www.csiro.au

Technical Guidelines for the Assessment and Management of Inland Freshwater Areas Impacted by Acid Sulfate Soils

Rob Fitzpatrick, Paul Shand and Warren Hicks

CSIRO Land and Water Science Report, 5/11

December, 2011

Australian Government
Department of Sustainability, Environment, Water, Population and Communities

Enquiries should be addressed to:

Dr Rob Fitzpatrick: CSIRO Land and Water, Private Bag No 2, Glen Osmond, South Australia, 5064

Email**:** rob.fitzpatrick@csiro.au
Phone**: 08 8303 8511;** Mobile**: 0408 824 215**

Copyright and Disclaimer

This report has been co-funded by the Australian Government Department of Sustainability, Environment, Water, Population and Communities and CSIRO Land and Water. The views and opinions expressed in this publication are those of the authors and do not necessarily reflect those of the Australian Government or the Minister for Sustainability, Environment, Water, Population and Communities.

Citation: 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. http://www.clw.csiro.au/publications/science/2011/sr05-11.pdf

Cover Photographs:

Top: photograph of a typical inland Acid Sulfate Soil of the subtype "Sulfuric cracking clay soil" in the dry river bed of Goolwa Channel - Currency Creek area, near north Goolwa (Sample. CUR 13 sampled in November 2008), looking west towards to the Adelaide Hills, South Australia. This shows: (i) trans-horizon polygonal cracks with very coarse columnar ped structures; the result of desiccation and dewatering of a former "Hypersulfidic subaqueous clayey soil" during drying due to recent extreme drought conditions; (ii) surface coating of the reddish-brown mineral, schwertmannite, with a pH between 3.0 and 3.6 (sulfuric material), (iii) sulfuric material (pH < 4) with pale yellow mottles of natrojarosite in a dark grey clay matrix between 10 cm to 30 cm, and (iv) very dark grey hypersulfidic material (iron sulfides) at depth (>30 cm).

Bottom: photograph taken at same locality in December 2009 after reflooding due to winter rainfall runoff from adjacent catchments and pumping from Lake Alexandrina following installation of a temporary flow regulator across the Goolwa Channel at Clayton Bay. The reflooded Acid Sulfate Soil stayed submerged under 80 cm of water for a period of six months and remained largely acidic (i.e. Sulfuric subaqueous clay) except for a thin 5 cm thick surface layer comprising black monosulfidic material, which overlies sulfuric material with pale yellow mottles of natrojarosite (second layer) and dark grey hypersulfidic material below 30 cm).
(From Fitzpatrick *et al.* 2011a)

Photographer: Rob Fitzpatrick (of Site No CUR 13 in November 2009) © 2011 CSIRO

Acknowledgements

This report was researched and written by Rob Fitzpatrick, Paul Shand and Warren Hicks (CSIRO Land and Water).

The authors greatly acknowledge significant editorial inputs from Bernie Powell (CPSS – level 3; QDNRW), Gerard Grealish (CSIRO), Richard Merry (CSIRO), Dr Steve Appleyard (WA DEC), Dr Brad Degens (WA DEC), Dr Liz Barnett (DENR) and Dr Maarten Ryder (The University of Adelaide). We especially thank Mr Greg Rinder (CSIRO) for graphics work on most figures and maps.

Report preparation and production was overseen by the Phase 1 working group from the Joint Steering Committee for Acid Sulfate Soils (JSCASS) comprising:

Chair (Prof Leigh Sullivan)	Southern Cross University
Mr Bernie Powell	Qld Department of Natural Resources and Water
Mr Dean Ansell	Murray Darling Basin Authority
Dr Liz Barnett:	Department of Environment and Natural Resources (DENR) [previously Department for Environment and Heritage, South Australia (DEH, SA)]

The report was comprehensively reviewed by:

Mr John Williams	NSW Department of Primary Industries
Mr Col Ahearn	Qld Department of Natural Resources and Water
Mr Doug Fotheringham	DENR
Mr Peter Donnelly	ACT Department of the Environment, Climate Change, Energy and Water
Dr Steve Appleyard	WA Department of Environment and Conservation
Mr Rob Kingham	Murray Darling Basin Authority
Ms Kim Forbes	SEWPaC
Mr Charles Edlington	SEWPaC
Ms Emma Warren	SEWPaC

This work was co-funded by Australian Government's Department of Sustainability, Environment, Water, Population and Communities (SEWPaC) [previously Department of Environment, Water, Heritage and the Arts (DEWHA)] and CSIRO.

EXECUTIVE SUMMARY

Acid sulfate soils (ASS) is the name given to those soils or sediments that contain sulfide minerals or are affected by geochemical or biochemical transformations of iron sulfide minerals. These soils may either contain sulfuric materials or have the potential to form sulfuric acid in amounts that have an effect on the main soil characteristics of inland wetlands, creeks and rivers in Australia. Other potential consequences of ASS disturbance or exposure include deoxygenation of surface waters and the release of metals and nutrients, which represent serious issues for the management of waterways.

These technical guidelines for the assessment and management of inland freshwater areas impacted by acid sulfate soils provide an authoritative reference that can be used to describe and support a broad range of assessment and management options, without advocating particular choices. The main intent of these guidelines is to provide the scientific basis for implementing such decisions in a more informed and sustainable manner. This document also provides a summary of available information on the properties and variations, both spatially and with time, of Australian Inland freshwater ASS using 36 case studies from different geographical areas in South Australia, Victoria, Western Australia and New South Wales. A set of Guidelines, employing 7-stages, was applied to these case studies that illustrate ASS assessment and management approaches. This report outlines the main tasks required to carry out each stage, so that decisions on ASS hazard/risk and appropriate management options can be adequately supported.

Guidelines were developed, based on the following 7-stages:

1. Initial characterisation – verify occurrence of ASS
2. Problem categorisation – desktop assessment
3. Design investigation - reconnaissance field investigations of ASS
4. Characterise and analyse in detail
5. Assess hazard/risk
6. Decide on management options
7. Report and communicate

This information has been developed to assist policy makers, planners, landholders, wetland managers and water managers as well as industry and consultants. It provides guidelines on approaches to assess hazard and effective management options for a wide range of ASS in inland freshwater areas.

The identification and treatment of Inland ASS problems is important, because the risk of environmental damage and economic loss due to Inland Acid Sulfate Soils has increased quite dramatically in recent years. Changes in land use and practice, extended drought and subsequent reflooding have combined to become major causal agents of ASS risk. Changes to the management of land (e.g. extensive vegetation clearing and excavation of drainage channels) and waterways (building of locks, barrages and weirs) have led to the accumulation of subaqueous soil layers and a build up of reduced sulfur compounds. These compounds have the potential to generate acidity and also lead to pollution by toxic metals or metalloids. The drying of subaqueous soils that contain reduced sulfur minerals, for example after prolonged drought and over-allocation of irrigation water, can lead to the mobilisation of acidity and metal pollution following re-wetting via rainfall or higher river levels.

Substantial areas of southern eastern Australia (see Case Studies) experienced these problems following the 2006-2010 drought and the 2010–2011 re-wetting events, leading to increased risk of harm to animal and human health, and the health of

ecosystems more generally (e.g. fish populations), as well as to public and private infrastructure.

The 36 case studies have been grouped into different “Geographical Areas of Acid Sulfate Soils” (GAAAS) such as Dundas Tableland in Victoria, Eastern Mt Lofty Ranges in South Australia, Lower Lakes in the Murray Darling Basin and Wheatbelt of Western Australia. These Geographical Areas differ markedly in soil type, geology, topography, climate, hydrology and vegetation etc. As a result, these areas often have different types of ASS problems, which may require different types of solutions. The 36 case studies presented include river channels, creeks, lakes, wetlands, evaporation basins, billabongs, seepages overlying mineralised zones, groundwater systems and drains. On the other hand, there are some key similarities between the Geographical Areas of ASS and the types of ASS that are found allowing extrapolation of management options that can be used to prevent or remediate the ASS problems. For example, the Dundas Tableland shares some characteristics in the types of ASS problems encountered with the soils of the Eastern Mt Lofty Ranges in South Australia and the preferred management options are similar for both areas.

Management principles and strategies: These technical guidelines outline principles and strategies, which can be employed to improve the environmental performance of inland freshwater areas impacted by acid sulfate soil drainage systems, whilst retaining their benefits for “agriculture” and “the environment” (e.g. Ramsar sites). The guidelines focus on impacts from drainage and consequences of acidification from areas with inland acid sulfate soils. The benefits, risks and limitations associated with management changes are also described in the 7-staged technical guidelines using 36 case studies, which emphasise the need to assess key features and hazards of ASS in inland systems before changing their management. Important characteristics included the range of water levels in the inland freshwater wetlands and lakes, the elevation of land, the presence of acid sulfate soils (e.g. permeability, texture and depth of Types and Subtypes of ASS), groundwater acidity, and the nature and type of native vegetation (e.g. Phragmites). This report presents examples of management strategies, for example, an assessment of subsidiary works (e.g. levee banks) to prevent or control inundation and limit water movement, restoring wetlands to conserve or enhance preventing continued or long term inundation, and minimising drainage of acidic groundwater. Another strategy highlighted is to use water retention structures to reduce seepage of acidic groundwater to drains in acid sulfate soil back swamps. These structures can also control unwanted intrusion of saline water, or reduce the risk of peat fires. Water retention strategies can also be used to reduce the drainage of acidic or deoxygenated surface water and aid the establishment of wetland pastures or wetland conservation areas.

The greater incidence of fire and loss of organic topsoil in back swamps has often led to long-term irreversible changes (irreversible formation of brick-like/ceramic fragments), further scalding, loss of agricultural productivity and surface accumulation of acid products.

Acid sulfate soil maps at local, regional and national scales, in combination with the conceptual toposequence models presents an improved spatial and temporal understanding of ASS distribution. Conceptualised temporal soil-regolith models have been included in most case studies to describe the current understanding of ASS distribution and to demonstrate predictive scenarios for changes occurring over time (e.g. progression from historical, pre-drought to drought or current conditions and future possible conditions such as reflooding or continuation of drought conditions).

In summary, this report documents the different types of Inland ASS in Australia. There are similarities in the types of acid sulfate soils that occur in specific environments, which have a bearing on the best management options. A summary table is presented (**Table 6-7**), which includes landscape characteristics and provides management principles applied in each of the 36 representative case studies. Management options and strategies that may be applied in an effort to control or prevent damage are not unique to geographic settings and users may find this table useful as a first pass, to look for similarities in ASS landscapes between their site and the case studies. In recommending management options, users should note that many impacted ASS areas and landscape processes remain in a state of dynamic change and adaptive management strategies are typically required.

Acid Sulfate Soils with varying hazard and impact potential are found across most of Australia. Having identified Geographic Areas and Inland ASS management options especially for southern Australia, it will be beneficial to extend the coverage to other parts of Australia, especially Northern Australia, where we may be able to identify other Geographic Areas of Inland ASS. As an example of this opportunity to extend coverage of ASS knowledge and management, one case study on Inland ASS is available for the Magela Creek floodplain in the Alligator Rivers Region of the Northern Territory.

CONTENTS

1. INTRODUCTION

These technical guidelines for the assessment and management of inland freshwater areas impacted by acid sulfate soils (ASS) are designed to provide an authoritative reference that can be used to describe and support a broad range of assessment and management options, without advocating particular choices. The intent of these guidelines is to provide the scientific basis for implementing those decisions in a more informed and sustainable manner. These guidelines also include case studies from different geographical areas in South Australia, Victoria, Western Australia and New South Wales that illustrate ASS assessment and management approaches at a local level.

1.1. Background

Areas impacted by Acid Sulfate Soils (ASS) in Australia form an estimated 215,000 km^2 and proper characterisation and management of these areas is, therefore, of major importance. ASS materials may occur in a wide range of coastal and inland wetland environments such as estuaries, wetlands, reservoirs, weir pools, river channels and drains. They may be found in subaqueous (submerged below water), waterlogged or drained wetland conditions or in mine spoil (see glossary).

Of the 215,000 km^2 of ASS in Australia, 58,000 km^2 comprises coastal ASS with 157,000 km^2 of inland ASS (Fitzpatrick *et al.* 2008e, 2010d). In the coastal zone of Australia, 41,000 km^2 are exposed at some point during the tidal cycle, with the remaining 17,000 km^2 being permanently subaqueous. More than 126 km^2 of coastal ASS with sulfuric material have been mapped, however this is a significant underestimate, which will be modified with ongoing field investigations and acquisition of more detailed local spatial data sets. The financial costs to infrastructure development and primary industries around Australia due to ASS impacts and management are significant (ca. $10 billion in 2000: National Working Party on Acid Sulfate Soils, 2000). The extent of inland acid sulfate soils has only recently been appreciated, largely due to impacts related to the Millennium Drought (Fitzpatrick et al. 2009b).

Under the current institutional arrangements that exist in Australia, ASS issues often cut across different agencies' responsibilities (e.g. agriculture, environment, fisheries/oceans, water, atmosphere, mineral exploration and mining; see Fitzpatrick *et al.* 1998). Public recognition of this serious problem has been reflected in government legislation in South Australia, Queensland, Victoria, New South Wales and Western Australia. In addition, there is much support from local government and affected fisheries industries to develop statutory requirements for rehabilitation.

Ineffective management of ASS may adversely affect significant natural assets such as Ramsar wetlands, which contain ASS (e.g. Lakes Alexandrina and Albert, Banrock Station Wetland Complex and the Gippsland Lakes). Existing and potential detrimental effects are broad and significant, and include:

- Soil acidification and degradation including loss of structure, base cations and nutrients, which in some cases may be irreversible
- Poor water quality with attendant loss of amenity, damage to aquatic environments and reduction in wetland biodiversity (e.g. photograph on front cover)
- Loss of fisheries and agricultural production
- Damage to public and commercial infrastructure and housing affected by acidic conditions (corrosion of concrete and steel)
- Human health implications due to liberation of dissolved toxicants (including heavy metals, aluminium) into the aquatic environment or the release of toxic gases

- High rehabilitation costs, usually at government expense (national, state and local)

These impacts can be measured in terms of:

- The need for rehabilitation of disturbed ASS-affected areas to improve water quality and minimise impacts
- Loss of fisheries and agricultural production
- Additional maintenance of public infrastructure affected by acidic corrosion

Whilst guidelines for characterisation and management of coastal ASS have been supported with a national strategy and State and Territory guidelines and policy, it is highly variable across Australia in its development.

1.2. Purpose of producing guidelines

This document attempts to address critical technical guidelines for assessment and management of specific types of ASS susceptible to land degradation under different management regimes (e.g. drainage schemes designed to manage rising saline watertables) and climate change and variability scenarios (e.g. drought-triggered) in a wide variety of inland freshwater settings, such as: river channels, creeks, lakes, wetlands, drains, evaporation basins, billabongs, seepages overlying mineralized zones, and ground water systems.

Context and rationale

Recent reviews (e.g. EPHC & NRMMC 2011; Fitzpatrick and Shand 2008; Fitzpatrick 2008; Fitzpatrick *et al.* 2009b) and further development of the National Atlas of ASS to map inland ASS (e.g. Fitzpatrick *et al.* 2008e,f,i; 2010c,d) have provided new information about the extent and potential for disturbance of Inland ASS. Inland ASS are extensive throughout the Murray-Darling Basin (MDBA, 2011) as well as in drains and lakes of the Wheat Belt in Western Australia (e.g. Degens *et al.* 2008a,b,c; Shand *et al*. 2008d) Dundas Tableland, Victoria (Fawcett *et al.* 2008) and in Tasmania (see Websites for ASS). They have the potential to acidify wetlands and in some localities have already done so (Baldwin *et al*. 2007; Shand *et al*. 2008d, 2010a, b). In addition, they pose a threat to ecosystems in lakes, floodplain wetlands and water storages, cause accelerated hillslope erosion in seepage zones and may lead to poor water quality in streams. Early management intervention is critical, because once they are disturbed, acid sulfate soils can degrade quickly. Proactive intervention will assist the management of the whole system and may prevent problems becoming worse. Rehabilitation is expensive, may not be feasible and the required technologies may not exist or be untested. Furthermore, the processes of acid sulfate soil formation and acid mobilisation are poorly understood in inland environments, so that progressing from hazard identification to risk assessment and management is difficult.

Needs analysis

The issues resulting from sulfidic materials in inland ASS being exposed as a result of the 2006–2010 drought and historic over-allocation of water has highlighted the lack of suitable guidelines or policy available to underpin appropriate and well-informed management. Many of the affected wetlands and lakes were re-flooded during the 2010–2011 floods. A response to these situations is necessary, and because inland freshwater Acid Sulfate Soils are a national problem, it is timely and relevant to develop national guidelines to assist decision makers in the task of managing inland ASS. This document addresses the immediate and critical need for guidelines on the appropriate assessment and management of inland fresh water wetlands, especially from the 2006-2010 drought-triggered ASS issues. However, there are additional disturbance threats to inland ASS such as climate change and drying induced by climate variability, increased demand for fresh water from a growing population, as well as industry. The specific purpose of this document is to provide the scientific basis to the development of technical guidelines for the assessment and management of freshwater areas impacted by acid sulfate soils. This document also provides an authoritative reference that can be used to: (i) describe and support a broad range of assessment and management options, without advocating particular choices, using 36 case studies from different geographical areas in South Australia, Victoria, Western Australia and New South Wales, and (ii) develop the more generalised *National guidance for the management of acid sulfate soils in inland aquatic ecosystems* and the National Water Quality Management Strategy.

Climate change is predicted to increase the severity and frequency of natural climate cycles, with increased occurrence of extreme events and reduced water availability (e.g. IOCI, 2002). These threats are beyond the control of wetland managers, and suitable adaptive management strategies to minimise harm are even more necessary under these circumstances.

A number of river and wetland management activities that are otherwise seen as beneficial have the potential to destabilise inland ASS. These include the decommissioning of salt disposal basins and imposing more natural wetting and drying cycles to wetlands. Activities such as water delivery down channels may disturb monosulfidic black ooze (MBO) or mobilise acidity stored in sulfuric material that has formed in dry channels of stream beds. Without suitable guidelines, inland ASS, which represent a serious and growing threat to water quality and have the potential to threaten biodiversity, primary industries and human health, pose an even greater risk. Managing inland ASS effectively and proactively wherever possible will help minimise the risks and severity of impacts. This will cut the consequent costs of rehabilitation, and reduce the impacts on the environment and agricultural activity.

2. CLASSIFICATION AND ASSESSMENT OF ACID SULFATE SOIL MATERIALS

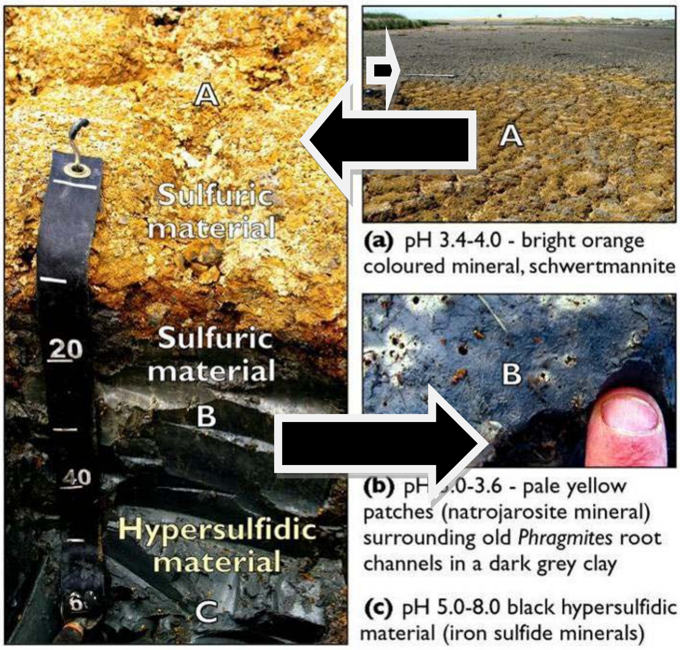
This section briefly defines Acid Sulfate Soils (ASS), the criteria used for the classification of sulfuric, sulfidic, hypersulfidic, hyposulfidic and monosulfidic materials; and methods used for assessment of ASS in freshwater systems.

2.1. What are acid sulfate soils?

Acid sulfate soils (ASS) is the name given to those soils or unconsolidated sediments that contain sulfide minerals or are affected by geochemical or biochemical transformations of iron sulfide minerals. These soils may either contain sulfuric acid or have the potential to form sulfuric acid in amounts that have an effect on the main soil characteristics (Pons 1973; Dent 1986; Dent & Pons 1995). Sulfuric acid forms when sulfide minerals are exposed to oxygen. Other potential consequences of ASS disturbance or exposure include deoxygenation of soil or surface waters and the release of metals and nutrients. In general, three broad types of ASS materials are recognized (e.g. Fanning 2002):

- **Sulfuric** material containing actual and/or stored acidity (pH < 4; may also contain iron sulfide minerals) usually at shallow depths (Figure 1-1 Glossary: ASS definitions). These materials were previously referred to as actual, active or raw ASS materials.

