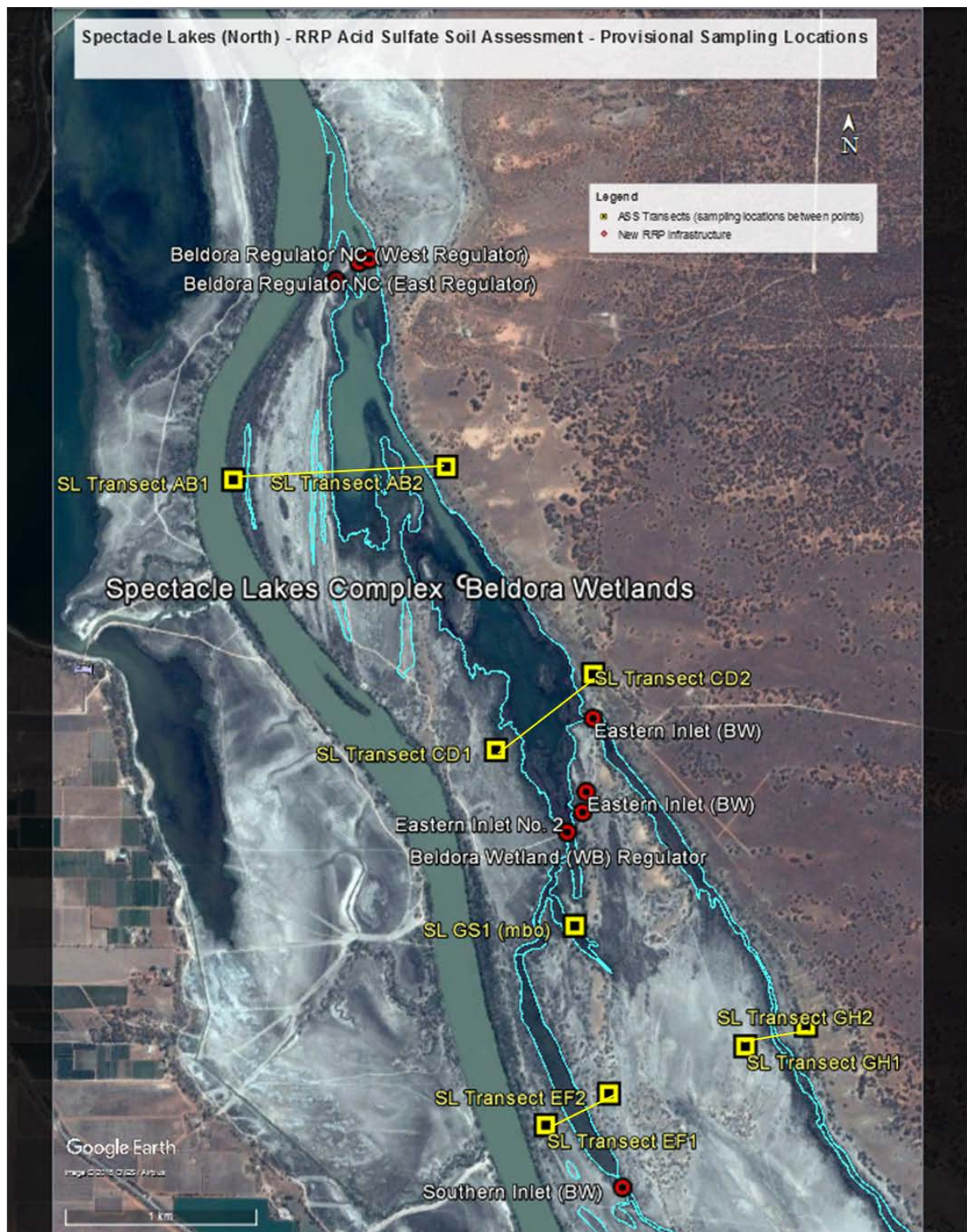


Figure 6a, Appendix 1. *Spectacle Lakes Complex (North)* – Provisional Acid Sulfate Soil sampling locations. A number of soil profiles will be located between the respective transect points displayed on the map, in accordance with the methodology described in this document. Transect locations will be finalised following a desk-top review, consultation with steak holders and field inspection of the wetland. Locations marked as “GS1” indicate a site of potential interest to visit during the field assessment.



Figure 6b, Appendix 1. Spectacle Lakes Complex (South) – Provisional Acid Sulfate Soil sampling locations. A number of soil profiles will be located between the respective transect points displayed on the map, in accordance with the methodology described in this document. Transect locations will be finalised following a desk-top review, consultation with steak holders and field inspection of the wetland. Locations marked as “GS1” indicate a site of potential interest to visit during the field assessment.

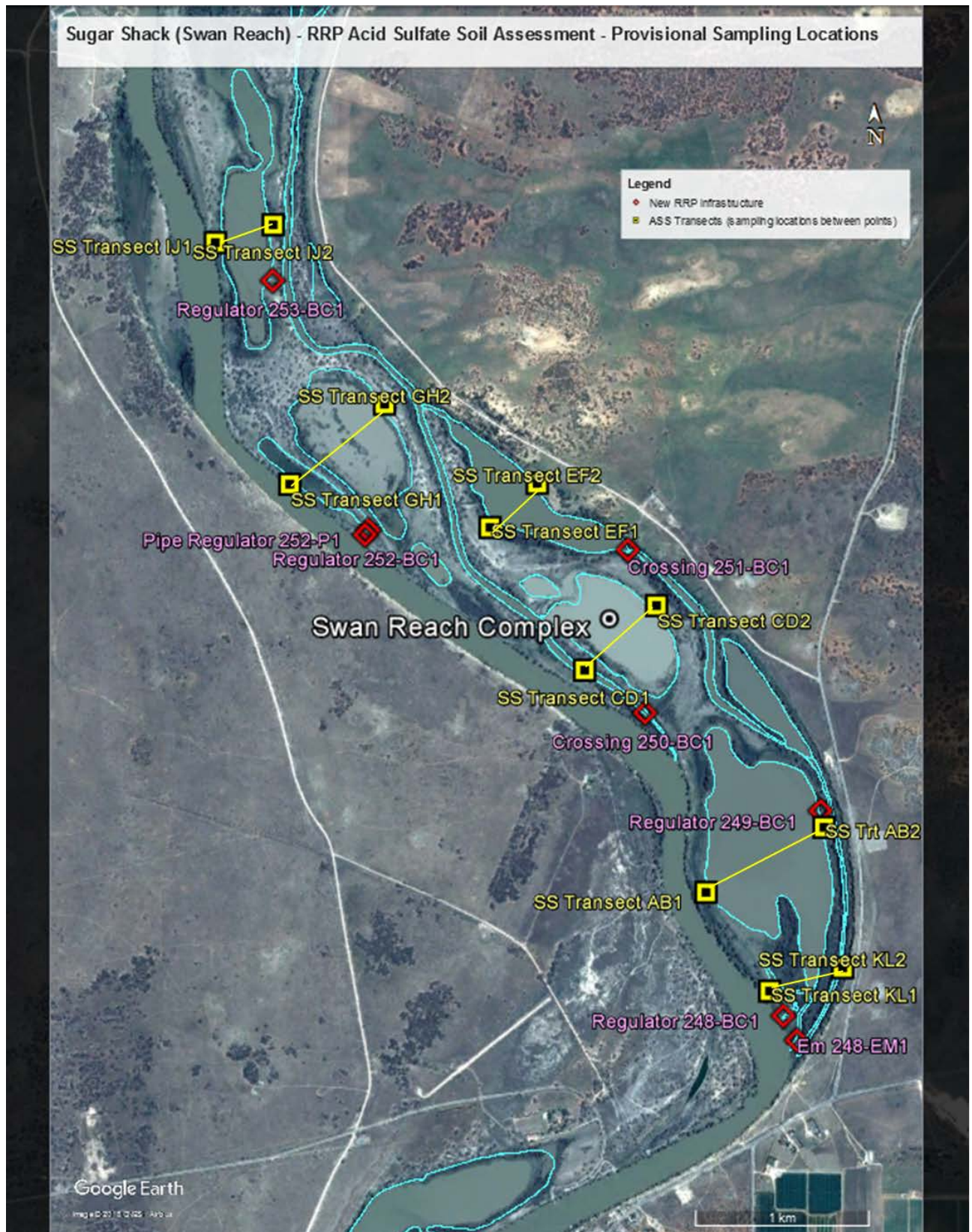


Figure 7, Appendix 1. Sugar Shack – Provisional Acid Sulfate Soil sampling locations. A number of soil profiles will be located between the respective transect points displayed on the map, in accordance with the methodology described in this document. Transect locations will be finalised following a desk-top review, consultation with stake holders and field inspection of the wetland.



Figure 8, Appendix 1. Silverlea (Swan Reach Ferry) – Provisional Acid Sulfate Soil sampling locations. A number of soil profiles will be located between the respective transect points displayed on the map, in accordance with the methodology described in this document. Transect locations will be finalised following a desk-top review, consultation with stake holders and field inspection of the wetland. Locations marked as "GS1" indicate a site of potential interest to visit during the field assessment.

Appendix 2: Clues obtained from field observations

- Clues from surface features
- *Clues from salt efflorescences*



Figure A1-1. Photograph of soft coatings of strong brown iron-rich precipitates with associated white salt efflorescences on soil and vegetation surfaces in wetlands near Toora belonging to SA Water, showing strong brown iron-rich precipitates (comprising schwertmannite) and white salt efflorescences (comprising Konyaite: $\text{Na}_2\text{Mg}(\text{SO}_4)_2 \cdot 5\text{H}_2\text{O}$ and Hexahydrite: $\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$) on dead grass. (Source: Fitzpatrick et al. 2017a.)

Iron precipitates in drains, ponds and wetland soil surfaces



Figure A1-2. Photographs of: (a) suspended strong brown coloured iron-rich precipitates in drains filled with water and (ii) **moist coatings or pastes of reddish-yellow coloured iron-rich precipitates** and associated salt efflorescences located in progressively drying ponds and drains (Source: Fitzpatrick et al. 2017a.)

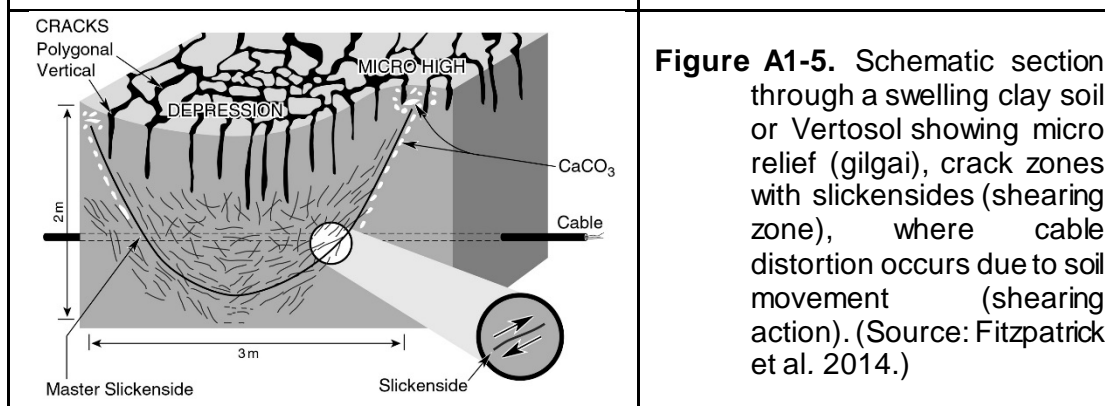
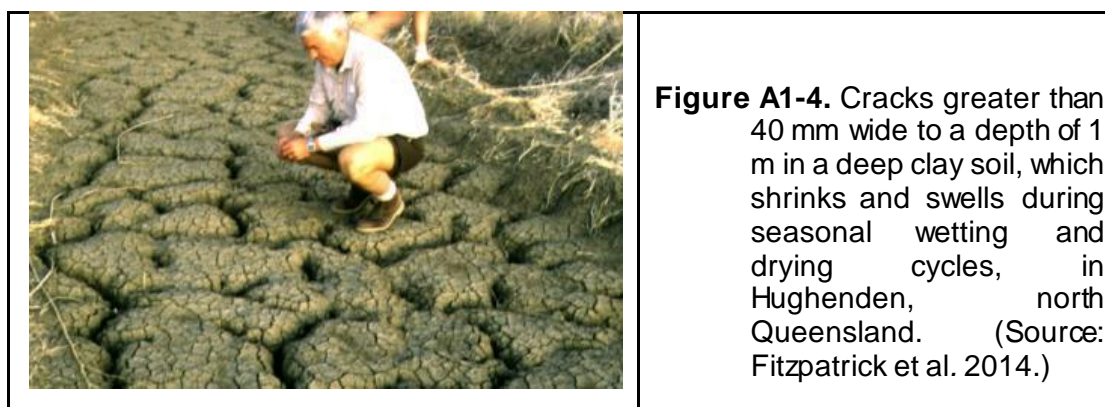
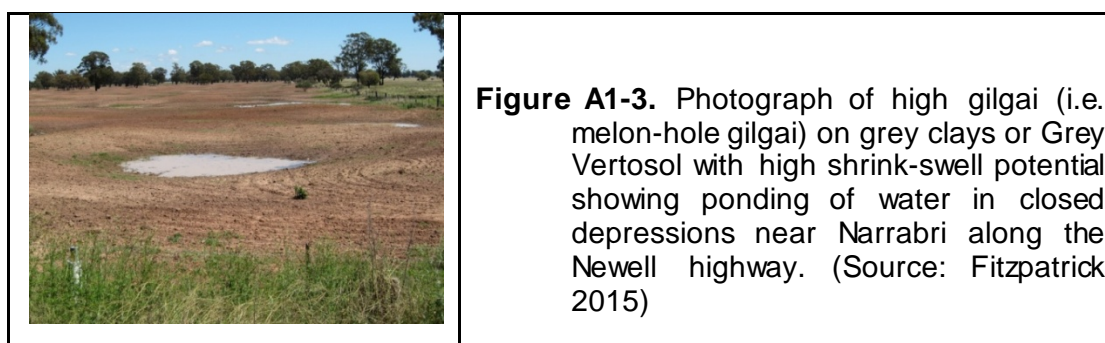
Gilgai