- **Sulfidic** material containing detectable sulfide: **hypersulfidic** (potential to acidify to pH < 4; Figure 1-1) **or hyposulfidic** materials (potential to acidify to pH ≥ 4) containing mainly iron disulfide minerals (FeS_2) (Figure 3-1; Glossary: ASS definitions), previously called potential or unripe ASS materials. In many cases, these materials are permanently saturated or are in subaqueous soils and benign unless disturbed.



(a) pH 3.4-4.0 - bright orange coloured mineral, schwertmannite

(b) pH .0-3.6 - pale yellow patches (natrojarosite mineral) surrounding old *Phragmites* root channels in a dark grey clay

(c) pH 5.0-8.0 black hypersulfidic material (iron sulfide minerals)

Figure 1-1. Acid sulfate soil in dry river bed of the Finniss River, South Australia (modified from Fitzpatrick *et al.* 2009a,b).

- **Monosulfidic** materials are low density materials, which contain monosulfide minerals (FeS) that are still waterlogged (e.g. Figure 3-6; Figure 3-7; Glossary: ASS definitions). These materials also incorporate the previously used term monosulfidic black ooze (MBO).

2.2. Visual indicators of Acid Sulfate Soils

The occurrence of Acid Sulfate Soils can often be inferred from the presence of deposits, formations or features of particular colour, form and composition in the landscape, including water bodies. For example, soil colour is usually the first property recorded in a morphological description of soils (and may be the only feature of significance to a layperson). Colour can provide an indicator of redox status and geochemistry, because soil colour often depends upon the specific types of Fe oxides present, and the soil's position in the landscape relates to soil aeration and organic matter content (see Glossary: Acid Sulfate Soil minerals; Bigham *et al.* 2002; Fitzpatrick *et al.* 2003c).

Visual indicators of ASS may be obvious (such as white or yellow salt accumulations on soil surfaces) or subtle (for example, subsoil mottling patterns, strong pedality). Several examples of visual indicators of ASS are given below and throughout this document. However, visual or descriptive soil indications should be supported by the collection of other more detailed field and laboratory or analytical testing (see sections 2.3 and 2.4 below). Combining descriptive and analytical indicators provides vital information about soil-water processes, leading to improved management and remediation of ASS, as will be demonstrated in several case studies across Australia.

A wide variety of ferric iron oxyhydroxide minerals, such as ferrihydrite or iron hydroxysulfate minerals, such as schwertmannite, may form as precursors to goethite depending on the local chemical environment (e.g. see Glossary: Acid Sulfate Soil minerals; Schwertmann and Fitzpatrick 1992; Bigham *et al.* 2002). These minerals often appear as reddish-brown rusty (e.g. ferrihydrite), reddish-yellow to orange-yellow (schwertmannite) or yellow (jarosite or sideronatrite) spots around pyrite or as crusts on completely weathered pyritic soil surfaces in soils, and as gelatinous precipitates in puddles and streams affected by ASS drainage. These secondary minerals in the form of variously coloured precipitates in waters, salt efflorescences, coatings on soils and in mottles are important to recognize because they may store acidity and contaminants that can subsequently generate poor water quality if mobilised.

2.3. Rapid field and laboratory assessment of ASS

The Murray-Darling Basin Authority (MDBA), in partnership with its Partner Governments and scientists, instigated the Murray-Darling Basin Acid Sulfate Soils Risk Assessment Project (MDB ASSRAP), which aims to assess the spatial occurrence of, and risks posed by, acid sulfate soil materials in the Murray Darling Basin (MDB). Given the very large number of wetlands in the Murray–Darling Basin, a four-step approach was taken to identify, prioritise and assess potentially affected wetlands in the Basin (MDBA 2010; 2011). The MDB ASSRAP project also aimed to identify and assess broad management options. All wetlands in the MDB were subjected to a tiered assessment process, whereby wetlands were screened through a desktop assessment stage (modified from Baldwin *et al.* 2007), followed by a rapid on-ground appraisal (RAP - based on the chip-tray incubation method developed by Fitzpatrick *et al.* 2010b and Creeper *et al.* 2010), and subsequent detailed on-ground assessment if the initial stages indicated an increased likelihood of occurrence of ASS (MDBA 2010). More than 19,000 wetlands underwent desktop assessment, and this identified approximately 1,450 wetlands considered to have a higher likelihood of ASS occurrence requiring further assessment. The RAPs were performed by state and regional NRM agency staff that had completed one of the six ASS rapid assessment training courses (Creeper *et al.* 2010).

During the assessments, wetland soil samples were collected from up to 3 different soil profiles within a wetland representing a toposequence (MDBA 2010, 2011). As part of the RAP, these soil samples were then submitted for incubation analysis (Fitzpatrick *et* *al.* 2010b; Creeper *et al.* 2010). The pH incubation is a method whereby ASS are kept in an unsaturated but moist state and exposed to the atmosphere allowing them to undergo oxidation reactions in an attempt to simulate the natural acidification behaviour of the soil. If the soil in question is hypersulfidic the pH will reduce substantially during incubation to a $\text{pH} < 4$, as a result of sulfide oxidation and hence pose an acidity hazard (Sullivan *et al.* 2009; 2010). The use of pH incubation for classification is often considered preferable to other methods, such as peroxide addition, because the result of the experiment is arguably more representative of what would be expected to occur in the field (Dent 1986).

2.4. Detailed field and laboratory assessment

A range of secondary minerals, such as jarosite, sideronatrite and schwertmannite may also form. Such minerals act as stores of acidity *i.e.* they may produce acidity upon dissolution. Therefore, any assessment needs to take these into consideration.

There is considerable debate as to the most realistic method to estimate if a soil will acidify, and the most effective method may vary according to the local environment and associated mineralogy of the soils. In CSIRO, we have combined the three most generally accepted methods for ASS testing: peroxide pH testing, acid-base accounting and ageing experiments (Shand *et al*. 2008b). These have different strengths and weaknesses and therefore all have been assessed in the current project. A summary is presented below and further details are provided in MDBA (2010).

Peroxide testing

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.

Acid-base accounting (ABA)

Acid-base accounting (ABA) is used to assess both the potential of a soil material to produce acidity from sulfide oxidation and also its ability to neutralise any acid formed Ahern *et al.* (2004).

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 + Retained Acidity – ANC*/Fineness Factor/1.5

***ANC = Acid Neutralising Capacity**

The components in this ABA procedure are discussed further 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. This method was developed specifically for analysing acid sulfate soil materials primarily to assess their potential sulfidic acidity (PSA) also known as the 'acid generation potential' (AGP) or reduced inorganic sulfur (RIS). The method is also described in Ahern *et al.* (2004), which includes the chromium reducible sulfur method (S_{CR} or CRS: 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.

Retained acidity **(RA):** is the acidity 'stored' in minerals such as jarosite, schwertmannite and other hydroxysulfate minerals. It is measured in samples where soil pH is pH_{KCl} <4.5. 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).

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 estimated by titration, and alkalinity present is expressed in $CaCO_3$ equivalents. By accepted definition, any acid sulfate soil material with a pH_{KCl} < 6.5 has a zero ANC (Ahern *et al.* 2004). The methods for determining ANC are also given by Ahern *et al.* (2004).

Fineness Factor **(FF):** This is defined by Ahern *et al.* (2004) as "A factor applied to the acid neutralising capacity result in the acid base account to allow for the poor reactivity of coarser carbonate or other acid neutralising material. The minimum factor is 1.5 for finely divided pure agricultural lime, but may be as high as 3.0 for coarser shell material". Fine grinding of soil materials may lead to an over-estimate of ANC when carbonates are present in the form of hard nodules or shells. In the soil environment, they may provide little effective ANC where 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.

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 to insoluble Fe oxides 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.

Soil incubation

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; e.g. Sullivan *et al.* 2009), which allows a more realistic oxidation of sulfide minerals to occur than that produced during peroxide testing. In CSIRO, we use the chip-tray incubation method (Fitzpatrick *et al.* 2010), which may mimic nature more closely and does not force reactions to occur (as in the peroxide test) or rely on total 'potential' reaction (ABA).

The current practice in CSIRO Land and Water 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. Acidification potential was based on the above methods: peroxide pH (pH_{OX}), incubation pH (pH_{INC}) and net acidity (NA). The criteria listed below were used to assign acidification potential rankings:

- peroxide pH ≤ 2.5
- NAGP > 0 or 18 mol $tonne^{-1}$
- Ageing pH ≤ 4.0

When a criterion was met, an acidification ranking point is allocated. These are then summed and an acidification potential category value assigned between 0 and 3.

The acidification potential categories were:

- (i) 0 = very low potential,
- (ii) 1 = low potential,
- (iii) 2 = medium potential and
- (iv) 3 = high potential.

Where all three criteria were met (i.e. high potential), soil material is considered more likely to become sulfuric material (Shand *et al.* 2009).

ASS with a net acidity of more than 18 moles H^+ t^{-1} of soil trigger the requirement for detailed ASS assessment, but only if that acidity is sulfide-related acidity and not simply naturally occurring organic acid acidity (Ahern *et al.* 2004).

It can be argued that the complex processes occurring in the field are not represented in any of these techniques 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 (e.g. groundwater) which, is often scenario specific.

2.5. Difference between “acidic soils” and “acid sulfate soils”

It is important to be able discriminate between “acidic soils” and “acid sulfate soils” (Sullivan 2011; Fitzpatrick 2008 p. 321). For example, some inland environments are naturally acidic [e.g. “Organic soils” or Organosols (McKenzie *et al*. 2004: pages 288 to 295; and “Soils with accumulation of organic matter, iron and aluminium” or Podosols (McKenzie *et al.* 2004 –pages 296 to 313)] and clearly support soil-landscape ecologies adapted to these acidic conditions. Consequently, it can be detrimental to treat these kinds of naturally acidic environments as if they needed remediation based on Acid Sulfate Soil criteria, e.g. with agricultural lime (Sullivan 2011; Fitzpatrick 2008 p. 321).

Finally, the guidelines and legislation relating to acid sulfate soil assessment and management, as a rule, refer specifically to ‘acid sulfate soil’ materials (e.g. Ahern *et al*. 1998; Dear *et al.* 2002). Therefore, it is important to ensure that the soil materials of interest are ‘acid sulfate soils’ [see Chapter 8 (Glossary)] and not other soil types such as Organosols or Podosols before commencing an expensive and unwarranted investigation and remediation. Several Organosols and Podosols have high actual acidity values and can also acidify upon oxidation with H_2O_2 as a result of reaction with organic matter. In summary, unless soil materials qualify as ‘acid sulfate soil materials’ then standard field and laboratory tests designed for acid sulfate soil materials can provide results that could be misdiagnosed as either/or: (i) being of environmental concern, and (ii) requiring remediation.

2.6. Subaqueous soils

Subaqueous soils are intended to accommodate submerged soil materials in both inland and tidal settings. With Australia’s seasonal climate, some inland forms may experience occasional periods of exposure during extreme drought. For soil materials exposed more frequently than 1 year in 9, on average however, the definition does not apply; more frequent drought-induced exposed lake beds and wetlands do not classify as Subaqueous.

Sediments in shallow water environments undergo soil forming processes (Demas and Rabenhorst 1999, 2001), are capable of supporting rooted plants, and meet the definition of pedological organization used in soil classification systems such as Soil Taxonomy (Soil Survey Staff 1999) and the Australian Soil Classification (ASC; Isbell 1996) (Bernie Powell and Rob Fitzpatrick have submitted a proposal to the ASC Committee to adopt the terminology and definition for “Subaqueous soils” [see Chapter 8 (Glossary)]. The depth range of the water column where these soils may be found is not known, and an arbitrary depth of 2.5 meters below the surface or MLWS is used. This aligns closely with the definitions of subaqueous and submerged soils adopted by Soil Survey Staff (1999).

3. SULFIDE ACCUMMULATION PROCESSES IN INLAND ENVIRONMENTS

This section describes how sulfides are formed in natural environments and how they especially accumulate under fresh water conditions in anthropogenic modified environments.

3.1. How are sulfides formed?

Iron sulfide minerals form as a product of the biochemical process of sulfate reduction (i.e. as SO_4^{2-} is utilised during microbial respiration) followed by iron sulfide precipitation (Figure 3-1). Sulfate reduction is a natural process that occurs in virtually all lakes, rivers, wetlands and oceans under suitably reducing conditions. However, the quantities of sulfide minerals that accumulate are a function of many factors. The requirements for high rates of sulfate reduction and sulfide accumulation are:

- High concentrations of dissolved sulfate in the water body.
- Saturation of soils and sediments for periods long enough to favour relatively highly reducing conditions (i.e. subaqueous and waterlogged soils - see glossary)
- Availability of highly reactive labile carbon (e.g. plant material) to fuel microbial activity
- Availability of dissolved Fe

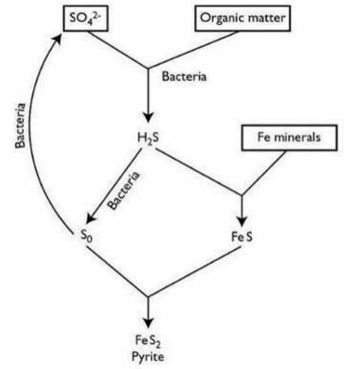


Figure 3-1. Schematic diagram for formation of pyrite (FeS_2) and iron monosulfides (FeS) in anoxic environments (after Berner 1984).

3.2. Accumulation of hypersulfidic and monosulfidic materials in anthropogenic modified environments of the Lower Lakes, SA

The River Murray system is a good example of a major inland anthropically modified environment, which has been highly managed for the last 70 to 80 years. The introduction of locks, weirs and barrages (see Figure 3-2) in the 1930's–1940's to contain water flow has allowed extensive agricultural development (Mack 1958-2003). The prolonged inundation of the river, wetland and lake systems, however, has had a significant impact on the formation of various types of ASS in these systems and limited them from the effects of natural wetting-drying cycles. Such cycles are considered critical for maintaining biodiversity and wetland functioning. This change has promoted the build-up of sulfide minerals (mostly iron pyrite) in newly formed subaqueous soils, which has greatly slowed the removal of these acid-forming minerals from the system (ultimately to the sea).

Prior to construction of the barrages in the Lower Lakes, which separate the freshwater in the Lower Lakes from the seawater of the Coorong and Southern Ocean (Figure 3-2), the water level within the Lower Lakes did not fall below sea level (0 m AHD). Consequently, subaqueous soils and sediments below sea level have not been exposed to oxygen for thousands of years. Therefore, the concentration of sulfides in these soils and sediments will often be significantly greater than those above the marine or fresh water inundation range shown in Figure 3-2.

Following installation of the barrages in 1940, the water level in the Lower Lakes was, until 2009, maintained around a pool level of +0.75m AHD. Hence, during periods of low flow or high evaporation, the lake level in Lake Alexandrina remained relatively constant (high) and only dropped to around +0.5 m AHD and very rarely lower than +0.4m AHD (e.g. as indicated by the graph shown in Figure 4-2, which shows water levels from 1974 to approximately June 2009). This major change to the management of waterways (e.g. building of locks, barrages and weirs) led to the significant accumulation of subaqueous soil layers and a build up of reduced sulfur minerals in form of sulfides (hypersulfidic and hyposulfidic material) and monosulfides (monosulfidic material).

A typical example of an inland ASS with **black clayey hypersulfidic material** at depth containing mainly iron disulfide minerals (FeS_2) is shown in Figure 1-1 from the Finniss River (tributary to Lake Alexandrina). **Organic-rich** or **peaty hypersulfidic material** excavated under water is shown in Figure 3-3 from Lake Albert. In contrast, **black monosulfidic material** (MBO) with gel-like consistence, excavated under water at the Tauwitchere Barrage in Lake Alexandrina adjacent to the Coorong, is shown in Figure 3-4. In most cases, all three of these materials were permanently saturated or are subaqueous soils and benign unless disturbed.

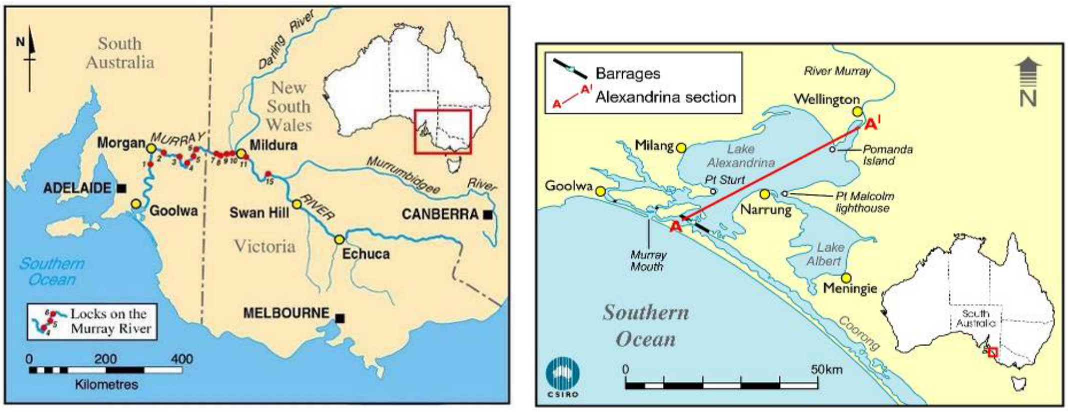


Figure 3-2. Locality maps showing: (i) part of the Murray and Darling River systems in the Murray Darling Basin (MDB) along with locks on the River Murray (left map) and (ii) barrages (constructed to keep sea water out of the Lower Lakes) and the cross section (A–A') across Lake Alexandrina used to construct the predictive soil-regolith models in Figure 12-1 to Figure 12-6 (right map) (from Fitzpatrick *et al.* 2009b).

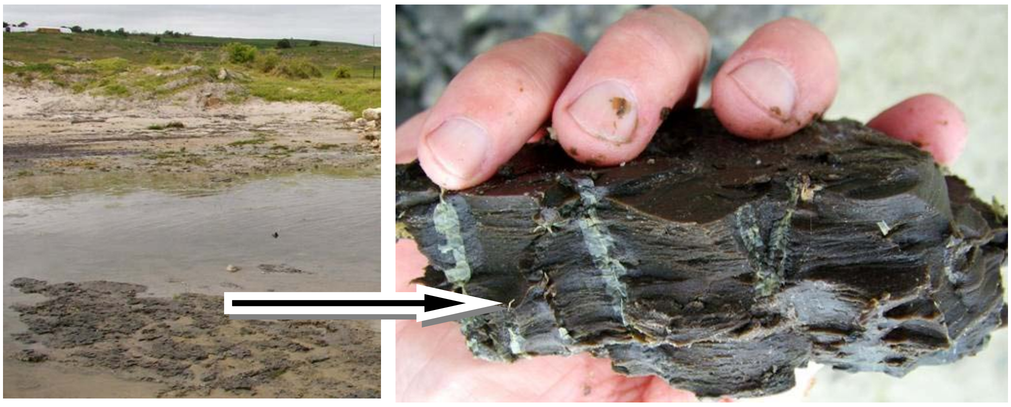


Figure 3-3. Organic-rich or peaty hypersulfidic material excavated under water in Lake Albert in 2007 at Site F2 in Figure 5-2; from Fitzpatrick *et al.* 2008f. This material is also known as Coorongite.

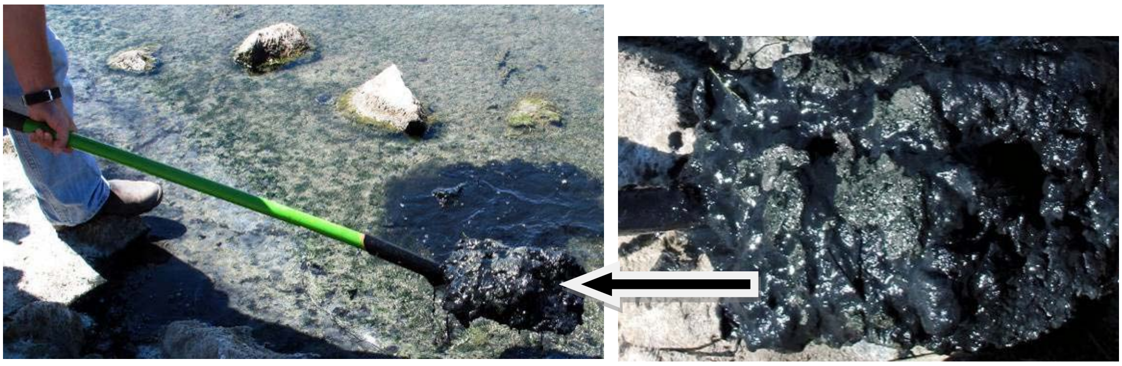


Figure 3-4. Monosulfidic material from under water at the Tauwitchere Barrage in Lake Alexandrina adjacent to the Coorong (Site A in Figure 5-2; from Fitzpatrick *et al.* 2008i).

3.3. Accumulation of hypersulfidic and monosulfidic materials in anthropically modified environments: billabongs, abandoned dairy paddocks, evaporation basins, drains, saline lakes and seepages

Hypersulfidic material accumulates (clayey and sandy) in almost all River Murray wetlands, swamps, adjacent lakes or billabongs (e.g. Tareena Billabong shown in Figure 3-5) and in the main River Murray channel (see Fitzpatrick et al. 2008c, d,f,g; Shand 2008b,c; 2009, 2010).