Gilgai are important indicators of swelling clay soils, and Australia is unique in the variety and extent of gilgai. They are associated with a range of shrink-swell clay soils with thick subsoil clay horizons. Gilgai (an Aboriginal word meaning small water-hole) are surface features consisting of a pattern of alternating mounds and depressions with a maximum difference in vertical interval of about 2 m. Water frequently ponds in depressions, thereby helping to identify the presence of gilgai. Prominent shrinkage cracks occur in dry seasons. There is a great deal of variation in the forms which gilgai can take and the soil profiles within which they develop.

However, there are essentially two broad groupings of gilgai:

- low gilgai that are characterised by a vertical interval of less than 300 mm (i.e. crabhole, normal, linear and lattice gilgai types)
- high gilgai with a vertical interval of more than 300 mm and commonly more than 800 mm (i.e. melon-hole and contour gilgai types).

High and low gilgai indicate very substantial soil movements, but high gilgai indicate greater movements than low gilgai.



Shrinkage cracks

Shrinkage cracks form during dry periods and may extend from the soil surface to depths as great as 1 m. If the soil is dry, the cracking pattern should be identified and the depth of cracking measured. However, cracking patterns can be hidden by loose surface aggregates (i.e. self-mulching) and these must be scraped aside in order to check for cracks which may be hidden beneath. Note that self-mulching, which forms as a result of shrink-swell processes, can be used to identify presence of shrink-swell soils.

Lime/gypsum

Lime nodules occur in neutral or alkaline soils and promote structural stability. Gypsum may be an indicator of salinity. What should you look for?

Look for white or light-coloured flecks in the soil. Remove these flecks (or nodules) and place them in a dish of acid (for example, vinegar, dilute hydrochloric acid 2M).

- If the nodule causes the liquid to bubble, then lime (calcium carbonate) is present.
- If bubbling does not occur, the deposit may be gypsum, which crystallises in clear, needle-shaped forms.
- If a white precipitate develops in acetone, gypsum is present.

Clues from soil profile features

Clues from a road cutting, soil pit or auger hole

In order to record the main soil features, it is necessary to briefly discuss the term 'soil profile'. A soil profile is a vertical cross-section of soil exposed in a pit, road cutting or auger hole; it may be divided into horizons (or layers — for example, surface salt efflorescences or crusts) for the purpose of characterisation. Horizons or layer are characterised by changes in colour, texture and structure. Horizon or layer boundaries generally run parallel to the earth's surface and are named downwards as follows:

- topsoil or A horizon (often organically and biologically rich)
- subsoil or B horizon (often clay rich)
- parent material or C horizon (often weathered or soft rock).

Cleaning the profile or auger hole face

The process of clearing the profile face of smeared soil is most important. As you clear the face, you can form accurate impressions of the soil's basic characteristics. After a profile has been dug (for example, by spade or backhoe or auger), it is often best left for a day or two so that the faces can dry out. This makes the removal of smeared clods much easier.

To see the true structure and colour of the soil revealed by the profile, it is necessary to expose undisturbed soil. This is best done with a large knife (or spatula) as follows:

- Start at the top left-hand corner.
- Push the spatula 1 to 2 cm into the profile 3 to 4 cm below the soil surface, and use a flicking motion to remove the soil.

- Move from left to right across the profile face. You will notice that the newly exposed soil is rough and not smeared.
- Continue moving down the profile using the same technique until the entire profile face is exposed.

The exposed face is known as the soil profile and should show topsoil and subsoil layers. These can be distinguished by colour and textural differences.

Sketch of the profile (optional)

In the appropriate space on the Field Recording Checklist/Table, draw the main features that can be seen in the pit or auger hole. Along the top of this space any gilgai mounds and depressions can be sketched. Drawings of this type complement profile test results.

Note, especially, the depth and extent of cracks or massiveness (no cracks). Small things such as lime nodules or gypsum crystals must also be noted. If the soil is very moist when the pit is dug, natural crack lines will be closed and hard to see; the soil may therefore appear to be massive. However, with closer observation, shiny surfaces along shear planes (slickensides) should be especially easy to see.

Colour

Colour can indicate the presence of problems (for example, a bluish tint can indicate waterlogging) or the absence of problems (for example, uniform coloured red or yellow sandy soils; see Table A1-1). It is sufficient for the present purposes to group soil colour into the following broad categories: Grey (gr), Black (bl), Brown(br), Red (r), Yellow (y). Make note of any mottling of the soil (flecks of one colour against a different background). Munsell Soil Colour Charts are available for more critical matching of soil colours.

Table A1-1. Interpreting soil colour (from Fitzpatrick 1996; Fitzpatrick et al. 1999)

Colour pattern of material in surface & subsurface layers	Accessory indicators Texture/Depth	Soil indicator	Environmental indication
Uniform coloured surface & subsurface	Sandy/Shallow (25-50cm)	Uniform coloured ¹ brown and red sand	Excessively drained: Water is drained very rapidly. Groundwaters are deep. Soils are commonly very coarse or sandy textured, rocky or shallow.
Uniform coloured surface & subsurface	Loams/very Deep	Uniform coloured ¹ brown and red loam (L) to sandy clay loam (SCL).	Well drained: Water is drained from the soil readily but not rapidly. Internal free water occurrence is very deep. Water is available to plants during most of the growing seasons and soil wetness does NOT inhibit growth.
Uniform coloured surface (0-30 m). Mottled subsurface.	Loams/deep (>100cm)	Uniform coloured ¹ brown and red L to SCL. Low chroma ⁴ mottling between 30 to 100 cm and no yellowish soil matrix hues or neutral colours within 150 cm	Moderately well drained: Water is drained from the soil slowly during some periods of the year. Internal free water occurrence is moderately deep (0.5 - 1 m). The soils are wet for only a short period of the growing season for mesophytic crops to be affected. Soils commonly have a slowly pervious layer within the upper 1 m, and periodically receive high rainfall.
<20% grey and bluish mottling in surface & subsurface.	Loams and clays Moderately deep (0-75cm)	<20% grey or bluish mottling ⁴ and >20% yellowish or red mottling ³ between 0-75 cm. (Few ⁶ to common ⁷ grey, bluish mottles ⁴)	Some what poorly drained: Water is drained from the soil slowly enough that the soil is wet at shallow depth for significant periods during the growing season. Internal free water occurrence is shallow (25 - 50 cm) and commonly transitory. Wetness restricts growth of mesophytic crops unless drained. Soils commonly have a slowly pervious layer and high water table, and can receive additional water from seepage or very high rainfall.
>20% grey and bluish mottling in surface & subsurface.	Shallow (25-50cm) Surface: Subsurface:	>20% grey or bluish mottling ⁴ and <20% yellowish or red mottling ³ between 0-75 cm. Many ⁸ grey, bluish or black mottles ⁴ Many ⁸ grey bluish mottles ³	Poorly drained: Water is drained very slowly so that the soil is wet at shallow depths periodically during the growing season. Internal free water occurrence is shallow (25 - 50 cm) or very shallow (<25 cm) and common or persistent. Free water is commonly at or near the surface long enough for most mesophytic crops not to grow unless drained. The soil is NOT continuously wet directly below the plough-depth, but free water is usually present at shallow depth because of: (i) slowly pervious layers (ii) very high water tables and (iii) additional water from seepage or very high rainfall.
Uniform grey or bluish material in surface & subsurface.	Very shallow (<25cm). Surface & Subsurface	Uniform grey or bluish material ² throughout the soil and with many ⁸ grey, bluish or black mottles ⁴	Very poorly drained: Water is drained very slowly. The soil remains wet at or very near the ground surface during most of the growing season. Internal free water occurrence is very shallow (<25 cm) and common or persistent. Free water is commonly at or near the surface long enough so that most mesophytic crops will not grow unless drained. The soils are on level land and are continuously wet and frequently ponded.

1. Uniform red & yellow coloured material = Strongly concentrated in iron with no localised iron depletions & concentrations (i.e. no mottles or stains present).

2. Uniform grey, bluish or bleached material (low chromas 2 or less for all hues) = Strongly depleted in iron.

3. Mottled or patchy red and yellow material or stains = Localised iron concentrations (Schoeneberger et al. 2012).

4. Mottled or patchy grey, bluish, black or yellow material (low chromas 2 or less for all hues) (mottles) = Localised iron depletions (Schoeneberger et al. 2012).

5. Very few = <2%.

6. Few = 2-10 %.

7. Common = 10-20%.

8. Many = 20-50%.

Structure

In this context, we will be concerned with the fabric of the soil (i.e. the presence or absence of slickensides or of peds).

(i) Slickensides (ss)

Planes of weakness along which movement occurs in shrink/swell clay soils are known as slickensides (Figure A1-8). These are shearing faults which exist permanently in wet or dry expansive clays. They take the form of cracked, polished or grooved surfaces, ranging from 10 mm to 200 mm across (Figure A1-8). Slickensides often run through the soil mass in many directions and may break it up into bowl-shaped blocks. Movement can be up to 25 mm per year on them. The presence of slickensides is indicative of soil movements which are very detrimental to cable operation, hence the frequency and size of slickensides present can quantify the potential capacity of the soil to shrink and swell. Soil pressures of up to 0.5 to 1.5 MPa can be exerted on a cable due to movement on slickensides.

Cautionary note:

(i) Do not confuse slickenside surfaces with the shiny smeared surfaces caused by implements (for example, by tools or tillage implements).

(ii) Slickenside surfaces can be obscured by the tools used to dig pits, hence the importance of observing a cleaned pit surface. When using an auger, it is more difficult to observe slickensides, and for this reason it is critical to always observe such features at the bottom of the auger.



Figure A1-6. Slickensides (also known as 'shiny backs') are shear planes found at depth in heavy, shrink-swell clays. They characteristically form in all planes with the production of lenticular or wedge-shaped structures. Slickensides can be polished, grooved or fluted, and when the soil dries they crack and have a dull lustre. NOTE: The majority of slickensides are small (for example, thumb-nail size), as shown in the upper part of the photograph. (Source: Fitzpatrick 2015.)

(ii) Peds (p)

If the soil is subdivided by fine cracks, then small blocks called peds (p) result (for example, see layer 2 in Strongly waterlogged sodic soil in Table A4-1, showing an example of prismatic ped structure). The cracks separating these blocks do not usually have shiny surfaces.

(iii) Massive (m)

If the soil is in one large block, it is classed as being massive (m) (for example, Sulfuric Soil in Table A4-1, showing an example of massive soil structure).

Texture

Texture is a measure of the proportions of sand, silt and clay in the soil (see Figure A1-9). Texture measurements need only be made once for soil profiles or layers that are uniform down to a depth of 1.5 m. If the soil profile is not uniform, take a texture sample each time you see a different layer.

How to determine soil texture

1. Take a sample of soil sufficient to fit comfortably into the palm of the hand (separate out large bits of gravel and stones).
2. Moisten soil with water, a little at a time, and work until it just sticks to your fingers and is not mushy. This is when its water content is approximately 'field capacity'.
3. Continue moistening and working until there is no apparent change in the ball (bolus) of soil (usually 1-2 minutes).
4. Attempt to make a ribbon by progressively pressing the bolus between thumb and forefinger (see Figure A1-10).

The behaviour of the worked soil and the length of the ribbon produced by pressing out between thumb and forefinger characterises the texture as shown in Table A1-2.



Figure A1-7. Photographs showing: (i) clayey soil with ped structures, (ii) loamy soil with massive structure (i.e. with no peds), and (iii) sandy soil with massive structure (i.e. with no peds). Source: Author.



Figure A1-8. Photographs showing the length of the ribbon produced by pressing out between thumb and forefinger to characterise: (i) a clayey soil texture with ribbon length $>75\text{mm}$ and (ii) a sandy soil texture with no ribbon. Source: Author

Table A1-2. Interpreting soil texture from the behaviour of a moist bolus (ball)
(from Fitzpatrick 1996; Fitzpatrick et al. 1999)

Texture*	Ribbon (mm)	Ball	Feel	Environment indication
Sand (S)	nil	coherence nil to very slight	Cannot be moulded. Clay is <5%.	No restriction on root growth for annuals and perennials but has a moderate susceptibility to mechanical compaction. No restriction on water movement but periodic soil moisture stress occurs because water is drained very rapidly.
Loamy sand (LS)	5	coherence nil to very slight	Cannot be moulded. Clay is 5-10%.	As above.
Clayey sand (CS)	5-15	coherence very slight	Cannot be moulded. Clay is 5-10%.	As above.
Sandy loam (SL)	15-25	coherence slight	Sandy to touch. Clay is 10-20%.	Root growth of annuals and perennials is not restricted but has a high susceptibility to mechanical compaction. Very slight restriction on water movement; soil water is available to most crops and trees. Water is drained from the soil readily but not rapidly.
Loam (L)	25	coherent and rather spongy	Smooth feel when manipulated but with no obvious sandiness; may be greasy to touch if organic matter is present. Clay is about 25%.	Root growth of annuals and perennials is not restricted, with moderate susceptibility to mechanical compaction. Very slight restriction on water movement; soil water is available to most crops and trees.
Sandy clay loam (SCL)	25-40	strongly coherent	Sandy to touch; medium-size sand grains visible in finer matrix. Clay is about 20% - 30%.	As above.
Clay loam (CL)	40-50	coherent plastic	Smooth to manipulate. Clay is about 30-35%.	As above.
Light clay (LC)	50-75	plastic	Smooth to touch; slight to shearing between thumb and forefinger. Clay is about 35-40%.	Root growth of annuals and perennials is frequently restricted, with moderate susceptibility to mechanical compaction. Some restriction on water movement; soil water is available to most crops and trees. Water flow is restricted, contributing to periodic waterlogging.
Medium clay (MC)	>75	smooth plastic	Handles like plasticine and can be moulded into rods without fracture; has some resistance to ribboning shear. Clay is about 45-55%.	Root growth of most species is severely restricted but with low susceptibility to mechanical compaction. Water is drained very slowly. This does not apply to self-mulching or sub-plastic clay properties.
Heavy clay (HC)	>75	smooth plastic	Handles like stiff plasticine; can be moulded into rods without fracture; has firm resistance to ribboning shear. Clay is about >55%.	As above.

The Texture Groups according to Northcote and Skene (1972):

1. The Sands = sand (S), loamy sand (LS), clayey sand (CS).
2. The Sandy Loams = sandy loam (SL), fine sandy loam (FSL).
3. The Loams = loam (L), sandy clay loam (SCL).
4. The Clay loams = clay loam (CL), silty clay loam (ZCL), fine sandy clay loam (FSCL).
5. The Light Clays = sandy clay (SC), silty clay (ZC), light clay (LC), light medium clay (LMC).
6. The Medium-Heavy Clays = medium clay (MC), heavy clay (HC).

Soil consistence

Consistence of a soil material can be measured in the field by simply manipulating a dry or moist piece of soil in the hand and determining the magnitude of force needed to cause disruption or distortion. Consistence is expressed as loose, soft, firm, very hard and rigid (Table A1-3; McDonald et. al 1990). Terms used to describe consistence vary depending on the moisture content of the sample tested such as soft (dry) or friable (moist). Changes in soil consistence with depth is measured from the soil surface in mm. An alternative, simplified and surrogate method of determining consistence is to assess the depths to restrictive and contrasting soil layers by determining the difficulty with which the soil is excavated.

Excavation of soil is a very common activity. The depth to each layer which is difficult to excavate is the first property noted and granted significance by a layperson. Accordingly, Table A1-3 lists the 5 classes of consistence by recording either

- the magnitude of force needed to cause disruption or distortion by manipulating a piece of block-like (25 mm to 30 mm on edge) soil in the hand or under foot. Stress is applied along the vertical in-plane axis of the block-like piece of soil by compressing it between extended thumb and forefinger, between both hands, or between foot and hard flat surface; or
- the difficulty of making an excavation (using either a shovel, pick or fence pole auger).

The depth to each consistency layer or class of excavation difficulty (i.e. restricting or contrasting layer) is recorded in metres. Depth of soil to the restricting or contrasting layers that would affect root growth or water movement has an important bearing on crop production and this is an important indicator of soil quality.

Soil consistence or consistency is also called rupture resistance and is a very readily observed feature in the field. In agricultural systems, this morphological attribute principally determines the various restrictive layers which determine the effective root depth for plants. It thus has a major bearing on

- the productive capacity of the soil for agricultural enterprises
- the suitability of the soil resource for different forms of land use
- the flow paths by which water moves within the soil and landscape
- how soil and landscape will respond to management practices.

The depth of root penetration in soils can be determined simply in the field by measuring changes in soil consistence progressively down the soil profile from the soil surface. The very hard and rigid classes are indicative of reduced porosity/permeability. Commonly, soil texture and root abundance are also used to make such judgements in the field. Soil consistency change (dry or moist state) is a preferred surrogate measure of different restrictive layers because soil texture is often difficult to measure consistently by the layperson and root abundance is highly dependent on other factors such as climate, soil fertility and land management. Sands will always have a loose consistence (see Figure A1-9). In contrast, the loams and clay loams have a greater diversity of consistence properties and can range from soft to very hard. In general, most medium-heavy clays will have a consistence of very hard to rigid.

Table A1-3. Interpreting soil consistence (from Fitzpatrick 1996; Fitzpatrick et al. 1999)

*Consistence Classes Dry (Moist)	Rupture Resistance on a 30 mm cube of dry or moist soil <i>#(Force needed for failure in Newtons)</i>	*Consistence test inferred from Excavation Difficulty	Environment indication
Loose (Loose)	Block-like piece not obtainable. Only individual sand grains can be picked up between thumb and forefinger. (0)	Can be excavated with a spade using arm-applied pressure. Neither application of impact energy nor application of pressure with the foot to a spade is necessary.	No restriction on root growth for annuals and perennials. No restriction on water movement. Periodic soil moisture stress occurs (except for self-mulching clays).
Soft (Friable)	Fails (i.e. crumbles) under slight force applied between thumb and forefinger. (<8-20)	Arm-applied pressure to a spade is insufficient. Excavation can be accomplished quite easily by application of impact energy with spade or by foot pressure to spade.	Root growth of annuals and perennials is not restricted. Slight restriction on water movement; soil water is available to most crops and trees.
Firm (Firm)	Fails under moderate to strong force applied between thumb and forefinger. (20-80)	Excavation with spade can be accomplished, but with difficulty. Excavation is easily possible with a full-length pick using an over-the-head swing.	Water flow is mildly restricted, contributing to periodic waterlogging.
Very hard (Very firm)	Cannot be failed between thumb and forefinger but can be by applying full body weight under foot. (80-800)	Excavation with a full-length pick using an over-the-head swing is moderately to markedly difficult. Excavation is possible in a reasonable period of time with a backhoe mounted on a 40-60 KW (50-80 hp) tractor.	Root growth of most species is restricted. Water flow is restricted, contributing to waterlogging.
Rigid (Rigid)	Cannot be failed by blow with hammer. (>800)	Excavation is impossible with a full-length pick using an over-the-head arm swing or in a reasonable time period with a backhoe mounted on a 40-60 KW (50-80 hp) tractor.	Root growth of most species is severely restricted. Water flow is strongly restricted, contributing to waterlogging.

*Modified from Soil Science Division Staff 2017; McDonald et al. 1990 (equivalent consistence classes: weak = soft and very strong = very hard).

#The force Newtons is calculated by determining the weight in kg in failure and multiplying by 9.806

Effective root depth

Visual observation of the presence and approximate abundance of roots in a soil is a surrogate indicator for estimating either available water, presence of restrictive layers or toxicity to plant or tree roots.

Effective root depth is estimated in the following manner:

1. Estimate and record approximately the number of <2 mm diameter roots in each layer in areas 100 mm square on a cleaned exposure face (McDonald et. al 1990).
Use the following simple procedure:
Place a 100 mm x 100 mm square wire or wooden frame vertically on each contrasting soil layer (soil layers with different consistencies and/or colours), and estimate the number of visible roots within the frame and classify per 100 mm x 100 mm area as:
Few = <10 roots; Common = 10-200 roots; Abundant = >200 roots.
2. Effective root depth = soil depth (measured from the soil surface) where the number of roots drops from abundant or common to few (i.e. <10 roots per 100 x 100 mm). Effective root depth is one of the surrogate indicators used to estimate plant-available water (Table A1-4). Layers that are incapable of supporting more than a few <2 mm diameter roots are considered to be root restricting. Based on the effective root depth, soils may be very roughly or arbitrarily classified for suitability for plant growth using 5 classes: very good, good, fair, poor and very poor (see Table A1-4).

Table A1-4. Interpreting effective root depth (from Fitzpatrick 1996)

Root abundance (roots per 100 mm x 100 mm)	Depth class (m)	*Effective root depth (Growth suitability for many plants)
>200 <10	0-0.50 >0.5	Very Good
>200 <10	0-0.15 0.15-0.50	Good
10-200 <10	0-0.50 >0.5	Fair
10-200 <10	0-0.15 0.15-0.50	Poor
<10	0-0.5	Very poor

*Effective root depth is defined as that soil depth, measured from the soil surface, where the amount of roots decrease from abundant (>200) or common (10-200) to few (i.e. <10 roots per 100 mm x 100 mm).

Appendix 3: Saline and sodic soil tests and interpretation of results

Soil salinity (electrical conductivity), sodicity (dispersibility) and gypsum assessment

Dispersibility (i.e. the ease with which clay will disperse) is strongly governed by salinity (presence or absence of salts), and exchangeable cations. Stable soils resist dispersion when immersed in rainwater.

Sample preparation (modified from Fitzpatrick et al. 1997; Cox et al. 1999):

1. This is a simple test that can be done by placing a sample of air-dried soil (i.e. thinly spread soil exposed to air for two days) in rainwater and leaving it to stand overnight. The test can be carried out on soil sampled either from a pit or auger hole. When using an auger, make sure that it is of large diameter, and take the soil sample for testing from the middle of the core. This is to avoid sampling remoulded soil that tends to disperse more readily.
2. If necessary, dry the soil sample in air for several days before gently breaking down large clods. Do not crush any rocks or fragments of lime.
3. Following a modified SASKIT method (after Rengasamy and Bourne 1997), weigh 100 g of soil (do not include clods more than 1 cm in width) into a clean 600 ml or larger glass jar. Pour rainwater gently down the side of the jar without disturbing the soil on the bottom. Gently add 500 ml of rainwater down side of the jar, without disturbing the soil at the bottom. This gives a **1:5 soil:water ratio**. If you do not have a balance, then place 4 scoops of soil to 30 scoops of rainwater (for example, coffee scoop or tea spoon).