Monosulfidic material or black ooze (MBO) accumulates readily in the surface sediments or in subaqueous or waterlogged ASS of many inland:

- ***Billabongs*** (e.g. Tareena Billabong shown in Figure 3-5 – right hand photo)
- ***Shallow back swamp/wetlands*** associated with abandoned dairy paddocks (e.g. Paiwalla wetland adjacent to the River Murray shown in Figure 3-6)
- ***Evaporation basins*** (e.g. Loveday evaporation basin shown in Figure 3-6 - right hand side photo)
- ***Drains*** (e.g. extensive drain works in the Western Australia Wheatbelt shown in Figure 3-7)
- ***Saline receiving lakes*** (e.g. extensive hypersaline receiving lakes in the Western Australia Wheatbelt with saline drainage channels shown in Figure 3-8)
- ***Saline natural lake systems*** (extensive hypersaline natural lake systems in the Western Australia Wheatbelt shown in Figure 3-9)
- ***Saline seepages*** (e.g. Saline seepages caused by extensive vegetation clearing at Dicks Creek in NSW shown in Figure 3-10 and in the Mt Lofty Ranges shown in Figure 3-11)

Monosulfidic material usually comprises organic-rich material that contains appreciable concentrations of monosulfides (e.g. Sullivan *et al.* 2002; Bush *et al.* 2004; Burton *et al.* 2006a, 2006b, 2008). Monosulfidic Black Ooze's are specific materials characterised by their gel-like consistence (see Figure 3-4 to Figure 3-11). Monosulfidic material generally has a field pH of 4 or more, commonly pH >7-8, and may not become extremely acidic (pH <4) when drained. The recognition of the occurrence and importance of monosulfides in soil materials led in 2005 to the inclusion of monosulfidic materials as a distinguishing property within mapping units of the Australian Atlas of Acid Sulfate Soils (Fitzpatrick *et al.* 2008e). High nutrient environments together with the activity of algae and micro-organisms generate reducing conditions, which result in the formation of black, smelly materials containing Fe monosulfides. When subaqueous materials rich in monosulfides are resuspended, for example during high flows in drains, they rapidly oxidise and potentially remove oxygen from the water column (Sullivan *et al.* 2002). This can lead to fish kills, especially in enclosed areas such as aquaculture ponds or in estuaries. Hence, MBO is reactive if exposed to oxygen, but is harmless if left undisturbed.

Monosulfidic material has the ability to favourably affect surrounding environments by immobilizing potential metal pollutants (Simpson *et al.* 1998). However, when a drain is cleaned, alunite supergroup minerals (especially alunite and jarosite) and Fe oxyhydroxy-sulfate salts (e.g., schwertmannite) may precipitate on the soil surface along the drain edges. These soluble salts dissolve during rain events and contribute to acidity and high contaminant concentrations in drainage waters.

Figure 3-5. Hypersulfidic material excavated under water in Tareena Billabong (left hand side photos) and black Monosulfidic material exposed on the surface in the cracked shallow back wetlands in Tareena Billabong (right hand side photo) at Site F7 in Figure 5-2; from Fitzpatrick *et al.* 2008c).

Figure 3-6. Monosulfidic material exposed on the surface in the shallow back swamp/wetlands located in Paiwalla wetland adjacent to the River Murray (left hand side photo) at Site E4 in Figure 5-2; Figure 15-2; modified from Fitzpatrick *et al.* 2010e) and (ii) Monosulfidic material excavated under water at Loveday evaporation basin (right hand side photo) at Site F2 in Figure 5-2; from Fitzpatrick *et al.* 2009b; Lamontagne *et al.* 2004, 2006).

Figure 3-7. Monosulfidic material under the surface (left hand side photo) and after being disturbed (right hand side photo) in a typical drain in the Western Australia Wheatbelt; Site M in Figure 5-2 and soil regolith toposequence model in Figure 23-2 and Figure 23-3 (Fitzpatrick *et al.* 2008a, 2010a).

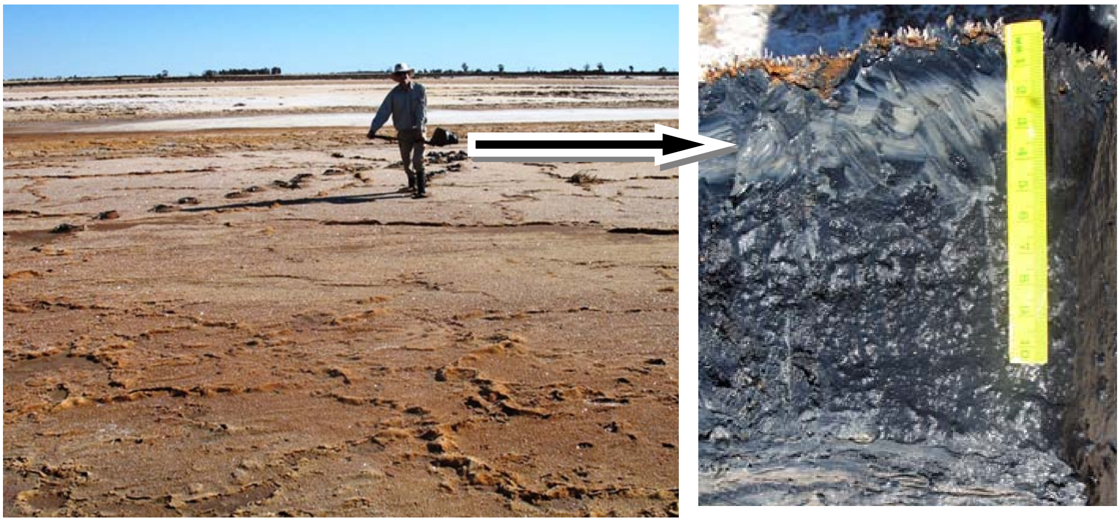


Figure 3-8. Monosulfidic material under the surface of an extensive saline receiving lake (left hand side photo) and after being dug (right hand side photo) in the Western Australia Wheatbelt; Site M in Figure 5-2 and soil regolith toposequence model in Figure 23-3 (from Fitzpatrick *et al.* 2008a, 2010a).

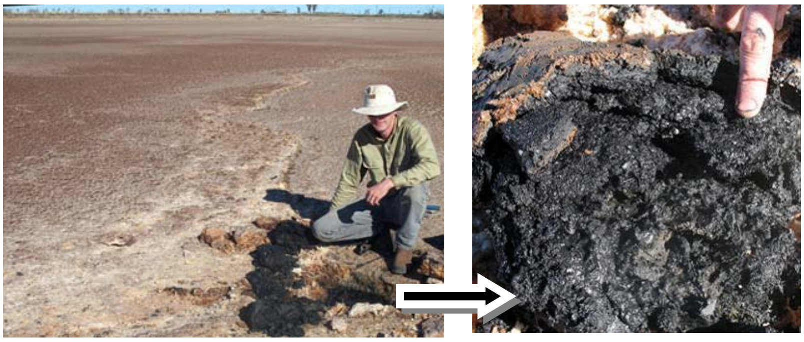


Figure 3-9. Monosulfidic material under the surface of a thick salt crust (left hand side photo) and after being excavated (right hand side photo) in a typical natural lake in Western Australia Wheatbelt; Site M in Figure 5-2 and soil regolith toposequence model in Figure 23-2 (from Fitzpatrick *et al.* 2008a, 2010a).

3.4. Formation of neutral reddish-brown gelatinous precipitates in seeps with monosulfidic material

Reddish-brown gelatinous precipitates shown in Figure 3-10 and Figure 3-11, indicate the presence of the Fe-rich mineral ferrihydrite with pH >7 (Fitzpatrick and Shand 2008) overlying black monosulfidic material. Ferrihydrite has an approximate composition $5Fe_2O_3.9H_2O$. Ferrihydrite forms part of the brown rusty scum or ‘oil slick’ visible on the surface water overlying most wetlands or swamps with subaqueous and waterlogged ASS. Ferrihydrite is commonly found in such surface environments where waters rich in Fe^{2+} are exposed to rapid oxidation in the presence of compounds such as organic matter that block crystal growth (Bigham *et al.* 2002). Thus, it may be expected to occur in ASS formed in zones where groundwaters and surface waters fluctuate seasonally. Ferrihydrite is metastable under most conditions and is often associated with goethite or lepidocrocite (Bigham *et al.* 2002).

Most ferrihydrite is associated with bacteria (*Gallionella* and *Leptothrix*), which gain their energy from the oxidation reaction $Fe^{2+} \rightarrow Fe^{3+} + e^-$. Ferrihydrite also precipitates from ferric iron solutions as pH increases.

Figure 3-10. Reddish-brown gelatinous precipitate is dominantly ferrihydrite and oil-like slick with prominent iridescence on water surface formed by oxidation from iron oxidising bacteria (*Gallionella* and/or *Leptothrix*) exposed in a shallow saline seep Dicks Creek, NSW with pH 7.5. (Fitzpatrick *et al.* 2003c). Iron mineral identified by X-ray diffraction as dominantly ferrihydrite (pH 7.5).

Figure 3-11. Reddish-brown gelatinous precipitate of dominantly ferrihydrite formed by oxidation catalysed by iron oxidising bacteria (*Gallionella* and/or *Leptothrix*), overlying black monosulfidic material in a shallow saline seep in the Mt Lofty Ranges, SA with pH 7.5.

4. SULFUR AND IRON OXIDATION PROCESSES IN INLAND ENVIRONMENTS

This section describes how sulfides in anthropically modified environments are oxidised to form sulfuric acid, iron-oxide minerals and salts e.g. during droughts, flooding, engineering works, erosion and removal of native vegetation, which results in changed soil, surface water and groundwater conditions.

4.1. How is sulfuric material formed?

The weathering of pyrite starts with exposure of pyrite to oxygen (in air). Pyrite is usually stable if submerged in water under anoxic reducing conditions. In general, it is the exposure of fine grained pyrite (typically as “framboids”, see Figure 4-1) to drying or repeated wetting/drying cycles and the action of bacteria that generates sulfuric acid.

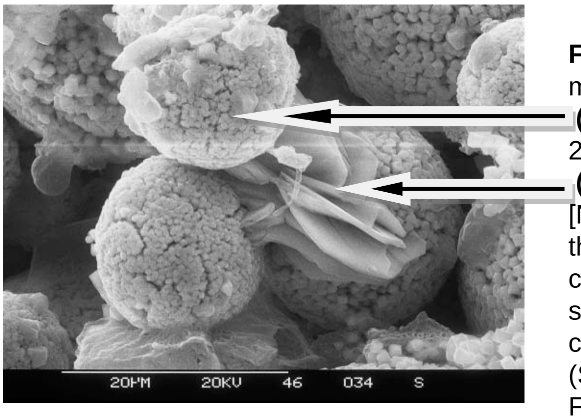


Figure 4-1. Scanning electron micrographs of:
(A) rounded pyrite “framboids” (up to 20 µm diameter) and
(B) large platelets of sideronatrite [$Na_2Fe(SO_4)_2.OH.3H_2O$] derived from the oxidation and dissolution of pyrite crystals in an acid sulfate soil profile shown in Figure 4-3 from Dairy Creek catchment in the Mt. Lofty Ranges (Site G3 in Figure 5-2) (modified from Fitzpatrick *et al.* 2000b).

The complex details of the sulfur oxidation process and formation of sulfuric material are described by several workers (e.g. Fanning & Fanning 1989; Fanning 2002; Nordstrom & Alpers 1999; Bigham *et al.* 1990, 1996, 2000, 2002). Acidification occurs if the amount of acidity produced exceeds the pH buffering capacity (the acid neutralizing capacity) of the soil. The oxidation of pyrite occurs via a series of steps, with the overall reaction generating significant amounts of acidity:

$$4FeS_2 + 15O_2 + 10H_2O \rightarrow 4FeOOH + 8H_2SO_4$$

ASS material that is capable of acidifying to form sulfuric material is called hypersulfidic material (see glossary; Sullivan *et al.* 2010). Exposure of pyrite to oxygen in the air results in oxidation, with each mole of pyrite yielding 4 moles of acidity (i.e. 2 moles of sulfuric acid). This process transforms hypersulfidic material to sulfuric material where, during oxidation, the material develops a pH of 4 or less (Isbell 1996); note that a sulfuric soil horizon has a pH of 3.5 or less in the US definition (Soil Survey Staff 1999, 2003).

For sulfuric material, the products of the chemical reactions can:

- Remain as dissolved constituents of soil pore waters (dissolved acidity)
- Form a component of exchangeable acidity sorbed to mineral surfaces
- Undergo a series of hydrolysis reactions and precipitate new minerals such as iron oxyhydroxides and iron oxyhydroxysulfates (e.g. schwertmannite and sideronatrite, jarosite, natrojarosite) at low pH (Retained Acidity)
- During evaporation, form a range of secondary minerals in the form of sulfate-rich salt efflorescences such as epsomite, hexahydrite and sideronatrite (Figure 4-3)

- Accelerate the weathering or dissolution of minerals (e.g. layers silicates containing Al, Si, Mg) in soils, and release and mobilise metals, such as aluminium and iron and precipitate new minerals nearby as shown in Figure 4-3

4.2. Drainage and disturbance of inland ASS materials

The drainage and disturbance of ASS materials is often the result of human action (anthropic modification), though some erosion and vegetation changes can result from natural processes, particularly during extended periods of low (drought) and high (flooding) rainfall conditions. Processes resulting in changes to soil, surface water levels, and raising or lowering of groundwater tables include:

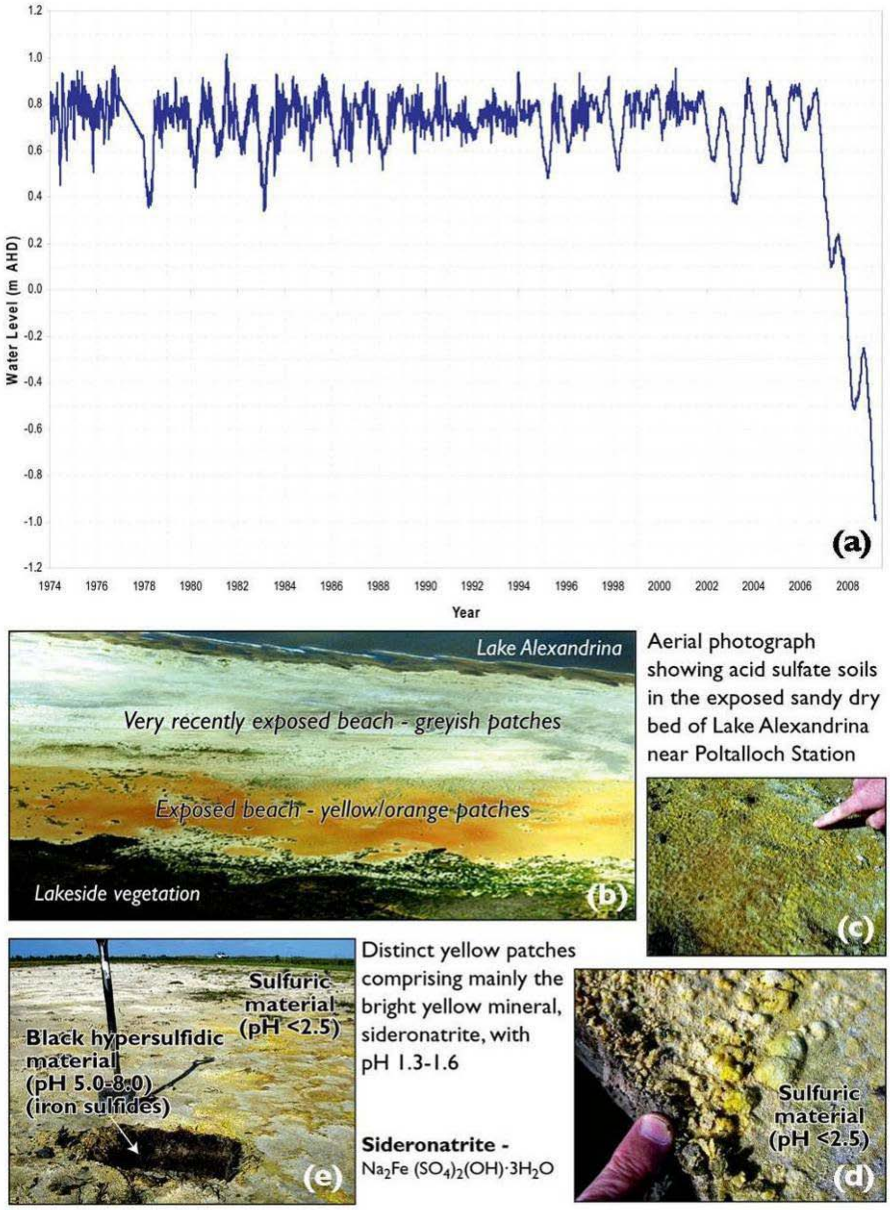
- ***Removal of native vegetation*** e.g. increasing recharge, rising of saline water tables (e.g. Coram *et al.* 2001; Fitzpatrick 1991).
- ***Agriculture*** e.g. tillage, pugging by cattle, creating hardpans or introducing oxygen to sulfidic discharge areas (e.g. Fitzpatrick *et al.* 2009b).
- ***Improved farming systems using vegetation*** e.g. reducing recharge, lowering of water tables by using deep-rooted plants (Barrett-Lennard *et al.* 2003).
- ***Erosion*** e.g. local lowering of the water table by formation and deepening of gullies; removal of surface soil layers by wind or sheet erosion forming scalds and exposing hardpans.
- ***Engineering works*** e.g. construction of weirs, blocking banks, levee banks and drains; surface and groundwater pumping (e.g. Shand *et al*. 2008a; Fitzpatrick *et al.* 2009b).
- ***Drought conditions*** causing the lowering of water levels in lakes (Figure 4-2), rivers and wetlands. Climate variability and change (e.g. Blöschl *et al.* 2007; IOCI 2002) are important considerations for sustainable management of Australia's water resources. The 2006 to 2010 drought in SE Australia is officially the worst on record, with minimal inflows to the Murray River and Darling River systems (Figure 4-2) between 2006 and 2010 (e.g. Fitzpatrick *et al.* 2009b).

Examples of inland freshwater ASS in the Riverland and Murraylands include seepages overlying mineralized zones (e.g. Skwarnecki and Fitzpatrick 2008), disposal/evaporation basins (e.g. Hicks and Fitzpatrick 2008; Lamontagne *et al.* 2004; 2006) and groundwater systems (e.g. Shand *et al.* 2008a).

4.3. Drought conditions: Formation of sulfuric material and salt efflorescences

Due to the extreme drought impacts in south-eastern Australia during Australia's Millennium drought from 1997 to 2010, water levels declined in Lake Alexandrina, Lake Albert and the River Murray system, especially in the section below Lock 1 at Blanchetown (e.g. see example for Lake Alexandrina in Figure 4-2). The reducing sulfidic materials once covered by water became exposed to oxygen at the river and lake margins (see example in Figure 4-2), and in adjacent wetlands. With continued lowering of water levels, the hypersulfidic material became progressively oxidised to greater depths in the soil profile (Figure 4-2).

With drainage, hypersulfidic materials in the reducing soils became oxidised and transformed to sulfuric material (pH < 4), with consequent accumulations of greenish-yellow and reddish-yellow (orange) coloured surface crusts of salt efflorescences comprising sulfate-rich evaporite minerals e.g. sideronatrite (yellow) and schwertmannite (orange) shown in Figure 4-2. These soils properties were affected by substantial wind erosion. Other hazards include noxious gas release (e.g. Hicks & Fitzpatrick 2008) as well as water quality, ecological and potential public health issues from mobilisation of metals/metalloids. These effects have been particularly severe in the Lower Murray and Lower Lakes region (Figure 4-2 and Figure 3-2) where research has progressed beyond studying the occurrence and distribution of ASS to understanding the impacts on adjacent environments through the mobilisation and transport of acidity and solutes (e.g. Fitzpatrick *et al.* 2008b,f, g; Simpson *et al.* 2008, 2009) and ecological risk assessment (Stauber *et al.* 2008).



Aerial photograph showing acid sulfate soils in the exposed sandy dry bed of Lake Alexandrina near Poltalloch Station

Distinct yellow patches comprising mainly the bright yellow mineral, sideronatrite, with pH 1.3-1.6

Sideronatrite - $Na_2Fe(SO_4)_2(OH)\cdot 3H_2O$

Figure 4-2. (a) Graph showing Lake Alexandrina water levels from 1974 to approximately June 2009 (DWLBC 2009) (in July 2009 the water levels were approaching -1.0m AHD, which is more than 1 m below the historically lowest water levels). (b) Aerial photograph showing the exposed sandy dry lake-bed of Lake Alexandrina (near Poltalloch Station, Narrung area; B4 in Figure 5-2) with surface crusts comprising the following coloured salt efflorescences: (i) bright yellowish colour on slightly elevated surfaces as seen in the close-up photographic views [(c) and (d)] and (ii) orange patches of the mineral schwertmannite occurring on the edges of slightly elevated surfaces [(c)]. (e) Soil pit with black hypersulfidic material (iron sulfides) at depth overlain by sulfuric material with distinct yellow patches of the bright yellow mineral, sideronatrite, with a pH ranging between 1.3 to 1.6 (modified from Fitzpatrick *et al*. 2008g; 2009b).