Replace the lid and gently invert. Rotate the jar while it is upside down, on an angle of 45 degrees, until the soil detaches itself from the base of the jar. Let jar with sample stand in a secluded place (out of reach of children, pets, etc., with no vibrations or bumping) for 4 hours.

4. **Sodicity** (dispersibility) (modified from Fitzpatrick et al. 1997):
 - i) After **4 hours**, without moving the jar, gently stir the liquid for 5 seconds so that only the dispersed clay on top of the sediment is agitated (i.e. do not disturb the whole soil sediment on the bottom of the jar!).
 - ii) Describe whether the solution above the soil sediment is 'clear', 'murky' or 'densely opaque' (see Figure A2-1) on the analysis sheet (Table A1-1).

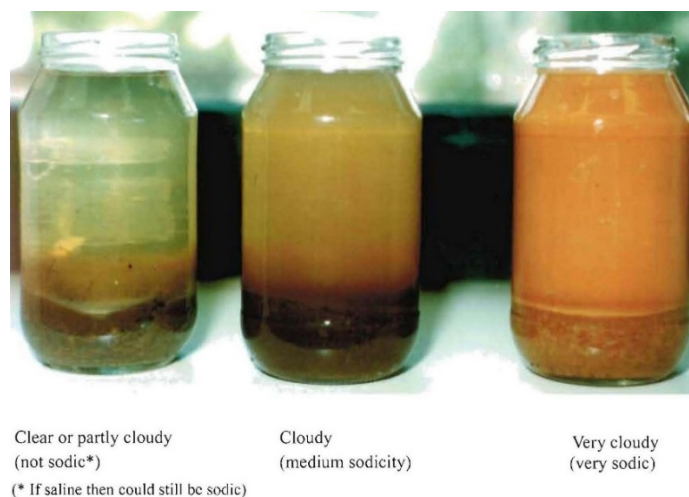


Figure A2-1. Estimating turbidity or cloudiness (soil sodicity) in a 1:5 soil/w ater suspension. (Source: Fitzpatrick et al. 1997.)

5. **Soil salinity** (electrical conductivity)
 - i) Completely stir the whole soil sediment vigorously for 15 seconds.
 - ii) Measure the electrical conductivity (EC) of solution after 10 minutes. Record the EC measurement (EC_{1:5}) in the unit of dS/m as shown in Table A2-1.
6. **Gypsum**
 Determine presence of gypsum by mixing approximately 20 ml of solution with 20 ml of acetone. If a white precipitate develops, then gypsum is present.

Table A2-1. Checklist/table for determination of soil salinity and sodicity hazards

Date of Soil Sampling: -----

Horizon/Layer description	Depth (mm)	Clear	Murky	Dense	EC dS/m

If EC is less than 0.7 dS/m and liquid is **clear**:

If EC is 0.7-1.4 dS/m and liquid is **clear**:

If EC is 1.4->3.5 dS/m and liquid is **clear**:

If EC is less than 0.7 dS/m and liquid is **murky**

If EC is less than 0.7 dS/m and liquid is **densely opaque**

If a white precipitate develops in acetone

Soil is non-saline and non-sodic.

Soil is moderately saline.

Soil is severely saline.

Soil is non-saline and moderately sodic.

Soil is non-saline and severely sodic.

Gypsum is present.

Sodicity (dispersibility) using the sodicity meter (modified from Cox et al. 1997):

After **4 hours**, check the suspension above the sediment at the bottom of the jar and estimate the amount of cloudiness using the sodicity meter. Lower the meter with the white disc at the bottom of the plastic tube into the suspension, until the disc is no longer visible when viewed from the top (Figure A2-2 A). Place a moistened finger over the top of the tube and withdraw the meter with a level of liquid in the tube. The level can be read against the coloured scale, which corresponds with the photographs and indicates whether the soil is non-sodic, sodic or highly sodic (Figure A2-2 B).

After checking for sodicity, invert the jar vigorously 15 times and allow to stand for a further 15 minutes. If you previously scored the jar clear and so non-sodic, but it now remains cloudy, the soil is likely to disperse not due to high sodium, but from structural breakdown due to mechanical cultivation.

Record the level of sodicity or mechanical dispersion on the Field Recording Sheet.



Figure A2-2. A. Left: Lowering the meter into the soil/water suspension until the white disc is no longer visible. B. Right: Reading the water level against the scale. (Source: Cox et al. 1999.)

Saline and sodic soil hazard

Saline soils: sandy or loamy soils (i.e. top layer in your profile) are saline if EC_{1:5} is above **0.40** dS/m (see Tables A2-1 and A2-2). Clay soils (i.e. bottom layers in your profile) are saline if EC_{1:5} is above **0.70** dS/m (see Tables A2-1 and A2-2). Saline soils comprise ‘flocculated clays’ (i.e. fluffy or loosely aggregated clay particles). Consequently, these saline topsoils or surface layers with salt efflorescences are prone to wind erosion. However, if these saline soils with relatively freely draining topsoils are not treated with ‘calcium-based soil amendments’ they will likely transform to ‘**sodic soils**’ over time, due to leaching with rainwater (i.e. low levels of salinity) (see Fitzpatrick et al. 1994 for examples). This will occur because of the leaching of the high levels of soluble salts and the formation of sodic soils with resultant low levels of total salt and high levels of exchangeable sodium (Na).

Sodic soils are characterised by low permeability and thus restricted water flow because the clay and organic fractions of these soils are dispersed (i.e. medium sodicity if the solution above the sediment in the dispersibility test shown in Table A2-2 is **cloudy**; very sodic if the solution above the sediment in the dispersibility test shown in Table A2-2 is **densely opaque**).

Sodic soils develop very poor structure and drainage over time because sodium ions on clay particles cause the soil particles to deflocculate, or disperse. Sodic soils are hard and cloddy when dry and tend to crust (Northcote and Skene 1972). Water intake is usually poor with sodic soils, especially those high in silt and clay. Poor plant growth and germination are also common.

Applying especially gypsum (highly soluble salt) and lime to clayey sodic soils, which have good drainage (for example, following the excavation of drains in poorly drained soils), will likely be most beneficial).

Table A2-2. Salinity hazard as defined by the electrical conductance of a saturation extract (EC_{se}) and 1:5 soil:water extract (i.e. soil is extracted with distilled water)¹

Salinity hazard	EC _{se} dS/m	Effects on plant yield	EC _{1:5} (dS/m) 1:5 Soil/Water Extract (dS/m)				
			Loamy sand	Loam	Sandy clay loam	Light clay	Heavy clay
Non-saline	<2	Negligible effect	<0.15	<0.17	<0.25	<0.30	<0.4
Slightly saline	2-4	Very sensitive plants affected	0.16-0.30	0.18-0.35	0.26-0.45	0.31-0.60	0.41-0.80
Moderately saline	4-8	Many plants affected	0.31-0.60	0.36-0.75	0.46-0.90	0.61-1.15	0.81-1.60
Very saline	8-16	Salt tolerant plants unaffected	0.61-1.20	0.76-1.45	0.91-1.75	1.16-2.30	1.60-3.20
Highly saline	>16	Salt tolerant plants affected	>1.20	>1.45	>1.75	>2.30	>3.20

EC 1:5 (EC_{1:5}) — the electrical conductance of a 1:5 soil:water extract (i.e. soil is extracted with distilled water) is normally expressed in units of Siemens (S) or deciSiemens (dS) per meter at 25°C. While the EC_{1:5} method is quick and simple, it does not take into account the effects of soil texture. It is therefore inappropriate to compare the EC_{1:5} readings from two soil types with different textures. It is possible to approximately relate the conductivity of a 1:5 soil-water extract (EC_{1:5}) to that of the saturation extract (EC_{se}) and predict likely effects on plant growth. The above criteria are used for assessing soil salinity hazard and yield reductions for plants of varying salt tolerance; EC_{se} is saturated paste electrical conductivity (after Richards 1954) and EC_{1:5} is the corresponding calculated electrical conductivity of a 1:5 soil:water extract for various soil textures.

Managing sodic soils

Sodic soils are prone to dispersion and erosion, even in arid areas where infrequent heavy rain events can cause rapid erosion, particularly on sloping land. Gypsum is usually applied to agricultural land to counteract sodicity, but is difficult to treat in subsoils. If a trench is excavated, it provides an opportunity to add gypsum to sodic soils when back-filling. To be effective, gypsum needs rain to dissolve it so the calcium can displace sodium from clay particles and assist in aggregation. The clay-rich soils in the LMRIA require 10 times more gypsum and for this reason generally it is not economically viable unless the area being treated is very small. This has been shown in a number of trials conducted on the LMRIA.

Appendix 4: Acid sulfate soil materials and pH tests

Acid sulfate soil materials

Acid sulfate soils (ASS) are those soils in which sulfuric acid may be produced, is being produced, or has been produced in amounts that have a lasting effect on main soil characteristics (Pons 1973). This general definition includes:

- (i) potential
- (ii) actual (or active)
- (iii) post-active ASS

which are the three broad generic soil types that continue to be recognised (for example, Fanning 2002). However, definitions of these broad generic types of ASS can be confusing and the Acid Sulfate Soil Working Group of the International Union of Soil Sciences agreed to adopt changes to the classification of ASS materials (Sullivan et al. 2010). This was also adopted

- (i) by the Scientific Reference Panel of the Murray-Darling Basin Acid Sulfate Soils Risk Assessment Project for use in detailed assessment of acid sulfate soil in the Murray-Darling Basin
- (ii) in the 2nd edition of the Australian Soil Classification (Isbell and National Committee on Soils & Terrain 2016).

This report follows these recommendations. Acid sulfate soils are essentially soils containing detectable sulfide minerals, principally pyrite (FeS_2) or monosulfides (FeS).

The definitions used in this report are:

Sulfuric material

Sulfuric material is soil material that has a pH less than 4 (1:1 by weight in water, or in a minimum of water to permit measurement), as currently defined in the 2nd edition of the Australian Soil Classification (Isbell and National Committee on Soils & Terrain 2016).

Sulfidic materials

Sulfidic materials are soil materials containing detectable sulfide minerals. The intent is for this term to be used in a descriptive context (for example, sulfidic soil material or sulfidic sediment) and to align with general definitions applied by other scientific disciplines such as geology and environment science (for example, sulfidic sediment). The method with the lowest detection limit is the Cr-reducible sulfide method, which currently has a detection limit of 0.005%; other methods (for example, X-ray diffraction, visual identification, Raman spectroscopy or infra-red spectroscopy) can also be used to identify sulfidic materials.

Note that this term differs from previously published definitions in various soil classifications (for example, Isbell 1996).

Hypersulfidic material (Isbell and National Committee on Soils & Terrain 2016).

Hypersulfidic material is a sulfidic material that has a field pH of 4 or more and is identified by experiencing a substantial* drop in pH to <4 (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:

- i) until the soil pH changes by at least 0.5 pH unit to below 4; or

ii) until a stable** pH is reached after at least 8 weeks 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.

Hyposulfidic material (Isbell and National Committee on Soils & Terrain 2016):

Hyposulfidic material is a sulfidic material that

(i) has a field pH of 4 or more

(ii) does not experience a substantial drop in pH to <4 (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.

Monosulfidic materials

These are soil materials with an acid volatile sulfide content of 0.01%S or more (Isbell and National Committee on Soils & Terrain 2016). Monosulfidic materials are subaqueous or waterlogged organic-rich materials that contain appreciable concentrations of monosulfides. Monosulfidic black oozes are specific materials characterised by their gel-like consistence. Monosulfidic materials have a **high index of squishiness or n-Value** as estimated in the field, which is a field estimate of mechanical properties that describes the ability of a saturated soil to support a load. (See field method below to estimate **n-Values**.)

Non-acid sulfate soil materials

In addition, the Scientific Reference Panel of the Murray-Darling Basin Acid Sulfate Soils Risk Assessment Project agreed to identify '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 (for example, 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). The acidity present in field soils may also be due to the accumulation of acidic organic matter and/or the leaching of bases. These acidic soil materials may also pose a risk to the environment.

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
 - i) 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
 - ii) soil materials with a pH_w ≥ 4 but <5.5 in the field.
2. **Other soil materials** — soils that do not have acid sulfate soil (or other acidic) characteristics.

Testing for presence of soil carbonates

Hydrochloric acid (HCl) is used when performing tests to assess the presence of carbonates in soil material. HCl is strongly acidic and is very corrosive to skin; therefore, caution is required when using it. Store HCl separately from buffer solutions, as HCl gas may slowly diffuse through the plastic bottles and alter the buffer solutions.