4.4. Erosion: Formation of acidic green & white salt efflorescences and white & reddish-yellow gelatinous precipitates

The exposure of black hypersulfidic material in stream banks caused by water erosion in the Mount Lofty Ranges, South Australia (Figure 4-3) has resulted in the exposure of pyrite formed in previously buried swamp deposits and rapid weathering of pyrite. Exposure of fresh pyrite surfaces to air and water initiates a series of chemical and microbial reactions that form sulfuric acid (sulfuric material). The sulfuric acid dissolves a variety of layer silicate minerals in the newly exposed soil profile in the stream bank, mobilising aluminium and other trace metals. In addition to pyrite, the underlying rocks in this region contain sphalerite and traces of galena and other minerals that contain zinc, lead and arsenic (Figure 4-3; see also Case Study involving seepages overlying mineralized zones discussed in Chapter 17). These elements are also concentrated as white (hydrated aluminium oxyhydroxide) and reddish-yellow (schwertmannite) gelatinous precipitates in puddles at the base of the eroded streamline (adjacent to Dairy Creek) and greatly exceed criteria for protection of freshwater aquatic organisms. In addition, the seeps and soil leachate contain elevated concentrations of dissolved iron, aluminium, and sulfate.

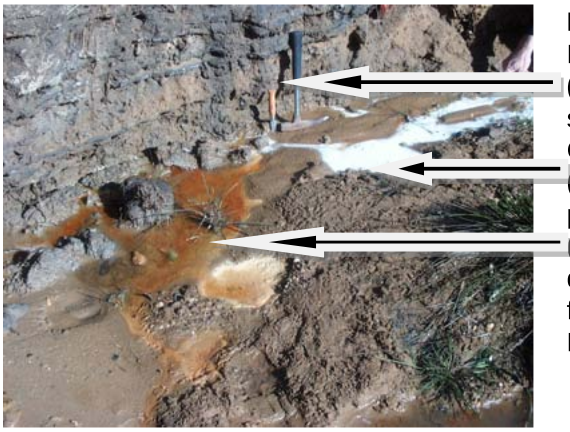


Figure 4-3. ASS in eroded stream bank in Mt Lofty Ranges showing:
(A) Sulfuric material (pH 2.5-3.5) exposed in stream bank by water erosion in upper Dairy Creek with sideronatrite (Figure 4-3, Figure 4-1
(B) White gelatinous precipitate is Al-rich and preferentially forms in sandy areas (pH 4.5),
(C) Reddish-yellow gelatinous precipitate is dominantly schwertmannite and preferentially forms in clay-rich areas (pH <4). (From Fitzpatrick and Shand 2008)

Greenish (sideronatrite) and white (tamarugite) soluble oxyhydroxysulfate minerals crystallize on the bank face immobilising metals when these waters evaporate (Figure 4-3; Figure 4-4). However, during rain events, these minerals readily dissolve again, releasing the stored acidity and metals to runoff and stream water as shown in Figure 4-3. The cycle of salt formation and dissolution contributes to acid drainage from the site as long as sulfidic material remains exposed to air and kept moist.

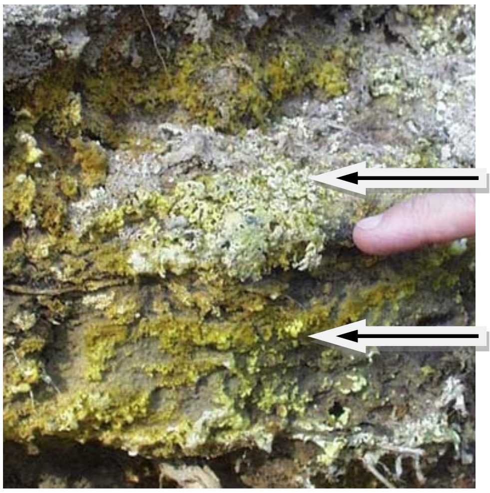


Figure 4-4. Close-up view of sulfuric material (pH 2.5-3.5) in exposed stream bank formed by water erosion in Dairy Creek shown in Figure 4-3 with:

White crystals of tamarugite [$Na_2Al(SO_4)_2.OH.H_2O$].

Greenish-yellow crystals of sideronatrite [$Na_2Fe(SO_4)_2.OH.H_2O$] formed in sandy layers, derived from the oxidation and dissolution of the pyrite framboids as shown in the scanning electron micrograph in Figure 4-1 (from Fitzpatrick *et al.* 2000b).

The acid leachate from sulfuric materials shown in Figure 4-3 dissolves clay minerals and to produce a range of hydrated white and reddish-yellow precipitates (Fitzpatrick *et al.* 1992; 2000b) depending upon pH. The white precipitate in Figure 4-3 is composed dominantly of Al_2O_3 (42 %), SiO_2 (8.28 %) and SO_3 (7.16 %) and Na_2O (1.07 %), as well as high As (<5 ppm). Transmission electron (TEM) and X-ray diffraction analysis suggest that it is an amorphous hydrated aluminium oxyhydroxide (with some evidence for pseudoboehmite-like characteristics). The reddish-yellow precipitate (dominant schwertmannite) is rich in Fe (35.6 %), Mn (0.5 %) and As (135 ppm), the latter preferentially scavenged by iron oxides. Several studies have shown that dissolution of salt accumulations along stream banks during a rainstorm may temporarily lower pH and increase metal loads in streams (e.g. Bigham *et al.* 1996).

The refilling of wetlands which contain sulfuric materials with salts is also known to have a significant effect on water quality, which may last a considerable time (e.g. Shand *et al.* 2010a, b). Such impacts on water quality can have damaging effects on aquatic ecosystems e.g. causing fish kills, and can complicate efforts to remediate acid drainage. Rainfall events can also flush salts from soils, leading to pulses of contaminated water flowing into streams (e.g. Figure 4-3). Such flushes mean that these various products or minerals may or may not be present at a given site on a given day, depending on weather conditions.

4.5. Agriculture: Formation of acidic reddish-yellow gelatinous precipitates in seeps

The reddish-yellow (or orange-yellow) gelatinous precipitates, which occur in ephemeral to semi-permanent saline seeps shown in Figure 4-5 from the Mount Lofty Ranges, South Australia are dominantly schwertmannite [$Fe_8O_8(OH)_6SO_4$]. In this region, Fitzpatrick (1991) identified the first occurrence of inland ASS with sulfuric materials and surface accumulations of the reddish-yellow Fe oxyhydroxides (schwertmannite) and other sulfate-rich salts. Inland ASS with sulfuric material overlies black, strongly reduced subsoil horizons containing pyrite formed by bacterial sulfate reduction in these degraded agricultural areas.

Schwertmannite was first sampled and identified in these acidic saline seepages (inland ASS) in 1990 (for photographs of the original site where schwertmannite was first identified see page 53 in Fitzpatrick and Shand 2008). Schwertmannite is indicative of a weathering environment with soil solutions having a pH in the range 3 to 4 and sulfate concentrations between 1000 and 3000 mg/L (Fitzpatrick *et al.* 1996; Bigham *et al.* 2000).

Figure 4-5. Reddish-yellow (orange) gelatinous precipitate and “oil-like slick” with prominent iridescence on water surface formed by oxidation by iron oxidising bacteria (*Gallionella* and/or *Leptothrix*) exposed in a shallow saline swamp/wetland at the Gutheries site near Mt Torrens in the Mount Lofty Ranges, South Australia. Dominant iron mineral identified by X-ray diffraction was schwertmannite (pH 3.5 – 4.0). See also Fitzpatrick and Shand (2008) for photographs on page 53 taken in the same wetland in July 1990 and August 1993 showing the original site where schwertmannite was first identified.

4.6. Irrigation drainage waters: Formation of acidic reddish-yellow gelatinous precipitates

The bright reddish-yellow (orange) plume of fine iron-rich precipitate, which is being mobilised under shallow acid (pH 2.5 – 3.5) drainage water using a shovel in April 2011 in Figure 4-6, is dominantly schwertmannite. These schwertmannite-rich precipitates have very high concentrations of metals (Al > Pb> As > Cu > Zn) because of likely co-precipitation/scavenging of these elements during formation of schwertmannite. They also contain high concentrations of Ni, Cr and Mn.

This situation from the Lower Murray Reclaimed Irrigation Areas (LMRIA) with low water tables has been created by the low water level in the River Murray during the drought (2006 – 2010) and the inability of irrigators to access water or much of their water allocation. These low water tables under the floodplain during the drought has resulted in oxidation of previously undisturbed hypersulfidic material in ASS. The rising river and groundwater levels since late 2009, and some recommencement of irrigation in 2011, has mobilised this soil acidity and caused precipitation of the bright orange-coloured mineral schwertmannite in drains (i.e. pH 2.5 to 3.5). The drains in these irrigation areas also receive regional groundwater inputs and require drainage to avoid back-flooding of pastures.

Figure 4-6. Acidic (pH 2.5 – 3.5) iron rich drain water in Burdett drain near Murray Bridge (Long Flat), Lower Murray Reclaimed Irrigation Area (LMRIA) in April 2011, comprising the reddish-yellow (orange) coloured precipitate identified as schwertmannite, which forms between pH 2.5 and 3.5.

4.7. Drought conditions: Formation of acidic yellowish-red gelatinous precipitates

Yellowish-red gelatinous precipitates containing a mixture of dominantly sideronatrite with minor schwertmannite (pH 2.5 – 3.5) was identified by X-ray diffraction exposed on the edge of a shallow saline swamp/wetland in Burnt Creek near Dunolly, Victoria (Figure 4-7).

Figure 4-7. Yellowish-red (orange) gelatinous precipitate with prominent iridescence on water surface formed by oxidation by iron oxidising bacteria (probably *Gallionella* and/or *Leptothrix*) exposed on the edge of a shallow saline swamp/wetland in Burnt Creek near Dunolly, Victoria (site BCR 1.Figure 21-3) (pH < 2.5 – 3.5). Comprising dominantly sideronatrite [$Na_2Fe(SO_4)_2.OH.3H_2O$] with schwertmannite (pH 3.5 – 4.0). identified by X-ray diffraction. (from Thomas *et al.* 2009).

In summary, most of the inland ASS in the Riverland and Murraylands are underlain by limestone and stranded coastal dunes, which are also often calcareous. Despite this significant local source of acid neutralizing capacity, ASS (some with sulfuric materials) are widely distributed in wetland areas of the region. These have been largely caused by either drought conditions (2006 to 2009; e.g. Fitzpatrick & Shand 2008) or rising saline sulfate-rich groundwaters. At Swanport near Murray Bridge (see Case study in Chapter 16: Figure 15-1), distinct golden yellowish or greenish crystals of metavoltine [$K_2Na_6Fe^{2+}Fe^{3+}{}_6(SO_4)_{12}O_2.18H_2O$] was identified by x-ray diffraction, indicating the presence of sulfuric material but with a pH < 2.5.

4.8. Drought conditions: Formation of alkaline white salt efflorescences

A black plume of likely monosulfidic material is being mobilised under shallow water in Lake Bonney by disturbance using a shovel in July 2007 as shown in Figure 4-8. Extreme drought impacts in south-eastern Australia from about 2006 to 2010, caused water levels to decline in Lake Bonney and the River Murray system (Figure 4-8). Consequently, a temporary embankment was constructed to help mitigate these drought-related problems in the MDB. The monosulfidic material once covered by water in Lake Bonney became exposed to oxygen at the lake margin (Figure 4-8), and in adjacent wetlands. With continued lowering of water levels, the monosulfidic material became progressively oxidised to greater depths in the soil profile (Figure 4-8; Fitzpatrick *et al*. 2008h; Shand *et al.* 2009). This resulted in accumulations of surface crusts of salt efflorescences comprising sulfate-rich evaporite minerals (thenardite, eugsterite and gypsum) shown in Figure 4-8.

Figure 4-8. Changes in water level at Lake Bonney due to a temporary embankment to help mitigate drought-related problems in the river channel. Clockwise from above: July 2007 (showing mobilising of black monosulfides with soil disturbance) to drying in April 2008, which shows white salt efflorescences along the beach at Barmera (Site F5 in Figure 5-2 (from Fitzpatrick *et al.* 2008h; 2009b, Shand *et al*. 2009).

The white salt efflorescences are mainly in the form of thenardite [$Na_2(SO_4)$], eugsterite [$Na_4 Ca(SO_4)_3 \cdot 2H_2O$] and gypsum

The significance of the minerals found in these salt efflorescences is that they appear each summer, or in dry periods, and are environmental indicators. A change in the minerals present may also indicate a change in the nature of the source of the dissolved components entering the system from surface or ground waters.

Hence, an extensive research and monitoring continues in the Lower Murray region to confirm seasonal/wet-dry period changes in morphological, chemical and mineralogical composition with the results being fed back into an adaptive management framework (e.g. Baker *et al.* 2010; Fitzpatrick *et al.* 2010e; 2011). As a consequence, the Lower Lakes management strategy can be refined to consist of a combination of management actions if trigger levels are approached.

5. DISTRIBUTION AND SPATIAL VARIABILITY

The section briefly describes the National, Regional and Local distribution and variation, both spatially and with time, of Australian Inland freshwater Acid Sulfate Soils. This section also provides a summary of how conceptual soil-regolith models are used to describe and explain the spatial heterogeneity of ASS properties. These models help to describe ASS processes that occur as a consequence of fundamental shifts in the "environmental equilibrium" brought about by the impacts of management practices, drought conditions and reflooding. Case studies illustrate the complexities and importance of understanding the spatial heterogeneity of ASS properties at specific sites to assess the implications and suitability of the different management options.

5.1. Background

Acid sulfate soils in a fluctuating water environment are not stable and therefore may undergo rapid change depending on whether water levels are dropping or rising. Acid sulfate soil materials change depending on the water status of the soil (saturated or unsaturated), which forms a control on whether chemical processes are oxidising or reducing, and the acid status. Consequently, an understanding of the detailed behaviour of various Acid Sulfate Soil materials (e.g. hypersulfidic or sulfuric) and features (e.g. cracks or salt efflorescences) in layers, horizons and deep regolith is fundamental to successful characterisation and mapping of inland ASS.

ASS maps represent a "snap shot" of conditions at the time of survey, and should only be interpreted within the context of the broader environmental conditions, i.e. whether the water levels are rising or decreasing, where are the hot-spots and what is the nature of assets to be protected? Given the complex nature of ASS and their response to environmental conditions, interpretation by lay-persons should be done with assistance of expert knowledge to achieve best management outcomes.

5.2. National distribution: Atlas of Australian Acid Sulfate Soils

The Atlas of Australian Acid Sulfate Soils is a web-based hazard assessment tool with a nationally consistent legend, which provides information about the distribution and properties of both coastal and inland acid sulfate soils across Australia (Fitzpatrick *et al.* 2008e; 2010c,d).

This tool is available on ASRIS (Australian Soil Resource Information System: www.asris.gov.au) and every polygon or mapping unit is attributed with information pertaining to: (i) classes of "probability of occurrence" (Figure 5-1) (ii) levels of confidence relating to the quality of the data source, and (iii) additional descriptors such as desiccation cracks.

The Atlas is a constantly evolving national map of available ASS information. Inland ASS are widespread throughout Australia as shown in the Atlas of Australian Acid Sulfate Soils (AAASS). They comprise an area of approximately 157,000 km^2 (Fitzpatrick *et al.* 2008e) and the 36 case studies discussed in this report illustrate their wide variation in properties. A product of contributions from all States, the AAASS delivers, via the web, the sum of ASS investigations and mapping in Australia in a seamless, systematic and uniform way (Fitzpatrick *et al.*, 2008e; 2010c). The map is largely modelled from small scale surrogate data, but where explicit ASS survey mapping exists, such in the Lower Lakes (Fitzpatrick *et al.*, 2010c), the AAASS depicts the most up to date ASS spatial information available. Extracts of the AAASS are regularly sought by government agencies, engineering firms, environmental consultants and farmers requiring spatial information on the land under their management responsibility. For example, knowledge of likely or potential ASS risks in a given area of interest will enable farmers and land managers to avoid or manage problems associated with the disturbance of sulfuric, sulfidic, hypersulfidic, and monosulfidic materials in ASS. The ASS database contains details on chemistry, soil descriptions and site specific evaluations of ASS affected areas. This information is spatially located and contributes to the classification and confidence rating of polygons in the AAASS.

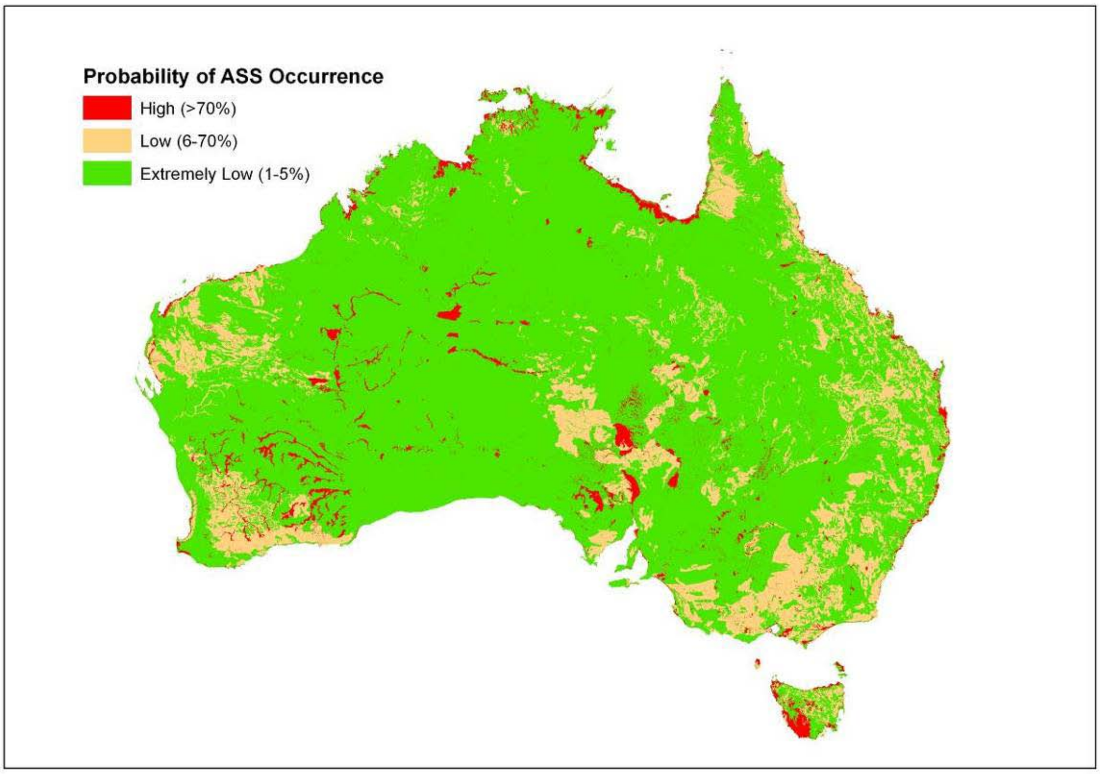


Figure 5-1. Map of Australian Acid Sulfate Soils. The latest mapping is disseminated live via Web served GIS facility at www.asris.csiro.au. (from Fitzpatrick *et al.* 2008e, 2010b,c)

Australia's current national soil classification system is the Australian Soil Classification (ASC; Isbell and CSIRO 2000). However, this system and other internationally recognised classification systems such as Soil Taxonomy (Soil Survey Staff 2003) require considerable expertise and experience to be used effectively. More importantly, these classification systems do not yet incorporate the new terminologies: subaqueous soils, monosulfidic material, hypersulfidic and hyposulfidic material. Therefore, a simplified "Soil Identification Key" (see Fitzpatrick *et al.* 2009e) was developed specifically for inland acid sulfate soils, initially for ASS in the River Murray and Lower Lakes systems to identify and classify the various types and subtypes of acid sulfate soils (Fitzpatrick *et al.* 2008b,e,f,i; 2010c,d).

The key was developed to assist users who are not experts in soil classification systems to easily identify types and subtypes of acid sulfate soils. 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.* 2008e) and separates out the same soil classes as would occur if the ASC or Soil Taxonomy was used. It recognises 5 Soil Types and 17 Soil Subtypes (Fitzpatrick *et al.* 2008e).

5.3. Regional distribution: Geographical Areas of Inland Acid Sulfate Soils

The geographical coverage of ASS examples described in this document includes different types and subtypes of ASS in different landscape settings or geographical areas (e.g. Figure 5-2), which occur in areas of different geology, geomorphology and soil materials (e.g. sands, clays and peats), together with different hydrogeological, hydrological and biogeochemical settings. The subdivision of Geographical Areas of ASS is helpful in the first step in constructing conceptual soil-regolith models based on the assumption that different soils and processes may be operating in different geomorphic landscapes.