Field pH test (pH_F)

The pH_F test measures the existing acidity of a soil:water **paste**, and is therefore used to help identify if sulfuric, hyposulfidic and hypersulfidic materials (see previous section for definitions) are present. If the measured pH of the soil paste is pH_F < 4, oxidation of sulfides has probably occurred in the past, indicating the presence of sulfuric material. The pH_F test does not detect any unoxidised sulfides (i.e. hypersulfidic and hyposulfidic materials). For this reason, this test must be used in conjunction with the pH_{incubation} test.

Making a soil:water paste is more practical for field situations and is recommended for ASS field pH (pH_F) tests. This is detailed in the procedure below. It is recommended that short test tubes are used for pH_F tests as they are easy to clean. Further, the paste must be stirred using a stirring implement (for example, a skewer or strong toothpicks). Stirring the paste well will enhance the accuracy of the pH result, as the electrode will get good contact with the soil.

Procedural outline for field pH_F testing

Incubation (ageing) testing

This method, which is often considered to represent a more realistic scenario for acid sulfate soil testing, is based on the 'incubation' (or ageing) of soil samples. A number of specific techniques are employed, but all are based on keeping the sample moist for a specified period (usually a number of weeks; recent recommendations have increased the period from 8 to 19 weeks), which allows slow oxidation of sulfide minerals to occur. Although this may mimic nature more closely and does not force reactions to occur (as with the peroxide test) or rely on total 'potential reaction', it can be argued that the complex processes occurring in the field are not adequately reproduced during this laboratory ageing — for example, complex processes including exchange with subsurface waters (containing ANC) or biogeochemical reactions. These factors should also be taken into consideration wherever possible, although they often require a thorough understanding of water movement (for example, groundwater), and are often site- and scenario-specific.

- Bulk soil samples (typically >500 g) should be placed in pre-labelled, thick, sealable plastic bags and mixed for pH analysis and bulk storage.
- Two sub-samples from the layers should be placed in two separate chip-trays (Fitzpatrick et al. 2010a).
- One chip-tray should be used to display morphologically representative aggregates for each of the sampled layers (compartments filled to ¾ full with preferably undisturbed clods/samples) for later visual reference (Figure A3-1).
- The second chip-tray for the acid sulfate soil incubation test (pH_{incubation}) should be stored in the shed or laboratory (compartments filled to 1/3 full with disturbed crushed samples and moistened with distilled or deionised water).
- Each compartment is to be adjacently labelled (on the inside of the lid) with the layer sample ID, and on the outside of the chip-tray labelled with survey locations and collection date (Figure A3-2).

Measuring pH_{incubation} is the standard method used in the current Australian Soil Classification (Isbell and National Committee on Soils and Terrain 2016). The method has been described in more detail by Fitzpatrick et al. (2010a). These measures are used to help determine the various types of acid sulfate soil materials present by undertaking the following range of pH measurements:

- pH_{incubation} at time zero (T 0) to estimate the field status of soil acidity based on the soil pH measurement (in a minimum of water to permit measurement) at the time of sampling in the field directly in the chip-tray to identify **sulfuric materials**; and after incubation the presence of **hypersulfidic or hyposulfidic materials**.



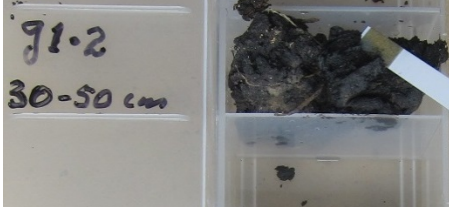


Photograph of soil profile from Mobilong	Depth (cm)	ID No	Chip-tray displaying representative soil aggregates with Merck strips
	0-30	g1.1	
	30-50	g1.2	
	50-60	g1.3	
	60-80 80-100+	g1.4	

Figure A3-1. Photograph of soil profile from Mobilong (left) and photograph of chip-tray showing soil pH as indicated by Merck pH strip colours at the time of sampling (T 0, at sampling in the field). Source: Author.

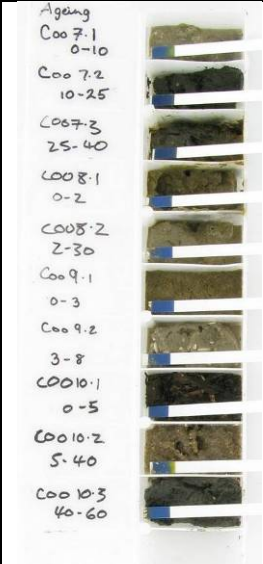
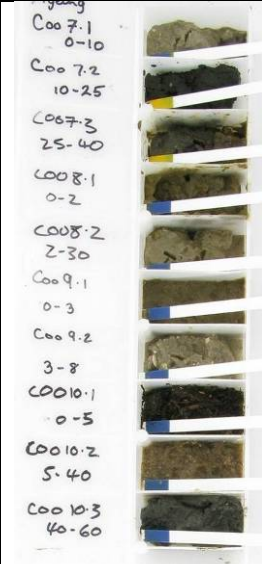
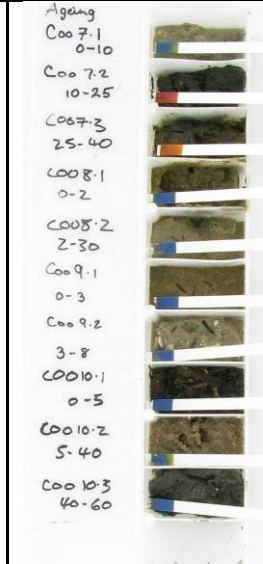
Field testing (T 0)	8 weeks (T +8)	10 weeks (T +10)
		

Figure A4-2. Time sequence (T 0, T +8, T +10) for a chip-tray of soils from the Coorong in South Australia undergoing incubation. Each photograph shows soil pH as indicated by Merck pH strip colours:

- (i) at T 0, at sampling in the field
- (ii) at T +8, after incubation for 8 weeks
- (iii) at T +10, at 10 weeks.

Here pH indicator strip colours indicate that most samples remain alkaline or neutral (blue colour >pH 7) with only two becoming acid after incubation for 10 weeks (red or pink colour - pH 3.9 to 4) (Fitzpatrick et al. 2008b). NOTE — The preferred method is to measure the pH of the whole soil using a calibrated pH meter. (Source: Fitzpatrick et al. 2008b.)

Field pH meter

1. Calibrate battery-powered field pH meter.
2. Prepare the test tubes in the test tube rack. Make sure the rack is marked with the depths so there is no confusion about the top and bottom of the profile. Use of separate racks for the pH_F and pHFOX tests is recommended, as contamination may occur when the pHFOX reactions are violent.
3. Conduct tests at intervals on the soil profile of 25 mm or at least one test per horizon or layer — whichever is lesser.
4. Remove approximately 1 teaspoon of soil from the profile. Place approximately ½ teaspoon of the soil into the pH_F test tube and place ½ teaspoon of the soil into the pHFOX test tube for the corresponding depth test. It is important that these two sub-samples come from the same depth and that they are similar in characteristics.
5. Place enough deionised or rainwater (pH 5.5) in the pH_F test tube to make a paste similar to 'grout mix' or 'white sauce', stirring with a skewer or similar to ensure all soil 'lumps' are removed. Do not leave the soil samples in the test tubes without water for more than 10 minutes.
6. This will reduce the risk of sulfide oxidation — the pH_F is designed to measure existing acidity; any oxidation subsequent to the soil's removal from the ground will not reflect the true situation. In some instances, in less than 5 minutes, monosulfidic material may start to oxidise and substantially affect the pH_F results.
7. Immediately place the spear point electrode (preferred method) into the test tube, ensuring that the spear point is totally submerged in the soil:water paste. Never stir the paste with the electrode. This will damage the semi-permeable glass membrane.
8. Measure the pH_F using a pH meter with spear point electrode.
9. Wait for the reading to stabilise and record the pH measurement. All measurements and pH calibration should be recorded on a data sheet.

Field test to estimate n-Value via the index of squishiness

The n-Value via the index of squishiness is a field estimate of mechanical properties that describes the ability of a saturated soil to support a load. The n-Value (sometimes referred to as 'index of squishiness') concept was developed by Pons and Zonneveld (1965) to define the degree of physical ripening of soft sediments (i.e. '**pelagic ooze**' materials) as they dewater. It is a measure of the physical bearing capacity of a soil material. The following definition has been modified from Fanning and Fanning (1989) and Soil Science Division Staff (2017, p189-190). It is mathematically defined for Soil Taxonomy for soil materials that are not thixotropic as follows:

$$n=(A-0.2R)/(L+3H)$$

A=% water in soil in field condition
(calculated on a dry-soil basis);

R=% silt + sand

L=% clay (<2 µm);

H=% organic matter (organic carbon x 1.724).

Photograph of Professor JL Pons undertaking the 'index of squishiness' or n-Value test. The photograph was taken by Rob Fitzpatrick in the Mekong Delta, Vietnam in 1992 during the 4th International Acid Sulfate Soil Conference.



This simple field test involves squeezing a fist-full of soil. If the soil flows between the fingers but with difficulty (i.e. if it is slightly fluid), the n-Value is likely between 0.7 and 1.0. If the soil flows easily (i.e. if it is moderately fluid or very fluid), it is greater than 1.0. If no soil flows between the fingers (non-fluid), it is less than 0.7. An n-Value of 0.7 or more is used in Soil Taxonomy (Soil Science Division Staff, 2017; Soil Survey Staff, 1999; 2014) to define certain classes considered to have **a low bearing capacity**. Sandy materials are considered to be physically ripe regardless of their water content.

Table A4-1. Index of squishiness classes or n-Values

n-Value	Definition/explanation
<0.7	Ripe material is firm, not particularly sticky, and cannot be squeezed between fingers.
0.7-1.0	Nearly ripe material is fairly firm; it tends to stick to the hands, and can be kneaded but not squeezed between fingers. Its water content is between 55-65%. It is not churned up; it will support the weight of stock and ordinary vehicles.
1.0-1.4	Half ripe mud is fairly soft; sticky; and can be squeezed between fingers. Its water content is between 65-75% and its mechanical strength when disturbed is low. A man will sink ankle- to knee-deep unless supported by vegetation.
1.4-2.0	Practically unripe mud is very soft; it sticks fast to everything, and can be squeezed between fingers by very gentle pressure. Its water content is between 70-80%. A man will sink to his thighs unless supported by vegetation.
>2.0	Totally unripe mud is fluid; it flows between fingers. In predominantly mineral sediments the water content is >80% by mass.

References

- Fanning, D.S. and Fanning, M.C.B. (1989). Soil: Morphology, genesis, and classification. John Wiley and Sons, New York.
- Pons J.L. and Zonneveld, I.S. (1965). Soil ripening and soil classification. Initial soil formation in alluvial deposits and classification of the resulting soils. Inst. Land Reclam. and Impr. Pub. 13. Wageningen, The Netherlands. 128pp.

Appendix 5: Soil identification key

Acid sulfate and salt-affected soils

Before we can manage acid sulfate soil (ASS) and salt-affected soil landscapes, we first have to define the type of soil landscape based on the hydrological characteristics and the category of salt-affected soil and ASS from its dominant geochemical properties. Salt-affected soils and ASS form under the following vastly different environmental conditions, under the influence of diverse hydrological, morphological, geochemical, mineralogical and physical processes.

Groundwater associated salinity (GAS)

This comprises salt-affected soils in areas that have had direct or capillary contact with saline groundwater water tables, and categories defined by the following hydrological and geochemical environments:

1. primary (natural) or secondary (anthropogenic)
2. alkaline (sodium carbonate dominant, pH >9)
3. halitic (sodium chloride dominant)
4. gypsic (gypsum/calcium sulfate dominant)
5. sodic (high exchangeable sodium percent on clay surfaces).

Poor drainage management typically results in saline groundwater tables rising near the surface in the LMRIA, hence drainage is critical to reducing GAS.

Non-groundwater associated salinity (NAS)

This comprises salt-affected soils in rain fed areas that have no direct contact with saline groundwater water tables, and with categories defined by the following soil chemical environments:

1. sodic (ESP ≥ 5)
2. saline (EC_{se} ≥ 2 dS/m) conditions in the solum (A- and B-horizons, typically <1.2 m deep).

Irrigation associated salinity (IAS)

This comprises salt-affected soils in irrigated areas with shallow (surface IAS) or deep (subsoil IAS) saline water tables.

Inland and coastal acid sulfate soils (ASS)

This is the common name given to all those soils with soil materials affected by iron sulfide minerals. These soils may either contain sulfuric acid or have the potential to form sulfuric acid in amounts that have a lasting effect on the main soil characteristics (Pons 1973) or cause deoxygenation or release contaminants when the sulfide minerals are exposed to oxygen. In general, the following two main genetic types of ASS materials are recognised (Fanning 2002):

- potential or unripe ASS materials containing pyrite and/or monosulfides that are still waterlogged (i.e. contain sulfidic or monosulfidic materials)
- actual, active or raw ASS material containing sulfuric acid and pyrite at shallow depths (sulfuric material).

However, it is impossible to separate the effects of salinity totally from those of ASS (especially those with sulfuric materials) as they go hand in hand, while the level of salt that might be present in an ASS is of utmost importance in determining how certain subtypes of ASS will behave from a physical and chemical point of view.

Classification of acid sulfate and salt-affected soils

Australia's current national soil classification (2nd edition of the Australian Soil Classification by Isbell and National Committee on Soils & Terrain 2016) and other internationally recognised classification systems such as Soil Taxonomy (Soil Survey Staff 2014; 1999) require considerable expertise and experience to be used effectively. More importantly, these classification systems do not yet incorporate new acid sulfate soil terminologies such as:

1. monosulfidic, hypersulfidic and hyposulfidic material (Isbell and National Committee on Soils & Terrain 2016)
2. subaqueous soils, a term which is used in the nationally consistent legend of 'The Atlas of Australian Acid Sulfate Soils' (Fitzpatrick et al. 2010b; available on the Australian Soil Resource Information System: http://www.asris.csiro.au/index_ie.html).

To assist users to identify types and subtypes of soils, a user-friendly soil identification key was developed to more readily define and identify the various types and subtypes of acid sulfate soil and non-acid sulfate soil (see Fitzpatrick et al. 2010b; Fitzpatrick 2013). The key is designed for people who are not experts in soil classification systems such as the Australian Soil Classification (Isbell and National Committee on Soils & Terrain 2016). Hence it has been used to deliver soil-specific land development and soil management packages to advisors, planners and engineers working in the Murray-Darling Basin.

The soil identification key uses non-technical terms to categorise acid sulfate soils and other soils in terms of attributes that can be assessed in the field by people with limited soil classification experience. Attributes include water inundation (subaqueous soils), soil cracks, structure, texture, colour, features indicating waterlogging and 'acid' status — already acidified, i.e. sulfuric material, or with the potential to acidify, i.e. sulfidic material — and the depths at which they occur or change in the soil profile.

The key consists of a systematic arrangement of soils into 5 broad acid sulfate soil types, each of which can be divided into up to 6 soil subtypes. The key layout is bifurcating, being based on the presence or absence of particular soil profile features (i.e. using a series of questions set out in a key). A soil is allocated to the first type whose diagnostic features it matches, even though it may also match diagnostic features further down the key. The key uses a collection of plain-language names for types and subtypes of ASS in accordance with the legend for the Atlas of Australian Acid Sulfate Soils (Fitzpatrick et al. 2010b; Fitzpatrick 2013). It recognises the following 6 acid sulfate, salt-affected and anthropogenic soil types (Table A5-1):

1. subaqueous soils
2. organic soils
3. cracking clay soils
4. sulfuric soils
5. hypersulfidic soils
6. hyposulfidic soils
7. Strongly waterlogged sodic soils
8. Strongly waterlogged saline & sodic soils
9. Strongly waterlogged saline soils
10. Anthropogenic soils
11. Other soils

These are further subdivided into 21 soil subtypes (Table A5-2) based on occurrence of sulfuric material, hypersulfidic material, clayey or sandy layers; monosulfidic material, firmness, sodicity and salinity.

Table A5-1. Soil identification key for soil types. (modified from Fitzpatrick et al. 2017)
After finding the soil type, use Table A5-2 to find the soil subtype

Diagnostic features for Soil Type	Soil Type
<p>Does the soil occur in shallow permanent flooded environments (typically not greater than 2.5 m)?</p> <p>NO ↓</p> <p>YES →</p>	 <p>Subaqueous soil</p>
<p>Does the upper 80 cm of soil consist of more than 40 cm of organic material (peat)?</p> <p>NO ↓</p> <p>YES →</p>	 <p>Organic soil</p>
<p>Does the soil develop cracks at the surface OR in a clay layer within 150 cm of the soil surface OR have slickensides (polished and grooved surfaces between soil aggregates), AND is the subsoil uniformly grey coloured (poorly drained or very poorly drained)?</p> <p>NO ↓</p> <p>YES →</p>	 <p>Cracking clay soil</p>

Does a sulfuric layer (pH <4) occur within 150 cm of the soil surface,
AND is the subsoil uniformly grey coloured (poorly drained)?

NO
↓

YES →



Sulfuric soil

Does sulfidic material (pH >4 which changes on ageing to pH <4) occur within 150 cm of the soil surface,
AND is the subsoil uniformly grey coloured (poorly drained)?

NO
↓

YES →



Hypersulfidic soil



Does sulfidic material (pH >4 which does not change on ageing to pH <4) occur within 150 cm of the soil surface,
AND is the subsoil uniformly grey coloured (poorly drained)?

NO
↓

YES →



Hyposulfidic soil

<p>Does the Top Layer have: (i) uniform grey colour with grey (bleached) mottles?</p> <p>Does Bottom Layer 1 have: (i) uniform yellow colour with or without some carbonate accumulations (ii) Test sample for dispersion to indicate sodicity (Appendix 2)?</p> <p>Does Bottom Layer 2 have: (i) yellowish brown colour with bluish-grey mottles, slickensides and/or carbonate accumulations?</p> <p>NO ↓</p> <p>YES →</p>	 <p>Strongly waterlogged sodic soil</p>
<p>Does the Surface Layer have features that indicate salinity such as white salt stains when dry, presence of sea barley grass or samphire?</p> <p>Does the Top Layer have: (i) uniform grey colour with red stains and/or grey (bleached) mottles, (ii) EC meter reading is more than 0.7 dS/m?</p> <p>Does Bottom Layer 1 have: (i) dark grey colour with yellow and some red mottles, (ii) EC meter reading is more than 0.4 dS/m, (iii) Test sample for dispersion to indicate sodicity (Appendix 2)?</p> <p>Does Bottom Layer 2 have: (i) Bluish-grey colour with yellow mottles and/or carbonate accumulations, (ii) EC meter reading is more than 0.7 dS/m (Appendix 2)?</p> <p>NO ↓</p> <p>YES →</p>	 <p>Strongly waterlogged saline & sodic soil</p>



<p>Does the Surface Layer have features that indicate salinity such as bare ground, white salt stains when dry, presence of sea barley grass or samphire?</p> <p>Does the Top Layer have: (i) uniform dark greyish colour with red stains and/or grey (bleached) and black mottles, (ii) EC meter reading is more than 0.4 dS/m?</p> <p>Does Bottom Layer 1 have: (i) grey colour with yellow mottles, (ii) EC meter reading is more than 0.7 dS/m, (iii) Test sample for dispersion to indicate sodicity (Appendix 2)?</p> <p>Does Bottom Layer 2 have: (i) Bluish-grey colour with yellow mottles and/or carbonate accumulations, (ii) EC meter reading is more than 0.4 dS/m (Appendix 2)?</p> <p>NO ↓</p> <p>YES →</p>	 <p>Strongly waterlogged saline soil</p>
<p>Does the Surface Layer have features that indicate soil has previously been transported (e.g. strongly compacted, raised levee bank or road)?</p> <p>Does the Top and Bottom Layers have non-uniform mixed/stratified layers (soil colour, texture and consistency)?</p> <p>NO ↓</p> <p>YES →</p>	 <p>Anthropogenic soil</p>
<p>Other soils</p>	<p>Other soils</p>

Table A4-2. Soil identification key for soil subtypes in the LMRIA

Soil type	Diagnostic features for soil subtype		Soil subtype
Subaqueous soil	Does sulfuric material occur within 150 cm of the soil surface?	Does the upper 80 cm of soil consist of more than 40 cm of organic material (peat)?	
	YES →	YES →	Sulfuric subaqueous organic soil
	NO ↓	NO ↓	
		Does a clayey layer with slickensides occur within 150 cm of the soil surface?	
	YES →	YES →	Sulfuric subaqueous clay soil
	NO ↓	NO ↓	
		YES →	Sulfuric subaqueous soil
	Does hypersulfidic material (pH >4 which changes on ageing to pH <4) occur within 150 cm of the soil surface?	Does the upper 80 cm of soil consist of more than 40 cm of organic material (peat)?	
	YES →	YES →	Hypersulfidic subaqueous organic soil
	NO ↓	NO ↓	
		Does a clayey layer with slickensides occur within 150 cm of the soil surface?	
	YES →	YES →	Hypersulfidic subaqueous cracking clay soil
	NO ↓	NO ↓	
		YES →	Hypersulfidic subaqueous clay soil

	Does hyposulfidic material (pH >4 which does not change on ageing to pH <4) occur within 150 cm of the soil surface?	Does the upper 80 cm of soil consist of more than 40 cm of organic material (peat)?	Hyposulfidic subaqueous organic soil
	YES → NO ↓	YES → NO ↓	
	NO ↓	Does a clayey layer with slickensides occur within 150 cm of the soil surface?	Hyposulfidic subaqueous cracking clay soil
		YES → NO ↓	Hyposulfidic subaqueous clay soil
Not subaqueous soil	Does sulfuric material occur within 150 cm of the soil surface?	YES →	Subaqueous soil
		NO ↓	
	YES → NO ↓	Does the upper 80 cm of soil consist of more than 40 cm of organic material (peat)?	Sulfuric organic soil
	NO ↓	Does a clayey layer with slickensides occur within 150 cm of the soil surface?	Sulfuric cracking clay soil
		YES → NO ↓	

	YES →	YES →	Sulfuric clay soil
Does hypersulfidic material (pH >4 which changes on ageing to pH <4) occur within 150 cm of the soil surface?		Does the upper 80 cm of soil consist of more than 40 cm of organic material (peat)?	
YES →		YES →	Hypersulfidic organic soil
NO ↓		NO ↓	
		Does a clayey layer with slickensides occur within 150 cm of the soil surface?	
		YES →	Hypersulfidic cracking clay soil
NO ↓		NO ↓	
YES →		YES →	Hypersulfidic clay soil
Does hyposulfidic material (pH >4 which does not change on ageing to pH <4) occur within 100 cm of the soil surface?		Does the upper 80 cm of soil consist of more than 40 cm of organic material (peat)?	
YES →		YES →	Hyposulfidic organic soil
NO ↓		NO ↓	
		Does a clayey layer with slickensides occur within 150 cm of the soil surface?	
		YES →	Hyposulfidic cracking clay soil
NO ↓		NO ↓	

		YES → NO ↓	Hyposulfidic clay soil
Strongly waterlogged sodic soil YES → NO ↓	Does a clayey layer with slickensides occur within 150 cm of the soil surface?	YES → NO ↓	Strongly waterlogged sodic cracking clay soil
		YES →	Strongly waterlogged sodic clay soil
Strongly waterlogged saline and sodic soil YES → NO ↓	Does a clayey layer with slickensides occur within 150 cm of the soil surface?	YES → NO ↓	Strongly waterlogged saline and sodic cracking clay soil
		YES →	Strongly waterlogged saline and sodic clay soil
Strongly waterlogged saline soil YES → NO ↓	Does a clayey layer with slickensides occur within 150 cm of the soil surface?	YES → NO ↓	Strongly waterlogged saline cracking clay soil
		YES →	Strongly waterlogged saline clay soil

Waterlogged soil			
YES →	YES →	YES →	Waterlogged clay soil
NO ↓			
Anthropogenic soil	Does a clayey layer occur within 150 cm of the soil surface?		
YES →	YES →	YES →	Anthropogenic clay soil
NO ↓	NO ↓		
	YES →	YES →	Anthropogenic soil
Other soils	YES →	YES →	Other soils

Appendix 6: Laboratory acid sulfate soil analysis methods

A summary of methods for laboratory analyses to be conducted is presented in Table A6-1. Following sampling, the soils will be transferred to the laboratory and kept cool at approximately 4°C until analysed. Samples will be stored in chip trays to conduct incubation tests to follow the course of potential acidification and determine ASS status. Oven and air dried/moist samples and chip tray samples will be kept for long-term storage to allow for future re-sampling and analyses, if required.