Assessment at regional soil-landscape scales involves the subdivision of landscapes into distinct Geographical Areas of ASS, such as (Figure 5-2):

(i) ***Tributaries***: SA [Mount Lofty Ranges (D)] and Victoria [Burnt Creek (J)].
(ii) ***Lakes and adjacent wetlands***: SA [e.g. Lake Alexandrina (B) & Lake Albert (C), Victoria [Lake Bolac (L)] and WA [Wheat Belt (M)]
(iii) ***Main river channels and adjacent wetlands*** – also comprising numerous billabongs, swamps, disposal evaporation basins, drains and minor lakes (e.g. Lake Bonney; F5 in Figure 5-2)]: SA [River Murray section below Blanchetown (E); River Murray section above Blanchetown (F)] and Victoria [Loddon River (K)].
(iv) ***Estuaries, River Mouth and Swamps*** with combined marine/freshwater influence in SA [e.g. Coorong and Murray Mouth (Area A in Figure 5-2) and WA [Perth Coastal Plain (N)].
(v) ***Seepages overlying mineralized zones****:* SA [Eastern Mount Lofty Ranges (G)] and Victoria [Eastern Dundas Tablelands (I)].
(vi) ***Abandoned mines*** also comprising waste rock stockpiles and tailing impoundments, which strongly impact on Inland freshwater systems**:** SA [Pyrite and Cu/Zn mines (H).

Examples of selected case studies from South Australia in the Riverland and Murraylands, Victoria and Western Australia are shown in Figure 5-2 and summarised within seven Geographical Areas of ASS. ASS materials in all these fresh water inland Geographical Areas studied (i.e. A to F in Figure 5-2) are much more abundant than previously recognised (e.g. Fitzpatrick *et al.* 2008a,g,h; 2010a,c,d,e). Additional case studies of inland freshwater ASS across Australia include examples from Victoria (e.g. sports fields: Hicks and Fitzpatrick 2008), New South Wales (e.g. Bottle Bend Lagoon: Baldwin *et al.* 2007; Hall *et al.* 2006; Tareena Billabong: Fitzpatrick *et al.* 2008, Tilley Swamp: Fitzpatrick *et al.* 2008d), Western Australia (drains and lakes in WA Wheatbelt: Degens *et al.* 2008a,b,c; Shand *et al*. 2008; Fitzpatrick *et al.* 2010a; Perth Coastal Plain: Appleyard and Cook 2009; Appleyard *et al.* 2004, 2006) and Northern Territory (e.g. Floodplains: Willett 2008).

5.4. Regional distribution: Lakes and adjacent wetlands (Lower Lakes Alexandrina (B) & Lake

A conceptual model (**Figure 5-3**) was developed to describe three sequential drying phases during Australia's Millennium drought from 1997 to 2009 and the development of different acid sulfate soil subtypes (Fitzpatrick *et al.* 2008b,d; 2009c). Applying this model, Fitzpatrick *et al.* (2008b,c) integrated locally detailed field survey and laboratory data and used the Australian Soil Classification (Isbell 1996) to derive 14 subtypes of ASS conforming to the map legend of the Atlas of Australian Acid Sulfate Soils (Fitzpatrick *et al.* 2008e).

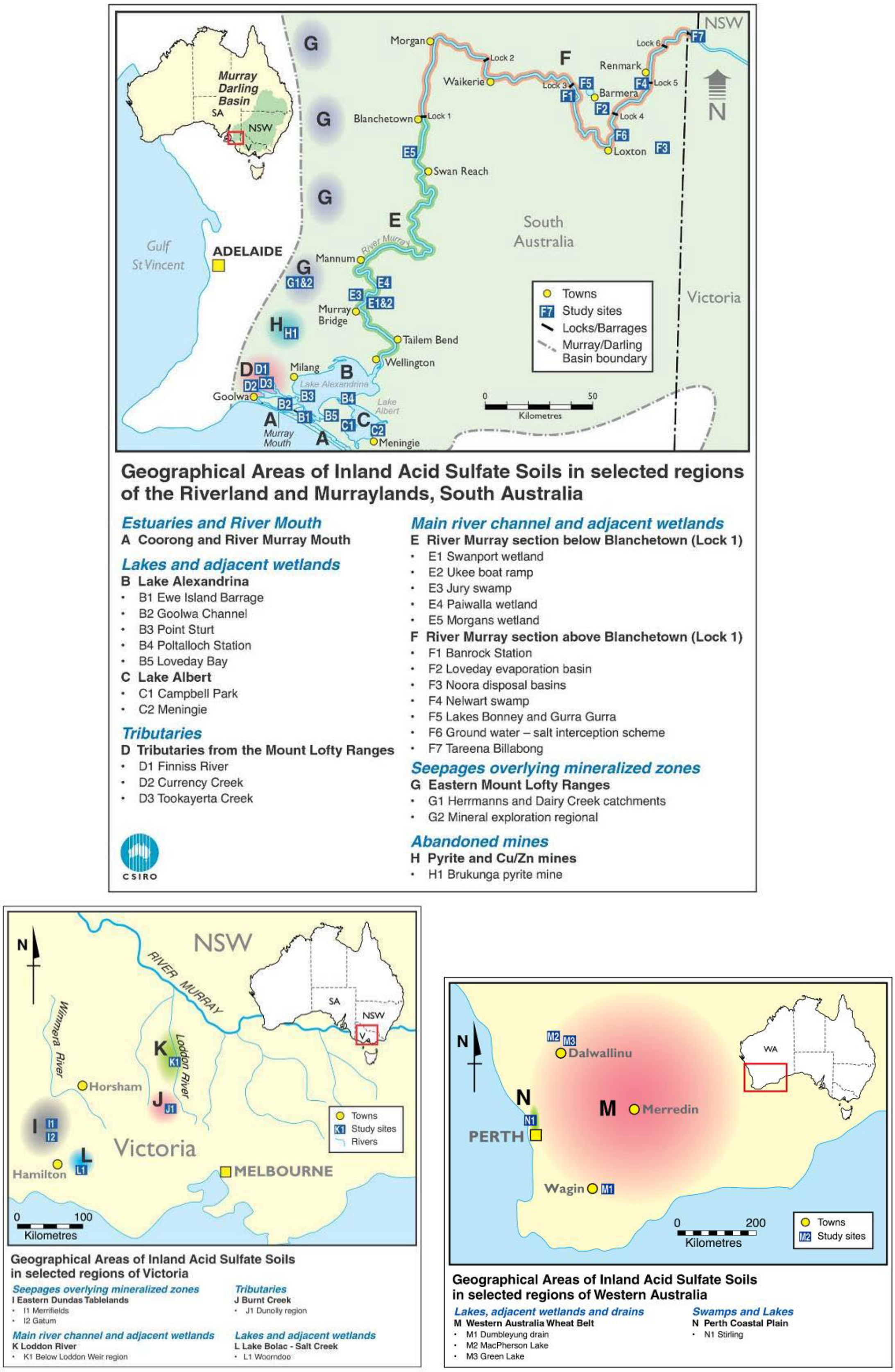


Figure 5-2. Maps showing Geographical Areas of Inland Acid Sulfate Soils in South Australia (Riverland & Murraylands) (top), Victoria (lower left) and Western Australia (lower right) showing 36 case studies.

A series of conceptual process models for each of the lakes (Alexandrina and Albert) and lower River Murray systems were applied to:

- explain the sequential formation and transformation of sulfidic material to sulfuric material in various subtypes of acid sulfate soil (5,500 B.C.E to the extreme drought conditions of 2006-2008)
- explain and predict new occurrences of minerals, their formation and transformation (e.g. pyrite to sideronatrite; sideronatrite to schwertmannite; pyrite to natrojarosite), and
- predict the impacts of further drought on acid sulfate soil oxidation and impacts

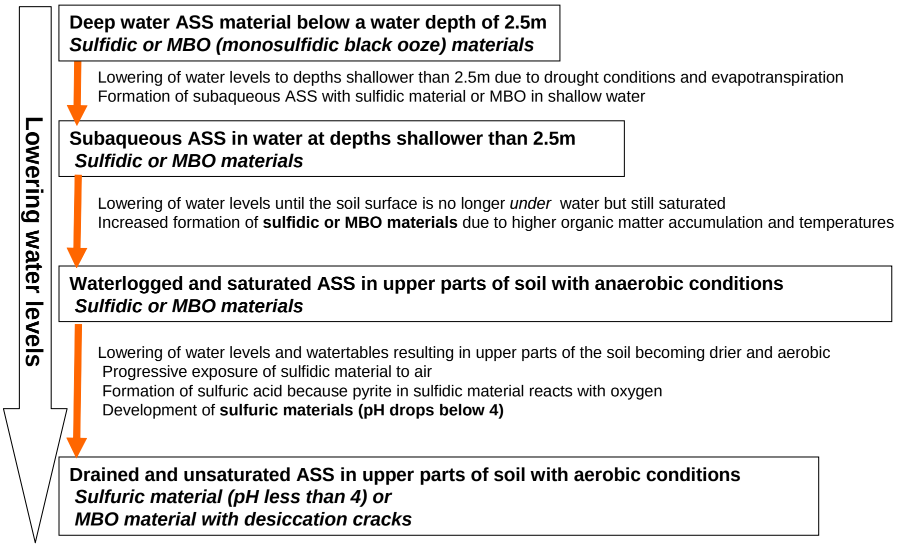


Figure 5-3. Generalised conceptual model showing the sequential transformation of four classes of acid sulfate soil due to lowering of water levels (from Fitzpatrick *et al.* 2008b,f,i).

Combined bathymetry, soil and vegetation mapping in a geographic information system (GIS) framework was used to help predict the distribution of different subtypes of acid sulfate soil according to three predictive scenario maps (Fitzpatrick *et al.* 2008b,f,i), which in Figure 5-4 depicts sequential changes in acid sulfate soil materials during different water levels in Lake Alexandrina and tributaries (e.g. Finniss River). These acid sulfate soil maps are constantly being revised as new information becomes available through site visits, field testing and the availability of new spatial data sets (e.g. Fitzpatrick *et al.* 2008b; 2009a; 2010a).

Field studies combined with these maps and predictive soil-regolith models were used to conclude that most of this region could produce widespread areas of sulfuric material if the water level fell to -1.5 m AHD (see predictive scenario shown in the acid sulfate soil maps in Figure 5-4). As a result of these types of predictions, deep concerns grew during 2009 that, without significant new river inflows to the lake, the ASS trajectories (presented in these maps and graphs) could eventually be realised. For example, at -1.5 m AHD, approximately 20,000 ha of sulfuric material will be produced (Figure 5-5) along with associated environmental degradation.

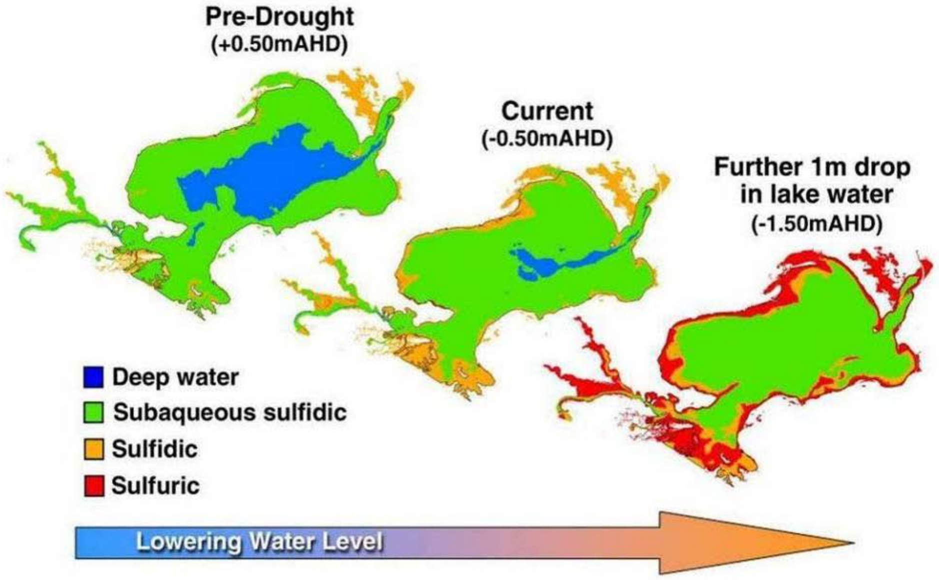


Figure 5-4. Predictive scenario maps depicting changes in acid sulfate soil materials at different water levels in Lake Alexandrina (+0.5 m AHD, –0.5 m AHD and –1.5 m AHD) from Fitzpatrick *et al.* (2008a,b,d; 2009c). Finniss River, Currency Creek and Goolwa Channel are the three extensions occurring on the left side of Lake Alexandrina.

In August 2009 the predictions expressed in Figure 5-4 and Figure 5-5 were verified based on extensive field investigations and laboratory analyses across the whole Lower Lakes region where 330 sites were described and sampled, which resulted in 706 samples being analysed for pH and acid base accounting parameters (Fitzpatrick *et al.* 2010c). The sampling sites were selected randomly using geostatistical techniques. This information was used to produce maps of various soil parameters across the whole Lower Lakes (Figure 5-6) using geostatistical techniques, which identified approximately:

- 80% (70,829 ha) of the total lake area (89,219 ha) had Hypersulfidic subaqueous soils with associated Hyposulfidic subaqueous soils and Hypersulfidic hydrosols
- 20% (18,226 ha) of the total lake area (89,219 ha) had Sulfuric unsaturated soils and Sulfuric hydrosols
- 0.2% (165 ha) of the total lake area (89,219 ha) had Sulfuric subaqueous soils

Spatial heterogeneity mapping by Fitzpatrick *et al.* (2010c) also identified:

- Tributary regions with poor connection to the main lake such as Currency Creek and Finniss River with widespread occurrence of ASS comprising both sulfuric and hypersulfidic materials, confirming the previous predictions of Fitzpatrick *et al.* (2008b,f,i; 2009a,b).
- Considerable variation in the vertical and horizontal extent of ASS materials and their net acidity, pH and Titratable Actual Acidity, highlighting significant variation in the risk profile of ASS around the lower lakes and adjacent tributaries.

This information was used as justification to construct a temporary flow regulator (earth dam) across the Goolwa Channel at Clayton Bay, to assist with raising water levels in the Goolwa Channel - Finniss River - Currency Creek region (see Figure 6-1; Figure 11-11) as a successful management option for preventing more sulfidic material oxidising to form sulfuric material.

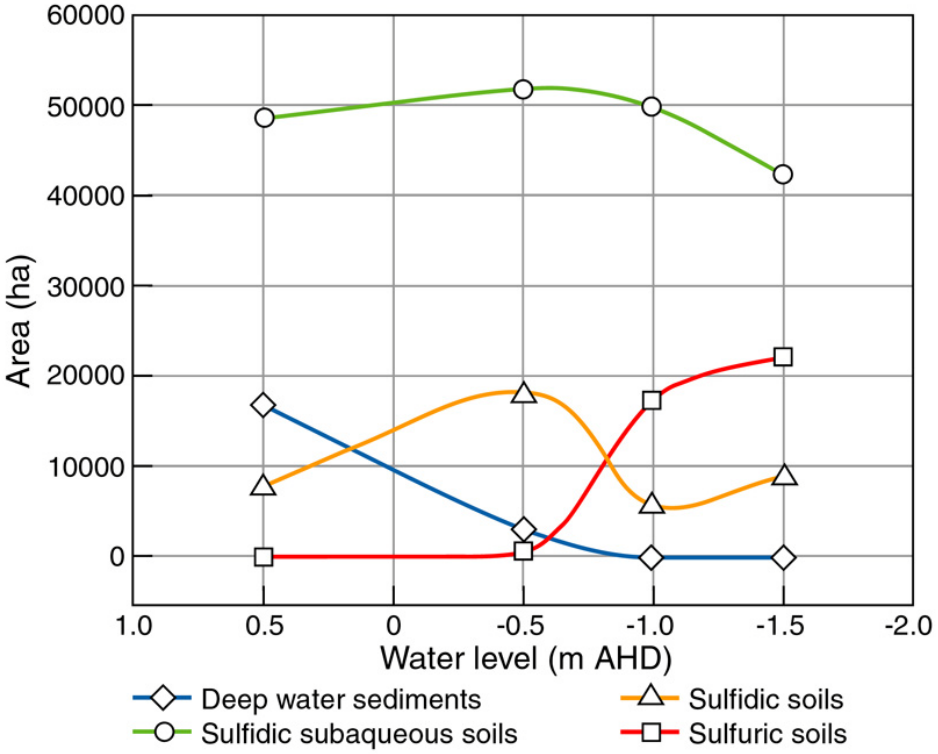


Figure 5-5. Graphic depiction of scenario changes in the spatial extent of ASS material at different water levels in Lake Alexandrina (+0.5 m AHD, –0.5 m AHD and –1.5 m AHD) from Fitzpatrick *et al.* (2008b,f,i; 2009a).

5.5. Local distribution: spatial and temporal variability of Inland Acid Sulfate Soils

An understanding of the detailed behaviour of various ASS materials (e.g. sulfuric, hypersulfidic, hyposulfidic and monosulfidic) and features (e.g. cracks or salt efflorescences) in layers, horizons and deep regolith is fundamental to successful site or regional characterisation of inland Acid Sulfate Soils. This section provides a summary of how conceptual models (see glossary) can be used to describe and explain the spatial and temporal heterogeneity of ASS properties and the main soil-regolith processes that occur as a consequence of wide-ranging and fundamental shifts in the “environmental equilibrium” brought about by the impact of European settlement. As explained previously, these changes included the building of locks and barrages to contain water flow (Figure 3-2) and over-allocation of irrigation water as well as large scale clearing of native vegetation. These changes have been exacerbated by extreme drought conditions since 2006, which have lowered water levels in rivers, lakes and wetlands (see Figure 4-2). The effects of these changes have led to an accelerated accumulation, then drying and oxidation of inland ASS materials. The transformation of hypersulfidic materials in inland ASS to acidic by-products arose from this disequilibrium, which can be presented in various categories of conceptual soil-regolith process models in graphical and/or written form.

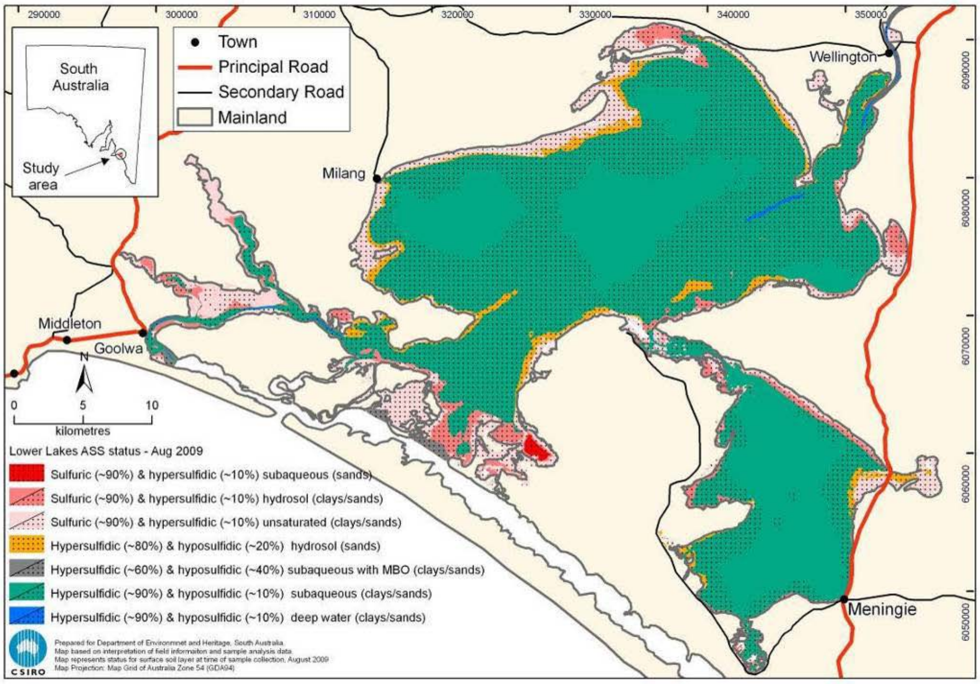


Figure 5-6. Soil classification map of the distribution of the wide range of acid sulfate soil subtypes. Map legend showing: i) acid sulfate soil materials with sulfuric (pH <4), hypersulfidic (pH <4 after incubation), hyposulfidic (pH >4 after incubation) and monosulfidic (MBO) materials; ii) soil characterisation with deep water (overlying water >2.5 m), subaqueous (overlying water 0 to 2.5 m), hydrosols (saturated to a depth of 50 cm below the mineral soil surface), and unsaturated (unsaturated to a depth of 50 cm below the mineral soil surface) soils; iii) soil texture with sands, loams, and clays.

5.5.1. Conceptual soil-regolith models

To aid in understanding the spatial heterogeneity of acid sulfate soil properties, soil landscape cross-sections in the form of conceptual soil-regolith toposequence models should be constructed from field and laboratory data and surveyor knowledge. Conceptual soil-regolith process models enable workers to develop and present a mechanistic understanding of complex spatial and temporal soil-regolith environments (Fritsch & Fitzpatrick 1994). The regolith is the unconsolidated earth material present above bedrock and includes the upper soil layers. These models are cross-sectional representations of soil-regolith-bedrock profiles that illustrate vertical and lateral changes that occur across wetland hydro-toposequences. They also help tell a story explaining the complex soil, hydrological and biogeochemical interactions that have led to the development of an ASS problem (e.g. Fitzpatrick & Merry 2002; Fitzpatrick 2008).

These models may also incorporate various predicted management outcomes linked to scenarios such as:

- The “no further action or minimum intervention” option such as permitting water levels to continue to lower, resulting in the progressive exposure and oxidation of hypersulfidic materials at depth, and formation of more sulfuric material (e.g. Jury Swamp example below)

- Implementation of various management options such as the construction of water flow regulators, addition of limestone to increase alkalinity or allow seawater entry to raise water levels

Example models: The following two sections describe six examples of soil-regolith models. These particular models were chosen to help visualise the results of several ASS investigations performed at typical sites with complex surface and subsurface ASS features, including several regolith layers and shallow surface water interface systems. Two categories of soil-regolith toposequence models (Fitzpatrick 2008) have been found to be useful for ASS scenarios:

- Descriptive (Figure 5-7) and Explanatory (Figure 5-8 and Figure 5-11) soil-regolith models
- Predictive soil-regolith models: generalised (Figure 5-12) and specific (Figure 5-13)

These examples of one (1) descriptive, three (3) explanatory, one (1) specific predictive soil-regolith model and one (1) generalised predictive soil-regolith model are presented for areas in the Lower Lakes and River Murray below.

5.5.2. Descriptive and Explanatory soil-regolith models

The descriptive soil-regolith process models shown in Figure 5-7 and (Figure 5-11) depict two typical scenarios of inland ASS; in Lake Alexandrina and the River Murray respectively. These models characterise the lateral and vertical spatial variability of soil-regolith layers, horizons, materials (e.g. hypersulfidic or sulfuric) and features (salt efflorescences and cracking) across complex wetland hydro-toposequences. Such models can represent current and past water levels and help in the development of practical frameworks and solutions for managing soils. These models are in turn used to help develop future temporal soil-regolith models (4D = space and time) for a particular wetland environment (generalised models) or wetland transect (specific models).

In the soil-regolith model examples shown in Figure 5-7, Figure 5-10 and (Figure 5-11) the spatial variation of acid sulfate soil materials identified are displayed using a standard set of graphic symbols (e.g. see symbols displayed in the legend of Figure 5-7). They also display other features formed in acid sulfate soil such as soil cracks, salt efflorescences and soil burning caused as a consequence of receding water levels due to extreme drought conditions.

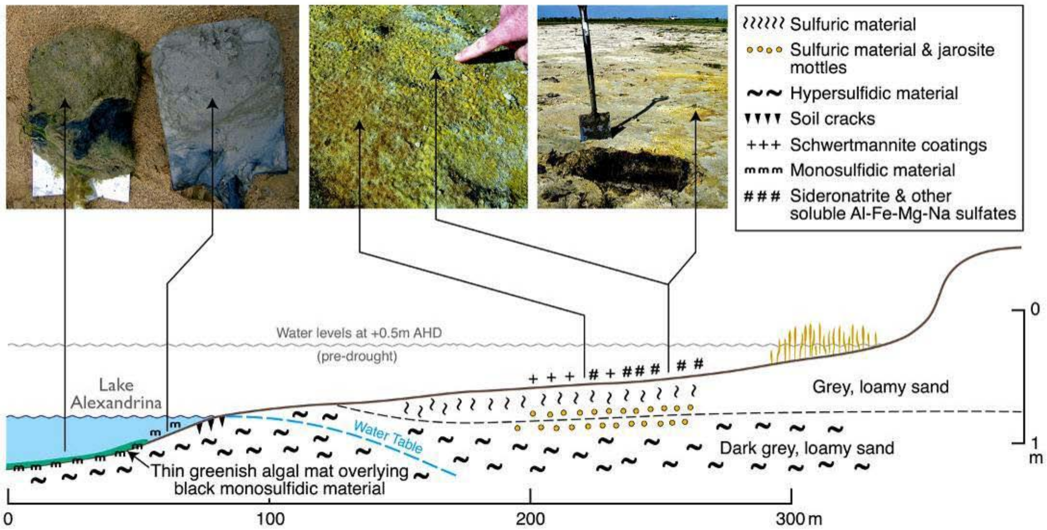


Figure 5-7. Descriptive soil-regolith model of a transect from Lake Alexandrina to elevated land near Poltalloch Station (Site B4 in Figure 5-2). NOTE: water table level pattern is exaggerated because of the inflated vertical scale necessary to display all soil features.

In the exposed sandy lake-bed of Lake Alexandrina, surface crusts and salt efflorescences contained: (i) the prominent bright yellow mineral sideronatrite, with a pH ranging between 1.3 to 1.6 as shown in Figure 5-7, which in turn overlay black hypersulfidic material and (ii) brownish-orange coatings of the mineral schwertmannite, which forms from sideronatrite (dissolves in rainwater and re-precipitates as schwertmannite).

The explanatory predictive soil-regolith models are constructed to characterise known specific sequential lateral and vertical changes to ASS layers, horizons, materials and other features e.g. caused by drying (droughts) and subsequent re-wetting (re-flooding); or caused by drying (droughts) and subsequent burning.

Drying and re-wetting example: Models were constructed for areas that were originally sampled when they were exposed and dry (i.e. 2008) and subsequently when they were covered with surface water (i.e. 2009) (see Figure 5-8). The top cross-section diagram with photograph of Site CUR 13 (Figure 5-8) was taken in November 2008, and describes the exposed/dry creek-bed of Goolwa Channel/Currency Creek, which shows an ASS profile with sulfuric material (pH < 4) to a depth of 30 cm. The lower conceptual model with photograph was constructed in December 2009 when the same locality was flooded due to winter runoff from the catchment and pumping from Lake Alexandrina following installation of the Clayton regulator. The flooded Acid Sulfate Soil stayed submerged under 80 cm of water for a period of approximately six months, but remained largely acidic (i.e. Sulfuric subaqueous clay) except for a thin 5 cm thick surface layer comprising black monosulfidic material, which overlay sulfuric material with pale yellow mottles of natrojarosite (second layer) and dark grey hypersulfidic material below 30 cm.

Drying, extreme drying and burning example: When the surface soil layer (0 to 50 cm) of Jury Swamp had completely dried, the dry vegetation (stands of willows, Phragmites and other dead reeds and rushes) and peaty materials were burned (Figure 5-11). The dried reeds and willow trees were up to 2 to 3 metres high when the burning occurred. With such a tremendous fuel load, the fires caused temperatures thought to exceed 500 °C (i.e. as though in a kiln or oven). Topsoil between 0 and 40 cm was transformed irreversibly into reddish hard cemented (fused) ceramic-like, porous fragments or ceramic brick-like soil material. Pyrite (FeS_2) was converted to the iron oxide maghemite (Fe_2O_3), releasing sulfur dioxide gas, but possibly retaining the same pyrite framboid shape.

Conditions for maghemite formation were ideal because the pyrite ‘framboids’ were completely coated in organic matter and heated to above 300 °C in a carbon-rich reducing atmosphere.

The severely burned locations at the site shown in (Figure 5-11) (see sequence of 3 photographs in top right hand corner of diagram) have a distinctive reddish colour on the soil surface with loss of organic matter, and sometimes white to gray ash on top of the soil. The reddened surface soil layer ranged in thickness from 1 to 50 cm and was underlain by a blackened soil layer 1 to 15 cm thick (Figure 5-11). Three separate sets of severely burned samples, including a blackened charcoal layer (B), reddened brick-like/ceramic fragments (R) and an intermediate yellow partly burned layer (Y)] were collected from the site (Figure 5-11).

The effect of this burning on these drained soils in Jury Swamp is unusual because it has resulted in the formation of abundant, irreversibly fused, particulate and discrete artefacts over the burnt area. The biomass burning has also had a profound effect on the functioning of these soils. Both the direct effects of fire and also the overall changes to the ecosystem in a post-fire situation has led to short-, medium- and long-term (irreversible) changes in these soils. These relate to soil functioning in the physical, biological and chemical sense and also include changes to aggregate stability, pore size distribution, water repellence and runoff response alteration, mineralisation rates, biomass production, species composition and carbon sequestration; as well as changes in C:N ratios, pH and nutrient availability.

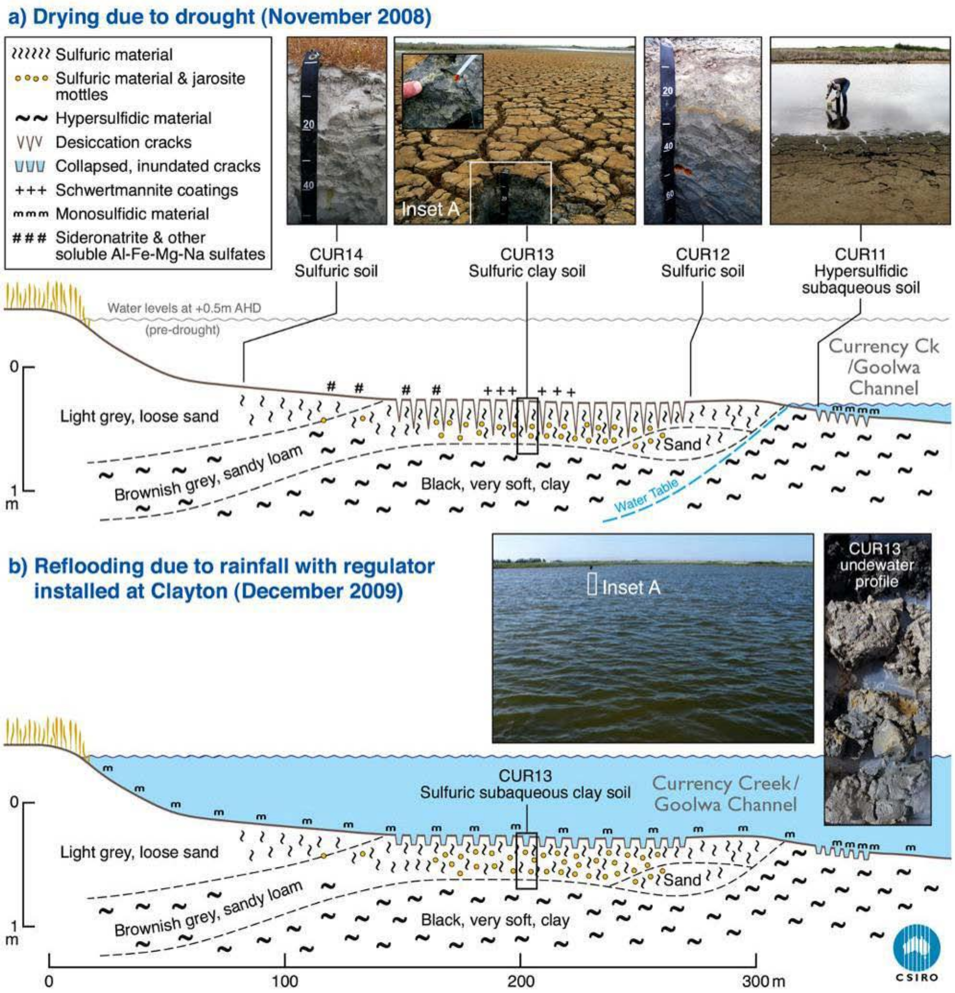


Figure 5-8. Explanatory soil-regolith model with photograph and cross-section diagram of Acid Sulfate Soil of the subtype “Sulfuric cracking clay soil” in the dry river bed of Currency Creek, near north Goolwa (Site No CUR 13 sampled in November 2008), looking west towards to the Adelaide Hills, South Australia. This shows: (i) trans-horizon polygonal cracks with very coarse columnar ped structures; the result of desiccation and dewatering of a former “Hypersulfidic subaqueous clayey soil” due to extreme drought conditions; (ii) surface coating of the reddish-brown mineral, schwertmannite, which has a pH ranging between 3.0 and 3.6 (sulfuric material), (iii) sulfuric material (pH < 4) with pale yellow mottles of natrojarosite in a dark grey clay matrix between 10 cm to 30 cm, and (iv) very dark grey hypersulfidic material (iron sulfides) at depth (> 30 cm). The lower photograph and conceptual cross-section diagram is taken at the same locality in December 2009 after reflooding following winter runoff from the catchment and construction of Clayton and Currency Creek water regulators (from Fitzpatrick *et al*. 2011a).

5.5.3. Predictive conceptual soil-regolith models

Specific or generalised predictive soil-regolith models are constructed to illustrate specific or generalised wetland transects and scenarios (e.g. see several case studies in sections 7 to 20). Predictive soil-regolith models (4D) are constructed using a collage of figures, which illustrate several stages of soil-regolith condition in response to natural or human induced (e.g. management) changes over time. These conceptual models can be used to predict processes and potential consequences but not the timing of events, which will depend on weather, changes in water level and land management.

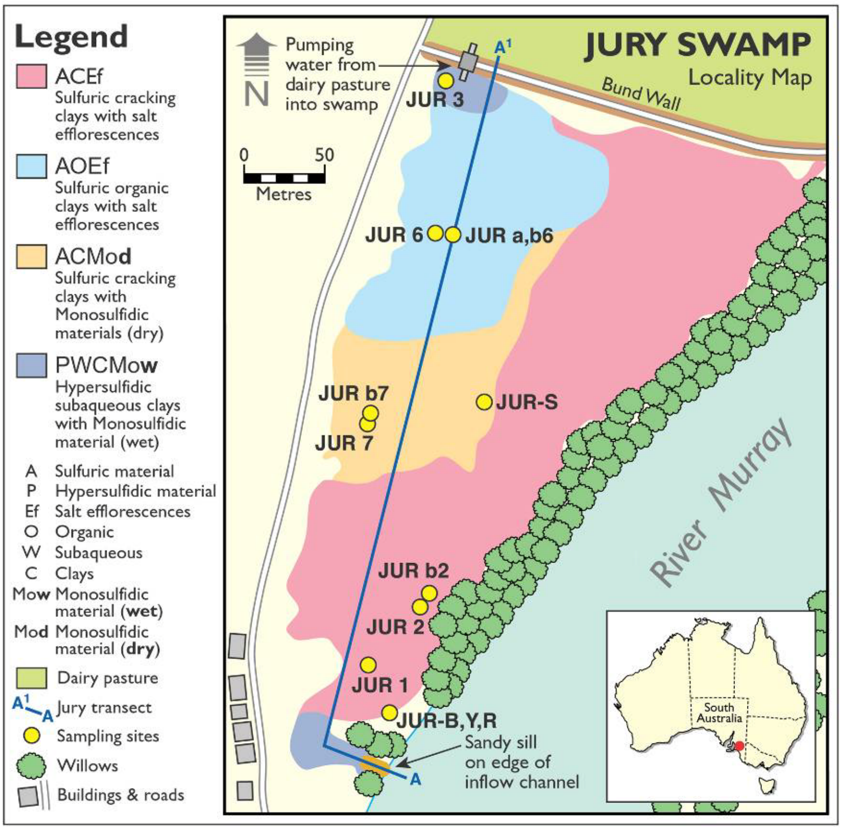


Figure 5-9. Acid Sulfate Soil map of Jury Swamp showing distribution of the following:
(i) wide range of ASS Subtypes such as Sulfuric cracking clays, Sulfuric organic clays to Hypersulfidic subaqueous clays;
(ii) features such as salt efflorescences and dried & wet monosulfidic material,
(iii) locality of cross section A–A' across Jury Swamp and
(iv) sampling sites

(from Fitzpatrick *et al.* 2010e)

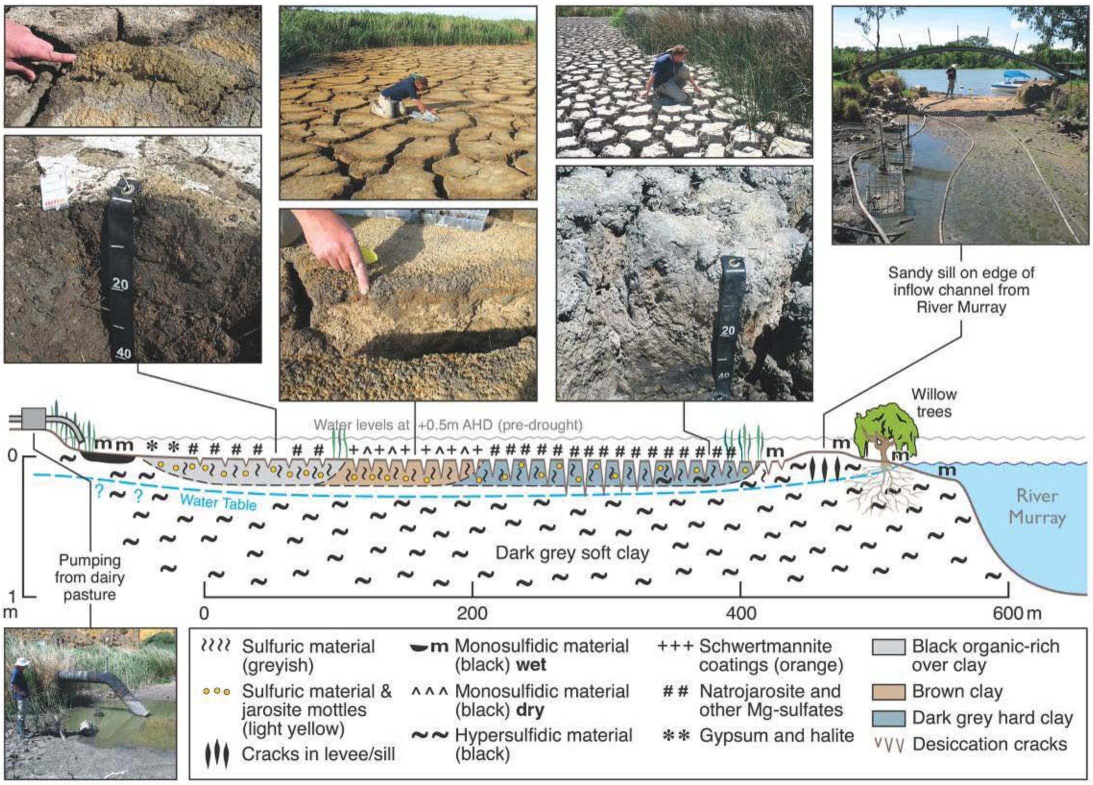


Figure 5-10. Explanatory soil-regolith model of Jury swamp showing a cross section along transect A'-A in the Acid Sulfate Soil Map in Figure 5-9. Model describes the spatial variation of ASS materials with time [e.g. water level at pre-drought or before 2006; followed by drying in 2008 and extreme drying in 2009). The water level pattern is exaggerated because of the inflated vertical scale necessary to display all the soil features (from Fitzpatrick *et al.* 2010e)

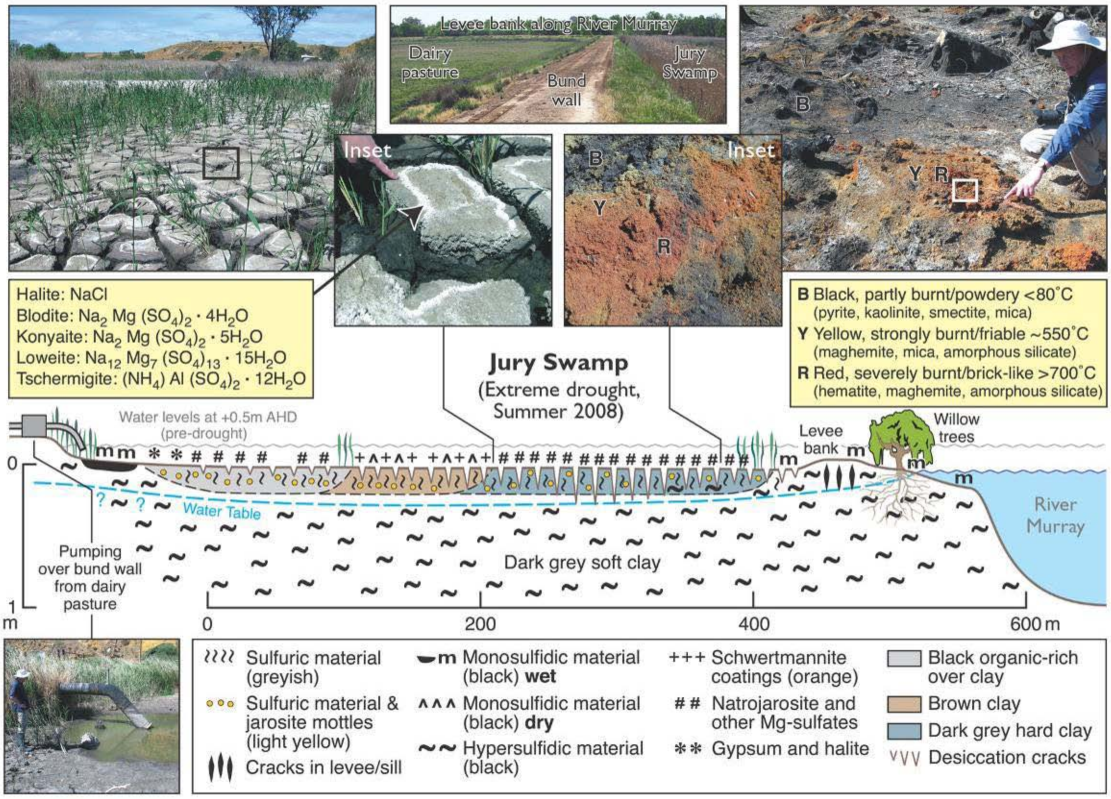


Figure 5-11. Explanatory soil-regolith model of Jury swamp showing a cross section along transect A'-A in the Acid Sulfate Soil Map in Figure 5-9 showing distribution and types of salt efflorescences, and impacts of burning (from Fitzpatrick *et al.* 2010e).