Samples for acid-base accounting (ABA) will be rapidly air dried at 80°C. Moisture contents will be recorded and bulk densities estimated. Samples for ABA analysis will be sent to the Environmental Analysis Laboratory of Southern Cross University (accredited laboratory which is most experienced in Australia for acid sulfate soil analysis).

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. It is a technique, which balances the potential acid generated from the sum of sulfide-S (S_{CR} or chromium-reducible S) and the titratable actual acidity (TAA) of the soil (AGP), with the total amount of potential alkalinity/acid neutralising capacity (ANC) generated. Details of the chemical methods used are given in Ahern *et al.* (2004). The ANC is usually only routinely measured when soil pH_{KCl} (measured in a high ionic strength KCl solution) is greater than pH 6.5. When pH_{KCl} is less than 4.5, this indicates that secondary less soluble acid-producing minerals such as jarosite are likely to be present. This is measured as retained acidity. The net acid generating potential (NAGP) is the acid generating potential (AGP) plus retained acidity minus ANC, which gives an indication of acid generation *if all components react fully*. Arguments against this technique include the fact that the carbonate may not be available to soil solutions (e.g. if it is coated and protected with organic material or iron oxides) or if it is in a form that is not particularly reactive (e.g. iron carbonates and dolomite (calcium magnesium carbonate) have much slower reaction kinetics than calcite). Net acidity aims to take this into account by introducing a “fineness factor”, whereby net acidity is calculated by dividing the ANC by a factor of 1.5. However, the oxidation of pyrite may also cause pyrite to not react fully if it becomes coated with protective secondary minerals. Thus, it may be difficult to assess acidification scenarios effectively.

The standard ABA applicable to acid sulfate soil is as described in Ahern *et al.* (2004) and summarised here. The equation below shows the calculation of Net Acidity (NA):

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

*ANC = Acid Neutralising Capacity

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

Potential Sulfidic Acidity (PSA)

The potential sulfidic acidity is most easily and accurately determined by assessing the chromium reducible sulfur (CRS or S_{CR}). This method was developed specifically for acid sulfate soil materials 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 method (Method Code 22B) and its conversion to PSA.

Existing Acidity

Existing acidity 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 material that has already oxidised. TAA measures the sum of both soluble and exchangeable acidity in acid sulfate soil material and non-acid sulfate soil material. The retained acidity (RA) is an operational term used to estimate 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 RA are given by Ahern *et al.* (2004). It is noted that many wetlands that had sulfuric ($\text{pH} < 4$) materials present in the Millennium Drought may still have jarosite present in deeper layers.

Acid Neutralising Capacity (ANC)

Soils with pH_{KCl} 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 calculated by titration, and alkalinity present is expressed in CaCO_3 equivalents. By definition (Ahern *et al.* 2004), any acid sulfate soil material with a $\text{pH}_{\text{KCl}} < 6.5$ has a zero ANC.

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.

pH testing after peroxide treatment

Hydrogen peroxide (H_2O_2) is a strong oxidising agent and is used to encourage the oxidation of sulfide minerals (principally pyrite: FeS_2) and the subsequent production of acidity. Since peroxide is a strong oxidising agent, it can be argued that the resultant pH measured is a worst-case scenario. In nature, the presence of carbonate minerals such as calcite (CaCO_3) may neutralise acid produced, however, in some cases the carbonate may not fully dissolve due to slow dissolution rates (reaction kinetics). The dissolution rates of individual minerals may be controlled by a number of factors, hence additional tests based on measuring the carbonate content are recommended.

Table A6-1. List of methods for laboratory analysis conducted.

Data and Analysis	Objective	Method
Laboratory Analysis		
pH _{water} (pH _w)	Measures the current sampled status of the soil acidity or alkalinity	pH meter; 1:1 soil:water (Rayment and Higgins on 1992)
pH _{peroxide} (pH _{ox})	Measures the potential end oxidized status of the soil pH	pH meter; Method 4E1 (Rayment and Higgins on 1992)
pH _{incubation} (pH _{inc})	Represents a scenario for soil sample on exposure to air (oxygen) for a specified period of time	Fitzpatrick <i>et al.</i> 2010
Electrical conductivity	Measure of the soil salt content	(Rayment and Higgins on 1992)
Soil texture	Assessment of texture to assist with interpretation of acid base accounting results	Hand texture determination placed into 3 classes – coarse, medium, fine
pH _{KCl}	pH value. Provides trigger value (pH _{KCL} >6.5) for deciding to test for acid neutralising capacity.	pH meter. Method 23A (Ahern <i>et al.</i> 2004)
Chromium reducible sulfur (S _{CR})	Identifies presence of sulfides. For acid base accounting	Method 23B (Ahern <i>et al.</i> 2004)
Titrateable actual acidity (TAA)	Identifies soil acidity. For acid base accounting.	Method 23F (Ahern <i>et al.</i> 2004)
Acid neutralising capacity (ANC) (where pH _{KCl} >6.5)	Identifies neutralising capacity of soil. For acid base accounting.	Method 19A2 (Ahern <i>et al.</i> 2004)
Retained acidity (RA)	Identifies stored soil acidity. For acid base accounting.	Method 20J (Ahern <i>et al.</i> 2004)
Net acidity (NA)	Identifies the soil acidity (or alkalinity)	Calculated (Ahern <i>et al.</i> 2004)

For coastal and inland acid sulfate soils in Australia, the action criteria or trigger values for the preparation of an ASS management plan are shown in Table 3.

Table A6-2: Criteria indicating the need for an ASS management plan based on texture range and chromium reducible sulfur concentration and amount of soil material disturbed (Dear et al. 2002).

Texture range	S _{CR} (%S)	
	<1000 t disturbed soil	>1000 t disturbed soil
Coarse: Sands to loamy sands	0.03	0.03
Medium: Sandy loams to light clays	0.06	0.03
Fine: Medium to heavy clays	0.10	0.03

The results from incubation experiments (see below) will be compared to these criteria to assess if they are appropriate as a risk management guide for RRP wetlands.

If a positive net acidity results, a theoretical “liming rate” will be calculated which indicates how much limestone would be needed to neutralise the soil. The neutralising requirement calculation includes a 1.5 safety margin for acid neutralisation (an increased safety factor may be required in some cases). This can help guide DEW in the event that limestone is required in the future in any acidic RRP wetlands.

Incubation (ageing) experiments

The third method used, which is often considered to represent a more realistic scenario for ASS testing is based on the ‘incubation’ of soil samples. A number of specific techniques are employed, but all are based on keeping the sample moist for a specified period (usually a number of weeks or months), which allows a more realistic oxidation of sulfide minerals to occur than that produced rapidly during peroxide testing. Although this may mimic nature more closely and does not force reactions to occur (as in the peroxide test) or rely on total ‘potential’ reaction, it can be argued that the complex processes occurring in the field are not represented, *e.g.*, exchange with sub-surface waters (containing ANC) or biogeochemical reactions. These should also be assessed, where possible, but often require a thorough understanding of water movement.

The current practice in the Acid Sulfate Soil Centre (ASSC) is to use all of the above techniques and, where possible, to monitor changes in the field during periods of drying to assess the most likely scenarios of acid generation and neutralisation.

This test used for these acid sulfate soil protocols is a modification of this incubation procedure which involves the following steps:

- Incubate mineral or organic soil materials, which have a natural pH (1:1 soil:water) value > 4, as a layer *ca.* 1 cm thick under moist conditions, while maintaining contact with the air at room temperature.
- Measure the pH and observe whether there is a drop in pH of 0.5 units or more to a value of 4.0 or less, including wetting and drying cycles.
- The duration of incubation shall continue for a “minimum of 8 weeks” until a stable pH is reached (differs from the “fixed 8 weeks” in the formal Australian Soil Classification definition) as described in Sullivan *et al.* 2009.
- Collection and storage of moist samples in plastic chip trays produces similar conditions, and thus chip trays are suitable for incubation testing as described and used in Fitzpatrick *et al.* (2008, 2009a; 2010).

Acid volatile sulfur

Iron-monosulfides (i.e. as found in Monosulfidic Black Oozes), are defined operationally as acid-volatile sulfur (AVS), are readily extracted by the diffusion method described by Hsieh *et al.* (2002) using a modified apparatus (Burton *et al.* 2006). Approximately 2 g of wet sample is equilibrated (orbital shaking at 150 rpm for 18 hrs) with 10 ml of 6M HCl/0.1M ascorbic acid in gas-tight 55 cm³ polypropylene reactors. The evolved H₂S(g) is trapped in 7 ml of 3% Zn acetate in 2 M NaOH, and subsequently quantified via iodometric titration. The quantitative recovery of acid volatile sulfur using this method is 96 ± 4%. Pyrite-S is not extracted by the acid volatile sulfur analytical method employed here (Hsieh *et al.* 2002). The slurry remaining after acid volatile sulfur extraction is diluted to 50 ml with deionised water and centrifuged (4000 g, 10 minutes).

Total carbon and nitrogen

Samples will be analysed for total carbon and nitrogen using a high temperature combustion method (LECO CNS2000 Analyser) described in Rayment and Lyons (2010). Total organic carbon will be obtained by subtracting inorganic carbon from total carbon.

Metal release experiments

Selected samples (one profile from each priority wetland, approximately 64 samples) will be analysed for their potential to release metals during rewetting. Many RRP sites will likely be underwater and approximately neutral pH at the time of sampling so analysis of oxidised samples and/or at the end of the soil incubations may be the preferred approach for assessing risks upon drying and rewetting of wetlands (to be discussed with DEW before commencement). The method is based on the methods from Simpson *et al.* (2010).

Soil samples will be air dried at 40 °C, and 25 g of each sample was weighed into clean acid-washed 250 ml Nalgene extraction bottles and resuspended in 250 ml of deionised water for a period of 24 hours in an end over shaker. Water blanks were run with the batch extraction to monitor water quality throughout the experiment. After 1 hour, a 25 ml aliquot was sampled to measure water quality at the start of the extraction, with the measurements repeated at the end of extraction (24 hours). Water quality measurements included dissolved oxygen, pH, alkalinity/acidity, redox potential (Eh), and specific electrical conductance (SEC).

At the completion of the extraction phase, the samples were centrifuged to settle solids and allow the supernatant to be filtered for chemical analysis using Millex 0.45 micron PVDF syringe filters. Analyses for a suite of major and trace elements including metals, metalloids nutrients were run on the filtered water extracts to provide a detailed profile of each sample's chemistry.

Nitrogen species, Cl and PO₄ will be analysed by colorimetric analysis using an Auto Analyser; Br, F and SO₄ by ion chromatography; and organic carbon by a TOC Analyser. For cation and metal analyses, water samples will be acidified (0.2% nitric acid) and analysed using an inductively coupled plasma-atomic emission spectrometer (ICP-AES) (Varian 730 ES or Agilent 700 series) fitted with an argon sheath torch using in-house method C-229 and operating instructions recommended by the manufacturer. Metals at lower concentration will be analysed by inductively coupled plasma-mass spectrometry (ICP-MS) (Agilent 7500 CE) using operating instructions recommended by the manufacturer.

Results will be compared to typical metal concentrations in River Murray water and ANZECC guideless to protect aquatic ecosystems. Relationships between pH and metal concentration will be plotted.

Mineralogical analysis by X-Ray Diffraction

Selected/priority soil samples (bulk and <2µm fractions), crusts and/or salt efflorescences will be sub-sampled and ground in an agate mortar and pestle for identification of minerals present (*note: a total of 50 samples have been budgeted for*). The resulting fine powders will be either gently back pressed into stainless steel sample holders or lightly front pressed onto silicon low background holders for X-ray diffraction analysis (XRD) analysis. XRD patterns of samples were collected with a PANalytical X'Pert Pro Multi-purpose Diffractometer in 'standard' configuration mode using iron filtered Co K radiation, automatic divergence slit and X'Celerator Si strip detector. The diffraction patterns will be recorded in steps of 0.017° 2 theta with a 0.5 second counting time per step (Fitzpatrick et al. 2017b,c).

Analysis of the XRD patterns were performed using in-house developed XPLOT software and commercial software, HighScore Plus from PANalytical. Mineralogical phase identification was made by comparing the measured XRD patterns with the International Centre for Diffraction Data (ICDD) database of standard diffraction patterns using computer aided search/match algorithms.

Appendix 7: Sampling protocol for microbial DNA analyses

Representative sites sampled for ASS characterisation will be sub-sampled to allow for potential microbial analysis (DNA extraction). Microbial sub-samples will be collected for all individual cores, and soil layers collected in the field.

All microbial sub-samples and chip tray samples will be stored appropriately to allow microbial analysis at the start and end of all lab incubations. It is noted that ASS sampling protocols are designed to minimise microbial activity and cross-contamination. Notwithstanding, additional sterilisation and decontamination measures will be undertaken to:

- Minimise cross contamination between samples and samples layers.
- Keep samples cool in field and freeze as soon as possible prior to or on return to the laboratory.
- Freeze all lab samples (e.g. incubation samples) as soon as sub-sampling has occurred.

Field sample collection and storage protocol:

1. Soil sampling device(s) (e.g. augers, shovels, spatulas, etc) need to be cleaned prior to collecting individual samples as follows:
 - a. Wash sampling device(s) with water and paper towel (or equivalent) to remove any attached debris.
 - b. Rinse with sampling device(s) clean sterile water (using same rinsate water source for every site).
 - c. Wipe surface of sampling device(s) down with ethanol and paper towel (or ethanol wipe).
 - d. Device is then ready for sample collection.
2. Representative soil samples will be taken from each individual soil core, and soil layer within each core (were cores are divided into layers) as follows:
 - a. Remove soil layer of interest from core and place in plastic bag, avoiding contamination between soil layers/samples, and keep cool. Alternatively (or in addition) the outer surface layer of soil could be removed first to avoid cross contamination from the drilling equipment; i.e. sampling from the soil not contacted by the auger).
 - b. As soon as practical, mix the soil sub-sample within a bag to homogenise the sample, take a representative sample (10-15 g) and place in a sterile labelled and capped tube (e.g. Sigma: T1818-500EA, or equivalent), avoiding contamination between soil layers/samples.
 - c. Refrigerate sample immediately and freeze at $<-20^{\circ}\text{C}$ as soon as possible (maintain a record of the time each sample was kept at ambient and refrigerated temperature prior to being frozen).

Lab incubations (ASS incubation samples in chip trays)

Soils for potential DNA extraction analyses are to be collected from all soil subjected to lab incubations (microbial sub-samples will be required from start and end of incubations).

- a. At the time an incubation is initiated, a representative soil sample (10-15 g) needs to be placed in a sterile labelled and capped tube (e.g. Sigma: T1818-500EA, or equivalent), avoiding contamination between soil layers/samples, and frozen immediately.
- b. At the end of a lab incubation, a representative soil sample (10-15 g) needs to be placed in a sterile labelled and capped tube (e.g. Sigma: T1818-500EA, or equivalent), avoiding contamination between soil layers/samples, and frozen immediately.

Appendix 8: Glossary of terms

Acidity:	Acidity of soils is usually not a problem unless the pH drops below 4 or 5. Oxidised acid sulfate soils can have very low pH (2 or less) values and are potentially very corrosive.
Alkalinity:	For the purposes of this investigation, 'alkalinity' describes soils which have an increasingly alkaline trend with depth such that the subsoil pH is greater than 8.5. Alkaline soils may have pH values in excess of 10 and these can be very corrosive.
Aggregate	Unit of soil (clod) that contains groups of micro aggregates.
Amelioration	To make or become better.
Calcareous soil materials:	Carbonate segregations or fine earth (soil matrix) effervescence with 1M HCl. The list of calcareous materials generally increases in hardness and excavation difficulty from segregations or fine earth carbonate to carbonate gravels to 'calcrete' (hard and indurated)
Ironstone gravels:	Ironstone gravel Massive nodular ironstone Ferricrete: The list of ironstone gravelly materials generally increases in hardness and excavation difficulty from pea size gravels to nodular ironstones and 'ferricrete'.
Clay	Soil particles smaller than 0.002 mm. Particles in this size fraction are involved in swelling and shrinking of soils and in holding exchangeable cations. This is the <0.002 mm material as the weight percent of the total <2 mm. The pipette method under 3A (Soil Survey Staff, 2011) is the standard. For soils that disperse with difficulty, the clay percentage commonly is evaluated from the 1500 kPa retention under 4B (Soil Survey Staff, 2011). Carbonate of clay size is included.
Colour-coded maps and the RAG traffic light system	Colour-coded maps have been frequently used by geologists to convey geological information to non-geologists and other specialists (for example, Donnelly and Harrison 2013). The Red-Amber-Green system, also known as the 'RAG' or 'traffic light' system, is a convenient method to facilitate the easy visualisation of complex information or data sets, in a manner that may be easily interpreted and executed for soil hazard. Red is frequently associated with highest risk or hazard, amber moderate risk and green the lowest risk. A red polygon designation on thematic maps signifies 'danger' or 'hazard'. Close liaison between soil scientists and farmers/planners ensures that research investigations are translated to practical outcomes.
Damage	In this context, damage refers to soil structure results from soil compaction, smearing, remoulding or pulverising.
Dispersion	Disintegration of micro aggregates into individual clay, silt and sand grains; the opposite of flocculation.
Duplex	Term applied to soil profiles which have relatively sandy A horizons, more or less sharply separated from underlying relatively clay rich B horizons.
Electrical Conductivity (EC)	Measured in deciSiemens/m (1 dS/m = 100 mS/m). It is a measure of the concentration of salts in solution. Low-salinity waters have values less than 0.25 dS/m and high-salinity irrigation waters have values greater than 0.75 dS/m. Water with an electrical conductivity of 0.01 dS/m contains about 0.1

me/litre anions or about 6.4 mg/litre dissolved salts. The salt tolerance of crops varies, some being adversely affected when the electrical conductivity of the 1:5 soil:water extract is in the region of 1 dS/m; a large number of crops are adversely affected when the figure is 1 dS/m or higher.

Gilgai	Regularly spaced humps and depressions found in the surfaces of some cracking clays. This micro relief is produced by swelling clays following prolonged expansion and contraction due to changes in moisture content; usually a succession of micro basins and micro mounds in nearly level areas, or of micro valleys and micro ridges parallel to the direction of the slope. There are two broad groupings of gilgai: low gilgai with a vertical interval <300 mm (i.e. crabhole, normal, linear and lattice gilgai types), and high gilgai with a vertical interval of >300 mm and commonly >800 mm (i.e. melon-hole and contour gilgai types).
Gypsum	Calcium sulfate (CaSO_4) used to reduce dispersion. A naturally mined substance or also formed as a by-product of fertiliser manufacture.
Impermeable	Not able to transmit water or air.
Lime	Calcium carbonate, often termed agricultural or calcitic lime to distinguish it from dolomitic lime.
Mottled	Having blotches of soil with a different colour.
Organic-rich	Organic materials are plant-derived organic accumulations that have 18% or more organic carbon if the material has 60% or more clay; 12% or more organic carbon if the material has no clay or a proportional content of organic carbon if clay content is between 12-18% clay (see figure in Isbell and National Committee on Soil and Terrain 2016).
Ped	An individual natural soil aggregate consisting of a cluster of primary particles and separated from adjoining particles by surfaces of weakness that are recognisable as being natural.
pH	A scale of measurement of acidity or alkalinity. The scale runs from 1 to 14 with 7 being neutral. Below 7 is acid and above is alkaline. Soil pH values can be up to 1.5 units lower when measured in a 0.01M CaCl_2 suspension than when measured in a water suspension. In the interests of standardisation it is recommended that a 0.01M CaCl_2 suspension (1 part soil:5 parts solution) is used. pH values below about 4 (very acidic) or above about 10 (very alkaline) may be corrosive of cable and infrastructure.
Salinity	An excess of water-soluble salts, usually sodium chloride, that restricts plant water uptake due to a process known as osmosis.
Self-mulching	Refers to cracking clay surfaces that develop a soft and crumbly condition after wetting and drying fracturing (of soil aggregates). Self-mulching refers to that condition of the surface soil, notably of clays, in which a high degree of pedality is exhibited with the peds falling apart naturally, as the soil dries to form a loose surface mulch. In cultivated soils, ploughing when wet may appear to destroy the surface mulch which, however, will reform upon drying.
Slickensides	Natural shiny surfaces found on soil aggregates formed by the parallel orientation of clay particles during swelling and shrinking cycles. Refers to polished or grooved surfaces within rocks or soils resulting from part of the mass sliding or moving against adjacent material along a plane which defines the extent of the slickensides. In soils, they occur only in clay-rich materials with a relatively high swelling clay content.

Smearing	Disruption of clay-rich aggregates under moist conditions to produce shiny, impenetrable surfaces.
Sodicity	An excess of sodium causing dispersion to occur.
Soil colour	Description of soil colour has been standardised through the use of Munsell Soil Colour notations (colour charts produced for use with soils are available from Munsell Color Company, Inc., Baltimore 18, Md., USA). Accordingly, colour is usually given for moist soil in a descriptive term (for example, yellowish brown) and as a notation (for example, 10YR 5/4), the latter being compounded from charts for hue (10YR) and notations for value (5) and chroma (4).
Soil pores	Channels and cavities in a soil. In clays these are extremely fine and can make water entry or removal difficult.
Soil structure	An arrangement of the soil material into aggregates in which the primary materials are held together by ties stronger than the ties between aggregates.
Substrate	An underlayer or stratum, as of earth or rock, lying immediately under another.
Shrink-swell potential	These are a set of classes of reversible volume change between field capacity and oven-dryness for a composition inclusive of rock fragments. Actual shrink-swell, in contrast, is dependent on the minimum water content that occurs under field conditions. The standard laboratory method 4D (Soil Survey Staff 2011) involves computation of the strain from the volume decrease of bulk density clods that are oven-dried from the water content at the suction selected to estimate field capacity.
Swelling clays	Most commonly referred to in soils literature in the reverse as cracking clays. Denotes the property of particular clays which enables them to expand considerably on taking up water and equally shrink in the drying cycle, often leading to the formation of gilgai and/or slickensides.
Texture	The proportions of clay, silt and sand in a soil.

Appendix 9: Factual key, salinity, size classes and sodicity

Factual Key	The Factual Key (Northcote 1979) is a soil type indication that uses a system of letters and numbers. It was used in the construction of the Atlas of Australian soils.			
	Profile Form		Sub-div	Description
	O	Peaty soils		Acid, neutral or alkaline
	U	Mineral soils, texturally uniform; subdivisions based on particle size and shrink/swell capacity	Uc	Coarse textured, sandy
			Um	Medium textured, loamy
			Uf	Fine textures, clayey
			Ug	Fine textured with periodic cracking in dry periods, unless irrigated
	G	Mineral soils, texturally gradational	Gc	Calcareous throughout (contains calcium carbonate)
			Gn	Not calcareous, but may be in subsoil
	D	Mineral soil, texturally duplex (coarse material overlies fine clayey material); colour sequence from red to grey indicates increasing wetness	Dr	Red-coloured subsoil clay; well drained
			Db	Brown-coloured subsoil clay
			Dy	Yellow-coloured subsoil clay
			Dd	Dark-coloured subsoil clay
			Dg	Grey-coloured subsoil clay (grey, greenish grey, bluish grey)
			These subsoil clays may be mottles with soil of different colour	
Salinity		Salinity is common in the more arid parts of Australia. It is usually associated with shallow water tables and is frequently responsible for damage to infrastructure.		
Size classes	Particle size classes are used to describe the mineral material that makes up soil.			
	Particle Name		Australian system (mm)	
	Clay		<0.002	
	Silt		0.002-0.02	
	Sand		0.02-2	
	Fine gravel		2-6	
	Medium gravel		6-20	
	Coarse gravel		20-60	
	Cobbles		60-200	
	Stones		200-600	
	Boulders		600-2000	
Large boulders		>2000		
Sodicity	Sodicity is a soil condition associated with present or past salinity, the legacy of which is to alter the properties of clays. Sodic clays are particularly susceptible to dispersion and erosion by fresh water even in arid areas where infrequent strong rainfall events can occur. Care is needed in restoring excavations in these soils. Gypsum application may help in some situations. Highly sodic soils also have alkalinity (high pH) and can be corrosive.			