The specific predictive soil-regolith model shown in Figure 5-12 illustrates the complex and varied distribution of ASS Subtypes in a small wetland (Jury Swamp) in the lower River Murray region near Murray Bridge that may experience the following future scenarios of (a) lowering of water levels due to drought (drying), (b) followed by high winter rainfall (rewetting) with higher water levels leading to the release and mobilisation of metals in the wetland and subsequent leaching into the river and (c) installation of a levee bank with a water flow regulator to better control water flow in and out of wetland to minimise release of metals and monosulfidic material to the river.

The generalised predictive soil-regolith model shown in (**Figure 5-13**) illustrates the Lower Lakes and River Murray region that experienced lowering of water levels due to drought followed by winter rainfall rewetting (Fitzpatrick *et al.* 2008b,f,i; 2009a,b). It outlines sequential transformations progressively through **five** sediment/soil types from:

1. Alkaline deeper water sediments →
    2. Alkaline subaqueous soils →
        3. Neutral waterlogged soils containing "benign" hypersulfidic material →
            4. Acidic drained soils containing "nasty" sulfuric material (pH< *4*) →
                5. Rewetted acidic subaqueous soils and water.

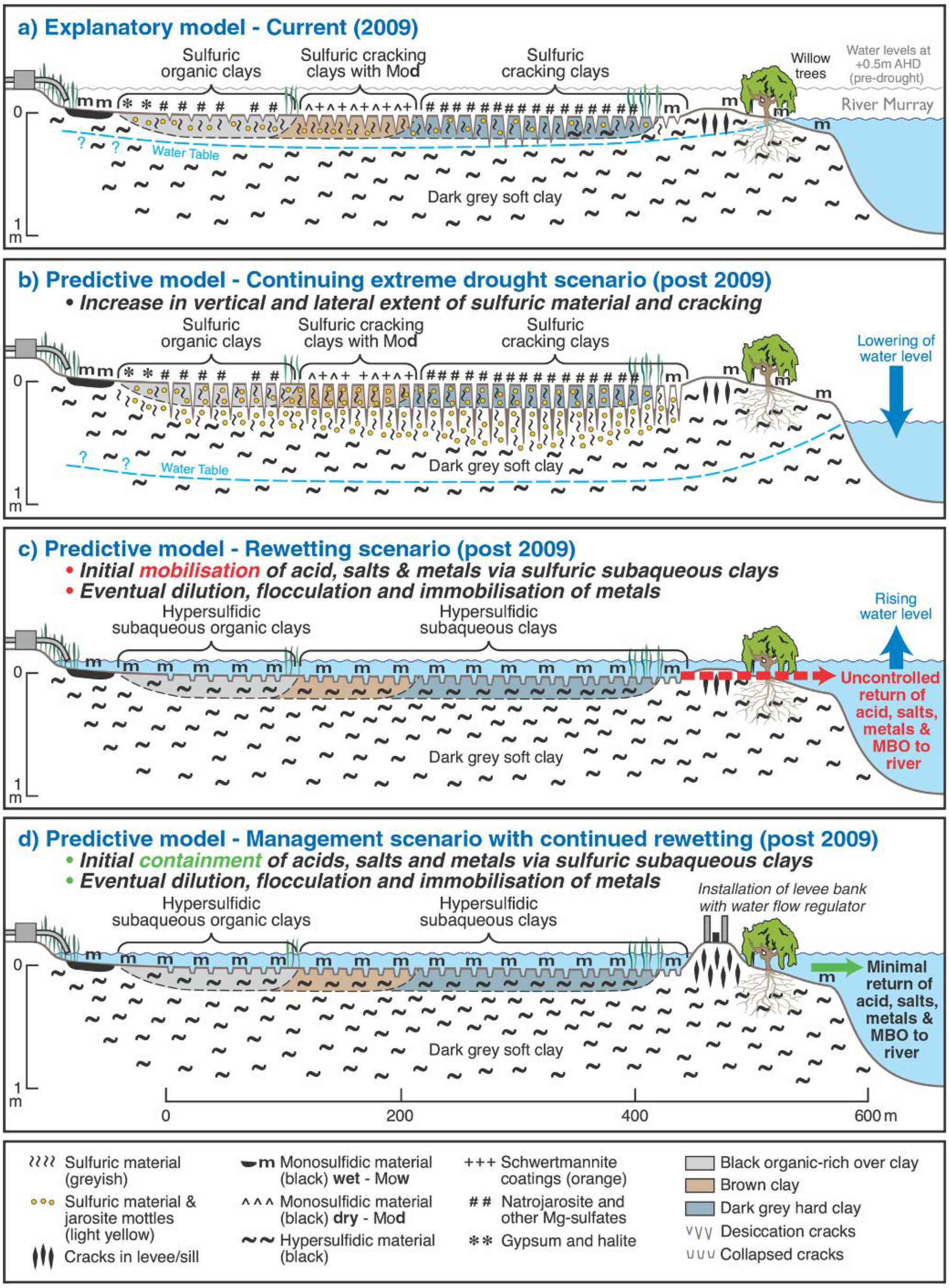
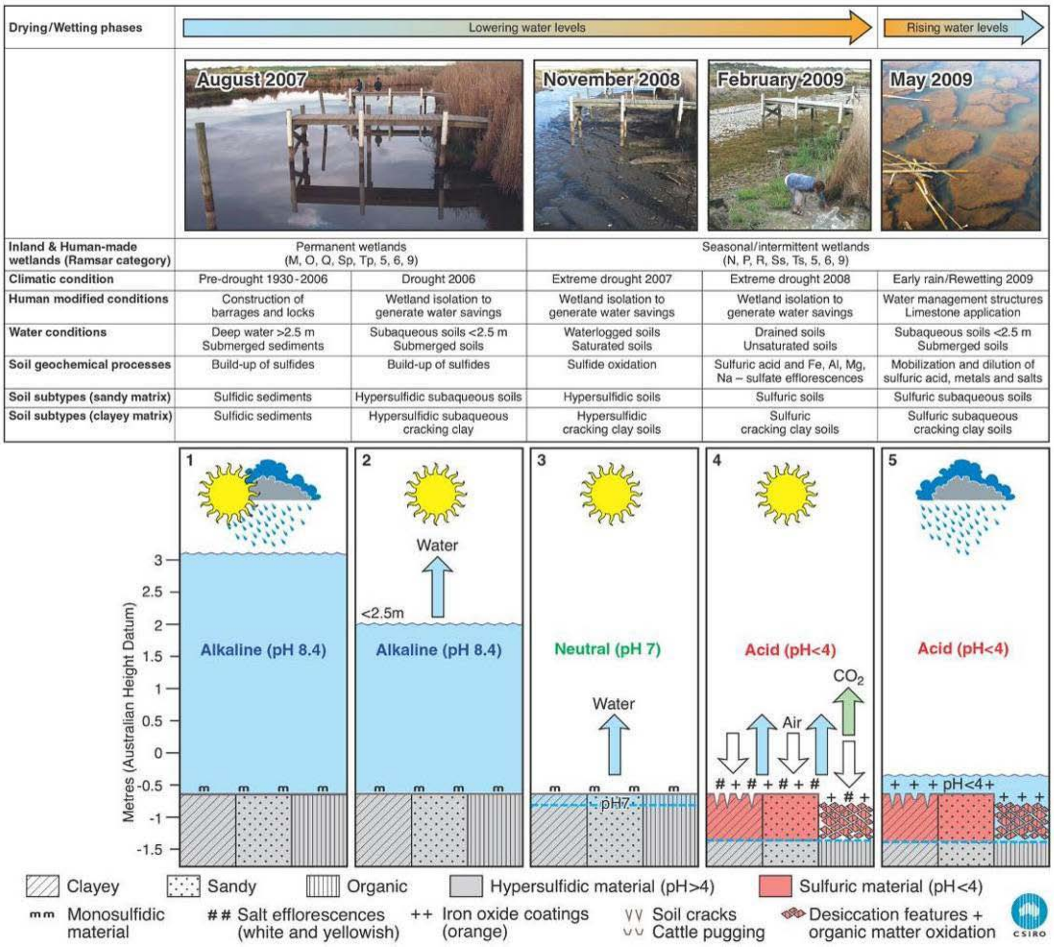


Figure 5-12. The current (2009) explanatory and 3 predictive soil-regolith models for Jury swamp with a current levee bank scenario and permanent water flow regulator structure scenarios – illustrating 2 possible management options). NOTE: The water table level pattern is exaggerated because of the inflated vertical scale necessary to display all the soil features.

The generalised predictive soil-regolith model (Figure 5-13) was constructed using all readily accessible information, which included data from archival/historical and published soil data (e.g. de Mooy 1959, Taylor and Poole 1931a,b; Fitzpatrick et al. 2008b,f,i; 2009a,b), vegetation, DEM data and geological information for the region together with the sequence of photographs from a typical area to help illustrate this generalised predictive model (e.g. in this case from the Finniss River at Wally's Landing see Figure 5-2, Figure 11-1, Figure 11-2).



Drying/Wetting phases	Lowering water levels				Rising water levels
	August 2007		November 2008	February 2009	May 2009
Inland & Human-made wetlands (Ramsar category)	Permanent wetlands (M, O, Q, Sp, Tp, 5, 6, 9)		Seasonal/intermittent wetlands (N, P, R, Ss, Ts, 5, 6, 9)		
Climatic condition	Pre-drought 1930-2006	Drought 2006	Extreme drought 2007	Extreme drought 2008	Early rain/Rewetting 2009
Human modified conditions	Construction of barrages and locks	Wetland isolation to generate water savings	Wetland isolation to generate water savings	Wetland isolation to generate water savings	Water management structures Limestone application
Water conditions	Deep water >2.5 m Submerged sediments	Subaqueous soils <2.5 m Submerged soils	Waterlogged soils Saturated soils	Drained soils Unsaturated soils	Subaqueous soils <2.5 m Submerged soils
Soil geochemical processes	Build-up of sulfides	Build-up of sulfides	Sulfide oxidation	Sulfuric acid and Fe, Al, Mg, Na – sulfate efflorescences	Mobilization and dilution of sulfuric acid, metals and salts
Soil subtypes (sandy matrix)	Sulfidic sediments	Hypersulfidic subaqueous soils	Hypersulfidic soils	Sulfuric soils	Sulfuric subaqueous soils
Soil subtypes (clayey matrix)	Sulfidic sediments	Hypersulfidic subaqueous cracking clay	Hypersulfidic cracking clay soils	Sulfuric cracking clay soils	Sulfuric subaqueous cracking clay soils

Figure 5-13. Generalised predictive soil-regolith model illustrating the role of climate variability (drought triggered and early winter rains), environmental conditions imposed by humans (e.g. modifications from barrages, isolating wetlands and weirs) and water conditions (subaqueous, waterlogged, dried and rewetted) which play a vital role in the alteration of soil geochemical processes and sequential transformation of various sandy, clayey and organic ASS subtypes (modified from Fitzpatrick *et al.* 2008b,f,i; 2009a,b).

6. ASSESSMENT AND MANAGEMENT OF INLAND ACID SULFATE SOILS

This section discusses how to apply the general guidelines for assessment and management of Acid Sulfate Soils in inland freshwater areas (Table 6-1). The stages in the process of site characterisation of ASS and the development of management options for particular sites and regions are presented in Table 6-1.

Table 6-1. General guidelines for assessment and management of Acid Sulfate Soils in inland freshwater areas

STAGES	MAIN TASKS AND DECISIONS
1. Initial characterisation ↓	• Verify incidence or occurrence of ASS • Conduct due diligence
2. Problem categorisation (Desktop assessment) ↓	• Consult stakeholders (owners, community, regulators) • Obtain existing historical and background information • Assess likely extent of regional/local investigations and develop an analysis plan (e.g. subdivide into 'geographical areas' of ASS: lakes, tributaries, main river channel and adjacent wetlands, Figure 5-2) • Desktop identification of various types and subtypes of ASS (from Atlas of Australian ASS), pathways of formation and exposure via preliminary descriptive soil-regolith models (e.g. Figure 5-7) • Develop a preliminary predictive soil-regolith model (e.g. Figure 5-13) • Determine the environmental values of the ASS-affected freshwater areas, interim goals, possible long term vision and end results • Identify regulatory requirements and develop communication plans • If sulfuric materials are widespread, immediately proceed to step 3.
3. Design investigation ↓	• Conduct reconnaissance field investigations of ASS • Design rapid ASS investigation to address: o Approaches based on risk (e.g. conduct detailed assessment if sulfuric material is identified in Stage 2) o Gaps and stakeholders questions • Decide on: o Sampling plans o Laboratory methods
4. Characterize and analyse ↓	• Conduct rapid or detailed field and laboratory investigations o Methods used must suit the sites • Interpret data: morphological, chemical (e.g. pH incubation data and acid base accounting) and mineralogy • Construct final explanatory soil-regolith models (Figure 5-7) • Update preliminary predictive soil-regolith model (Figure 5-13)
5. Assess hazard/risk ↓	• List and rank hazards/risks for each geographical area: high, medium or low • Develop final predictive soil-regolith model • Develop predictive ASS maps using terminology from National ASS Atlas legend in ASRIS (if required)
6. Decide on management options ↓	• Determine likely management options to mitigate ASS effects, e.g.: o Liming o Flooding with fresh, brackish water or possibly seawater o Closing-off selected areas (isolate sources of acid) o Construction of temporary control structures o Pumping water into areas to maintain water levels o Dredging of lakes and river channels o Adjustment to new agricultural practices
7. Report and communicate	• Update findings based on internal and external peer review • Complete final reports and upload to public ASS websites • Present report to inform stakeholders and other organisations • Develop and implement communication plans, especially public reporting procedures (e.g. Information Sheet on ASS); conduct field training courses

How to apply the guideline

The flowchart in Table 6-1 contains the main tasks and decisions required to adequately complete a regional or site characterisation at an impacted inland ASS site. The guideline involves a preliminary investigation, followed by more intensive investigations as outlined in Table 6-1. The information provided in this section is intended to assist the user in applying the intent of the guideline to a real situation. However, caution is advised, particularly when applying the checklist in Table 6-1. Each site to be characterised will be different, often with unique requirements, and therefore the user should not “blindly follow” all the stages or checklist. Rather, the stages promoted in the guideline should be followed and an appropriate site-specific approach be formulated for each region or site being investigated. In general, the approach outlined in Table 6-1 allows data collected at each stage to be assessed and fed into planning the next stage of investigation and used to update conceptual ASS models and maps. However, in some special cases this approach can be time consuming and expensive, e.g. for areas where all the evidence suggests that sulfuric material appears to be widespread, investigations could immediately proceed to the detailed stages of ASS investigation (e.g. stages 3 or 4 in Table 6-1).

6.1. Initial Characterisation– Stage 1

If there is a location such as a waterfront or land development, or particular agricultural or other land use, where Acid Sulfate Soils are suspected, an investigation can be initiated. This initial or screening stage (Stage 1) comprises verification of the presence of ASS at a particular site. The Atlas of Australian Acid Sulfate Soils (AAASS) should be used in the first instance to identify the presence of ASS. ASS Standard tests and observations sufficient to diagnose ASS should be undertaken and discussions held with key stakeholders or landholders.

6.2. Problem categorisation – Stage 2

This stage essentially involves a desktop assessment by gathering reconnaissance information on ASS characteristics and extent (e.g. AAASS and State agency maps and data bases should be interrogated to estimate percentage coverage of ASS), site characteristics, historical background (e.g. see Chapter 9), background monitoring data and environmental values. This will provide background information on the likely exposure pathways and effects of ASS. If practical, it should include a brief field trip, more in-depth consultation with key stakeholders (e.g. landowners, community and regulators) followed by a comprehensive literature review on potential impacts of ASS in the range of existing environments present (e.g. water bodies, soil types and geology). The literature review may include searches of existing and historical reports and databases, stakeholder websites and journal articles or reports. This information will permit identification and the initial demarcation of “Geographical ASS Areas” (e.g. Figure 5-2).

6.2.1. Subdivision into Geographical Acid Sulfate Soil Areas

Assessment at regional and/or local soil-landscape scales involves the subdivision of the particular landscape into distinct Geographical Areas of inland ASS as displayed in Figure 5-2) such as:

1. Tributary streams and rivers (e.g. South Australia - Mount Lofty Ranges),
2. Lakes and adjacent wetlands (e.g. South Australia - Lakes Alexandrina and Albert; Victoria - Lake Bolac-Salt).
3. Main river channel and adjacent wetlands (South Australia - River Murray section below Blanchetown; Victoria - Loddon River) and
4. Seepages overlying mineralised zones (SA - Eastern Mount Lofty Ranges; Victoria - Eastern Dundas Tablelands.

The subdivision into Geographical Areas of ASS is helpful for the first step in constructing conceptual soil-regolith models based on the fact that different soil-regolith and hydrological processes may be operating in different geomorphic landscapes.

6.2.2. Development of conceptual soil-regolith models

Based on all the accumulated data and ideas gained from preliminary investigations, identify the various types and subtypes of ASS and the generalised pathways of formation and exposure to construct a preliminary soil-regolith model. Firstly, use all readily accessible information, which may include data from desktop studies such as available archival/historical published soil (e.g. Taylor and Poole 1931a,b), vegetation, DEM data and geological map information. Data from the initial field reconnaissance, laboratory investigations and interviews is then used to improve the model. For example, the general model shown in (Figure 5-13) for a wetland describes the sequential transformation of the following ASS subtypes at a location that has dried due to drought lowering water levels and then after winter rainfall partial rewetting:

1. *Alkaline* deep water sediments → 2. *Alkaline* hypersulfidic subaqueous soils →3. *Neutral* hypersulfidic soils → 4. *Acid* sulfuric soils → 5. *Acid* subaqueous sulfuric soils.

The preliminary predictive soil-regolith model (generalised) is developed prior to any detailed field or laboratory ASS investigations (see flowchart outlined in Table 6-1). This provides a framework for identifying gaps to be filled by more detailed field and laboratory investigations. This will also be of benefit in stakeholder and community discussions regarding the key issues, vision and goals for a specific Geographical Area (e.g. Figure 5-2).

A general conceptual model helps to clarify complex regions and sites by aiding in the demonstration of site characteristics and is a valuable tool for decision-making. A reliable soil-regolith model is valuable to both technical and non-technical observers and can be used to demonstrate the most basic or the most intricate details of a site.

These models also show the vertical and horizontal relationships between surface and subsurface ASS features, demonstrate where certain areas are changing with time and finally where areas of uncertainty or concern exist at a site. They also provide the framework for detailed analyses between areas of known and interpreted results to be displayed. Soil-regolith toposequence models have the ability to display both detailed surface features (e.g. different types of cracking and salt efflorescences) and the deep underlying (>~1 m to 1.50 cm) layers (e.g. olive grey clays, calcretes).

Finally they are a valuable way to convey the past and present conditions at a site, and can be extremely useful for devising a path forward to rehabilitate a site or demonstrating compliance to a regulatory agency.

Whilst it is true that these models require an initial investment, client and regulatory feedback has shown that, for complex sites, the benefits far outweigh the costs when soil-regolith visualisation is incorporated into initial project work plan.

6.3. Design investigation – Stage 3

An investigation (Stage 3) is designed to address gaps identified in the generalised predictive soil-regolith model and to answer stakeholder questions. This stage should also involve a more detailed reconnaissance field ASS investigation in order to determine sampling plans and choose the suite of laboratory methods to use.

For example, a “rapid ASS assessment method” could be selected such as the Murray-Darling Basin Authority ‘Acid Sulfate Soils Rapid Field Guide’ (MDBA 2009), which comprises: (i) field measurements of water quality, (ii) field measurements of soil pH and (iii) collection of soils in chip trays followed by laboratory pH testing before and after incubation (Fitzpatrick *et al.* 2010a). The data collected through this rapid assessment method should be screened and interpreted by experienced scientists using agreed criteria. The information should be communicated to concerned agencies responsible for the Geographical Area to determine if more detailed ASS investigations should be conducted (Table 6-1).

The design of field sampling plans (e.g. Soil Morphology description, chip tray sampling method) for the characterisation of sites with ASS is a complex subject and more detailed guidelines and protocols exist (Shand et al. 2008e; Fitzpatrick *et al.* 2009a). Suffice to say, sampling plans must be site-specific to account for varying site conditions, as illustrated in Figure 4-2 and Figure 5-7, that can range from subaqueous to waterlogged to dried soils. It is beyond the scope of this technical guideline report to provide detailed information on the protocols for field sampling and laboratory analyses. Hence the reader is referred to the following report entitled: "Detailed Assessment of Acid Sulfate Soils in the Murray-Darling Basin: Protocols for sampling, field characterisation, laboratory analysis and data presentation" (MDBA 2010) for more detailed information, particularly in designing soil sampling plans and detailed laboratory methods. The laboratory methods and techniques must be nationally recognised (published and tested), consistent and meet the objectives of the investigation.

6.4. Characterize and Analyse – Stage 4

Detailed investigation

Field and laboratory investigations (Stage 4) should be conducted according to standard field and laboratory protocols, for example, as outlined in MDBA (2010). The methods used must be suited to the sites. Interpretation of morphological, pH incubation data, chemical (e.g. acid base accounting) and mineralogical data can be used to help construct the final soil-regolith models (e.g. Figure 5-7; several displayed in Sections 7 to 16) and final preliminary predictive soil-regolith model (e.g. Figure 5-13). Soil-regolith models with accompanying acid base accounting data should be constructed for each Geographical Area studied. The models should describe the vertical and horizontal changes in ASS materials over space and time.

The combination of soil morphological features allows similar soil layers to be matched between different sites (e.g. Figure 5-7). A number of sites are generally placed in a transect stretching from the water to the higher landscape position as indicated in Figure 5-7. By observing the site landscape position and correlation of soil layers between sites, conceptual soil-regolith models can be constructed (e.g. they show how the soil properties vary across an area by integrating what is seen at multiple sites). These soil-regolith models represent a powerful tool to visualise how the soil materials change both vertically and horizontally in the landscape and hence how the various acid sulfate soil materials may be distributed across landscapes.

The detailed toposequence models also provide an understanding of soil distribution that then allows the earlier predictive maps to be tested and updated with more confidence (see Figure 11-9). For example, Fitzpatrick *et al.* (2009a), identified large areas of extremely acidic soils (sulfuric materials: pH < 4.0) in the Currency Creek and Goolwa channel areas and confirmed previous predictions (Fitzpatrick *et al.* 2008b) that these areas have a high potential of developing sulfuric materials (i.e. soil pH < 4).

Updating soil-regolith models

Acid sulfate soils are a key component of terrestrial ecosystems, especially because of their location in most wetland systems. Water processes in ASS are complex, subject to human and drought influence and depend on the variability in time and space of intrinsic properties.

As discussed in Section 3.3, soil-regolith models are an extremely valuable approach for displaying and explaining complex spatial variability at field scale, which for example can:

- Explain the sequential formation and transformation of hypersulfidic material to sulfuric material in various subtypes of acid sulfate soil.
- Explain new occurrences of minerals, their formation and transformation (e.g. pyrite to sideronatrite; sideronatrite to schwertmannite; pyrite to natrojarosite),
- Explain the impacts of future conditions (e.g. drought, disturbance, management) on sulfidic material oxidation and impacts.
- Identify the best set of soil and landscape field indicators of soil-landscape condition for a region, which in turn can be used by land managers to provide land use options

Preliminary soil-regolith models for geographic areas (e.g. Figure 5-2) can be updated many times in the course of area ASS investigations, even continuously with some "real time" monitoring investigation methods (e.g. see time series investigations in Figure 11-6 to Figure 11-7 to Figure 11-8 and Figure 13-7 with continuous field and laboratory monitoring data).

6.5. Hazard or risk evaluation – Stage 5

Stage 5 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.

Defining and Assessing Hazards

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

a. Acidification;

b. Contaminant release; and

c. Deoxygenation.

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 emanating from the detailed assessment of acid sulfate soil materials. These form the basis for determining risk when taken alongside a range of other factors and impacts e.g. to environmental values and water quality.

The field and laboratory analyses carried out using the Murray-Darling Basin Acid Sulfate Soil protocols for sampling, field characterisation, laboratory analysis and data presentation (MDBA 2010) will determine whether ASS materials present a potential hazard to wetlands (Phase 1 analyses) and whether further investigation is required through a Phase 2 analyses to elucidate risk. Information emanating from Phase 1 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 through a Phase 2, including the number of samples to be analysed.

Defining and Assessing Risk

The phase 2 analyses will assess the risk of acid sulfate soil materials to the wetland/s.

According to MDBA (2010), risk is a measure of both the consequences of a hazard occurring, and the likelihood of its occurrence. Consequence is the impact of the acid sulfate soil materials being expressed, and primarily takes into account environmental and water quality impacts, both to the wetland and adjacent waters. Level of consequence will be determined in consultation with wetland managers for each identified hazard at a wetland using a standardised Table 6-2.

Table 6-2: Standardised table used to determine the consequence of a hazard occurring (MDBA 2010).

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 requiring an 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 will be determined by assessing the probability of disturbance of the acid sulfate soil materials (Table 6-3).

Examples of disturbance include:

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

Table 6-3: Likelihood ratings for the disturbance scenario (from MDB 2010).

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 (Table 6-4) as the product of the likelihood of disturbance of the acid sulfate soil materials and the consequences to wetland values and/or adjacent waters. 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 Phases 1 and 2 analyses.

According to MDBA (2010), Acid sulfate soil scientists conducting detailed assessments cannot alone determine the level of consequence or likelihood at a given wetland – input of relevant wetland managers will be critical. As such, assessment of risk through Phase 2 must be made in consultation with wetland 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 6-4: 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:

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).

Reporting on Risk

Reports of Phase 2 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.).

6.5.1. Acid Hazard Classification based on Soil Net Acidity and Lime Treatment Category models

The acid hazard classification assessment for coastal acid sulfate soil materials is conducted according to well recognised criteria established for preparing coastal acid sulfate soil management plans (Dear *et al.* 2002). The acid hazard class assigned to the soil layers ranges from Low to Very High and these ratings relate to the amount of lime required to neutralise the net acidity (Lime Treatment Category) in order to maintain a soil pH above 5.5. The acid hazard classification is assigned by determining which of the soil layers with a total thickness of at least 15 cm within each soil profile requires the highest lime treatment (to neutralise Net Acidity).

The acid hazard class is based on a simplified version of Dear *et al.* (2002), which estimates lime treatment classes. This simplified interpretation for use in these technical guidelines is modified here in three ways:

1) the 500 tonne level of disturbed material is used as a threshold. This approximates to about 20m x 20m x 1m of disturbed material,
2) existing plus potential net acidity is expressed in mol H^+/tonne instead of converting these values to %S_{CR}, and
3) a ‘No treatment’ class (N) has been added to approximate the ‘Low treatment’ (L) class added for the 500 t disturbed acid sulfate soil level set at the S_{CR} analysis level of 0.01%.

Users are referred to Table 2 in Dear *et al.* (2002) for details relating to lime use and quality. Note that while the liming rates provided show a relative difference between soil samples as a measure of net soil acidity, they are not necessarily a recommended lime rate for management purposes, as this requires consideration of other information such as the chemistry of the surface or receiving waters.

Each of the soil layers in a profile is then assessed to determine the overall hazard class for the site; along with an assessment of the acid sulfate soil material that characterises the greatest hazard at the site (e.g. Fitzpatrick *et al.* 2009a).

In summary, the assessment method of Dear *et al.* (2002) is used as a guide to determine the level of acid sulfate soil problems. Essentially a lime requirement calculation is made.

6.5.2. Acidification, metal mobilisation, and de-oxygenation hazards determined by soil material categorisation

Several investigations of inland ASS have used the robust and tested coastal acid sulfate soil assessment methodologies (e.g. peroxide testing, acid-base accounting, water soluble sulfate, soil incubation/ageing and surface and ground water quality measurements; see methods outlined in Chapter 2) to characterise various types of ASS materials identified in the wide range of ASS including Lake Alexandrina and Lake Albert, SA and adjacent wetlands (e.g. Finniss River, Currency Creek, Goolwa Channel and Black Swamp areas (see Fitzpatrick *et al.* 2009b,f,i; 2009a; Baker et al. 2010), wetlands between Locks 1 and 9 (Shand et al. 2008b; Shand *et al.* 2009).

With this approach, each ASS material type identified is assessed for existing hazards or its potential to present a number of environmental hazards, specifically:

- **acidification** (of soil, groundwater and surface waters)
- **metal mobilisation** (from acid sulfate soil material to groundwater and surface water)
- **deoxygenation** of surface waters

The hydrogeochemical processes that are responsible for these hazards are inherently linked, in that both acidification and redox status are likely to influence the mobilisation of metals and metalloids. ASS materials may present a **'current'** hazard to an environment where the hazard has been measured or observed, **or** present a **'potential'** hazard to a particular environment where laboratory analyses of soil properties indicates that a hazard is likely to eventuate if environmental conditions change. The general relationship between the acid sulfate soil material types and the hazard condition is presented in Table 6-5.

Table 6-5 General relationships between ASS materials/other acidic materials and hazard condition (from Fitzpatrick *et al.* 2009a).

Type of Acid Sulfate Soil Material	**Hazard Type and Condition**		
	Acidification	**Metal Mobilisation**	**Deoxygenation**
Sulfuric	current	current	none
Hypersulfidic	potential	potential	none
Hyposulfidic (S_{CR} ≥ 0.10%)	potential	potential	none
Monosulfidic (observed)	potential	current	current
Monosulfidic (potential)	potential	potential	potential
Hyposulfidic (S_{CR} < 0.10%)	potential	potential	none
Other acidic soil materials (pH_w &/or $pH_{incubation}$) 4 - 5.5	current or potential	current or potential	none
Other soil materials	none	none	none

6.5.3. Developing predictive Acid Sulfate Soil maps of drought-triggered Acid Sulfate Soil areas

Acid Sulfate Soil maps of survey areas should be generated, which may range from individual wetlands as shown for Jury Swamp in **Figure 5-6** or for specific catchments (e.g. Finniss River and Currency Creek shown in Figure 11-9) or for large regions such as the Lower Lakes (e.g. Figure 5-6). Based on the definitions of acid sulfate soil materials (see Chapter 4), all of the samples are classified (e.g. sulfuric or hypersulfidic material) using pH and chip tray incubation methods (Fitzpatrick *et al.* 2010b). Finally, for each soil profile, information on the ASS materials and soil texture throughout profiles (often 3 layers to at least 50 cm depth) is considered and the soil profile allocated to a soil class (ASS Type or Subtype) based on the Acid Sulfate Soil Identification Key (e.g. Fitzpatrick *et al.* 2008e,f,i; 2009a; 2010c,d).

For example, the approach used to map ASS in the Lower lakes region shown in Figure 5-6, involved utilisation of bathymetry, soil and vegetation mapping in a geographic information system (GIS). These layers were combined to predict the distribution of different subtypes of ASS (deeper than 2.5 m; subaqueous sulfidic; sulfidic and sulfuric) as lake water levels dropped and soils de-watered. These can be displayed as predictive scenario maps (e.g. Fitzpatrick *et al.* 2008b,f,i), which depict sequential changes in acid sulfate soil materials at different water levels in Lake Alexandrina and tributaries such as the Finniss River. The water level scenarios included: (i) pre-drought conditions (+0.5 m AHD), (ii) present day drought (-0.5 m AHD), and (iii) prolonged drought, causing water levels to drop to -1.5 m AHD, i.e. 2 m below pre-drought water level (Fitzpatrick *et al.* 2008b,f,i). Such information is presented for the Goolwa Channel-Finniss River area (Figure 11-6)) and for Lake Alexandrina (Figure 12-9).

These predictive acid sulfate soil maps can be constantly revised as new information becomes available through site visits, field testing and the availability of new spatial data sets (e.g. Fitzpatrick *et al.* 2009a, 2010c,d).

Field studies combined with the maps and predictive models were used to conclude that most of this region could produce sulfuric material if the water level fell to -1.5 m AHD (see predictive scenario shown in the acid sulfate soil maps in Figure 5-4 and graphs in Figure 5-5).

6.6. Decide on management options – Stage 6

A summary of management options for the main subtypes of inland ASS encountered are presented below and summarised in Table 6-6. Several examples of site specific management options and scenarios have also been presented for 36 Case Studies discussed in sections 8 to 22 and summarised in Table 6-7.

The relevant biophysical and biogeochemical processes in hypersulfidic, sulfuric and monosulfidic materials in Inland ASS are generally well understood, and essentially relate to the presence of sulfide minerals, soil saturation and soil aeration. Successful land management decision making in areas affected by ASS requires very careful assessment of the relative importance of a range of these interconnected biophysical and biogeochemical contributing factors, which have been shown to vary from region to region, including:

- climate
- ASS soil types and subtypes
- hydrology
- the size, geology and topography of wetland systems
- the depth and salinity of the water table across wetland systems
- the sulfur (sulfides) store (both above and below the water table)
- the extent of various subtypes of ASS and their position in the landscape
- land use options, and economic/social/political constraints and factors

Table 6-7 summarises the information from 36 representative case studies (Sections 10 to 24). It gives the ASS environment (geographical setting and ASS disturbance processes) and the specific management principles applied to ameliorate ASS impacts in each of the case studies. In some instances, landscape processes are still in a state of change and have not fully adjusted to the changed environment. Consequently, management responses may need to adapt as further information becomes available. Guideline users may find it useful to consult Table 6-7 in conjunction with the relevant diagram for the conceptual soil-regolith model.

Summary of principles with examples of selected case studies

A primary preventative consideration for acid sulfate soils should be an avoidance strategy. Such strategies may include the decision not to drain wetlands with sulfidic material, and to divert or relocate a proposed land use to an alternative site. If use of the site is unavoidable, then treatment to prevent sulfide mineral oxidation and export of any existing acidity is necessary.

Whilst increased disturbance of hypersulfidic material is the principal cause of the formation of sulfuric materials, one would expect that the principal management option would be to reverse the situation (i.e. keep materials anoxic or under anaerobic conditions) or to slow or stop the rate and extent of pyrite oxidation). This can be achieved either by keeping sulfidic material anaerobic under saturated conditions or by rapid drying of sulfidic material to minimize the oxidation caused by the biogeochemical processes that are responsible for the formation of acid. However, the selection of appropriate management options to prevent oxidation of sulfides will depend on the nature and location of the ASS materials, and their position in the landscape such as availability of sufficient amounts of water to either maintain or generate anoxic or waterlogged conditions (i.e. Geographic Areas of inland ASS in Australia see Figure 5-2 and Table 6-7). Reversing the process by rewetting, once oxidation has occurred, is not straightforward, because it is at this time that the risks from acid and metal mobilisation are highest. Recent detailed studies (Baker *et al*. 2010; Shand *et al*. 2010a, 2010b) have also shown that the timescales of reversal are difficult to predict, but may be much longer than the oxidation which generated the problem. This is why developing reliable ASS risk or hazard maps, at appropriate scales, and the characterization of ASS landscapes are so important. Understanding the soil properties and processes as well as the local sub-surface hydrology and hydrogeology is fundamental to selecting the best options for drainage and the most appropriate management of the soils when they are drained.

Appropriate management of ASS during land development can minimise degradation of discharge water quality, and protect infrastructure and the environment. Such improvements can generally be achieved by applying low-cost land management strategies (e.g. see Ahern *et al.* 1998; EPHC & NRMMC 2011; Dear *et al.* 2002; Johnston *et al.* 2003, 2004, 2005; Tulau 2000; Thomas *et al.* 2003). Once the presence of ASS has been established, characterisation of the proposed infrastructure or land development areas for acid sulfate properties is undertaken, taking into account this guideline approach (see Table 6-1). Ranked in order of priority ASS management options, the following general principles can be applied (Fitzpatrick *et al.* 2008i):

Oxidation prevention - Minimise disturbance or drainage of Acid Sulfate Soil materials: (a) in Table 6-7

Select an alternative non-ASS site, rather than be required to undertake remediation. If an alternative site is not feasible, design works to minimise the need for excavation or disturbance of ASS materials by undertaking shallow excavations for drainage measures or foundations if feasible, and avoid lowering groundwater table that may result in exposure of soils. If ASS materials are close to the surface, cover with suitable clean non-ASS material to minimise the chance of disturbance and to lessen ASS contact with oxygen.

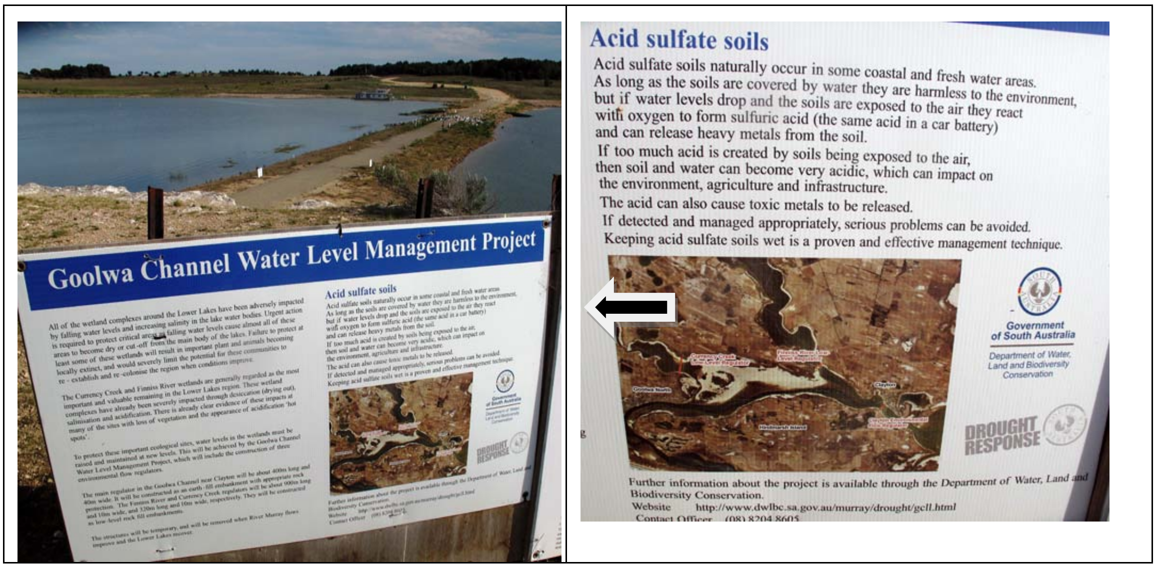
Case Study Example: Recommendations and provision of a manual of appropriate best management practices (e.g. see top half of Figure 17-5; Table 17-1) for Inland ASS seepages in the Mount Lofty Ranges (Fitzpatrick *et al.* 1997; 2003a,b) and Woorndoo region in Victoria (Figure 22-1; Cox *et al.* 1999; Fitzpatrick *et al.* 1997; 2003a,b) where fencing and protecting saline-sulfidic wetlands from physical disturbance (i.e. cattle) has:

- Facilitated reestablishment of reducing soil conditions in degraded soils
- Decreased the amount of pyrite oxidation in degraded soils
- Allowed rapid recovery of wetland vegetation in degraded soils
- Prevented water erosion
- Allowed a return to circumneutral pH (pH = 6.5 to 7)

Prevent or reverse oxidation of sulfidic material: (b) in Table 6-7

This may include staging the land or infrastructure development project to prevent oxidation of sulfidic material by covering it with an impermeable barrier (e.g. clay), or placing any excavated sulfidic material quickly back into an anaerobic environment, usually below the water table. Rewetting is an option to reverse the oxidation of sulfuric materials. However, this approach should be coupled with knowledge of surface groundwater interactions and any effect on the main river channel if any backflow occurs.

Case Study Example: Information on ASS especially from maps showing the current and predicted distribution of ASS with sulfuric materials by Fitzpatrick *et al*. (2008b,f, 2009a; 2010c; Figure 5-5, Figure 5-6) was used to underpin the installation of the main temporary flow regulator across the Goolwa Channel in 2009 at Clayton Bay (see Figure 6-1, Figure 11-11) and Currency Creek as management options to mitigate ASS impacts in the Goolwa Channel. These temporary regulators allowed water levels in the Goolwa Channel, Finniss River and Currency Creek region to rise rapidly in 2010 due to pumping from Lake Alexandrina (along with inflows from tributaries) and saturate the existing exposed sulfuric material (e.g. see ASS maps displayed in Figure 11-9; soil-landscape photo and caption on front cover of report; Figure 11-11).



Goolwa Channel Water Level Management Project

Acid sulfate soils

Acid sulfate soils naturally occur in some coastal and fresh water areas. As long as the soils are covered by water they are harmless to the environment, but if water levels drop and the soils are exposed to the air they react with oxygen to form sulfuric acid (the same acid in a car battery) and can release heavy metals from the soil.

If too much acid is created by soils being exposed to the air, then soil and water can become very acidic, which can impact on the environment, agriculture and infrastructure.

The acid can also cause toxic metals to be released.

If detected and managed appropriately, serious problems can be avoided.

Keeping acid sulfate soils wet is a proven and effective management technique.

Government of South Australia

Department of Water, Land and Biodiversity Conservation

DROUGHT RESPONSE

Further information about the project is available through the Department of Water, Land and Biodiversity Conservation.

Website http://www.dwlbc.sa.gov.au/murray/drought/gcll.html

Contact Officer (08) 8204 8605

Figure 6-1. Main temporary flow regulator across the Goolwa Channel - looking eastwards from Clayton Bay to Hindmarsh Island. Public notice in foreground explaining the "Goolwa Channel Water Level Management Project" with information on acid sulfate soils, which included the following statement: "Keeping ASS wet is a proven and effective management technique".

Case Study Example: Pumping water from Lake Alexandrina to Lake Albert to maintain water levels as a successful management option for preventing more sulfidic material in Lake Albert oxidising to form sulfuric material. Figure 13-6 and Figure 13-7 show soil-regolith models that illustrate 5 scenarios: (a) pre-drought (2007), (b) drought (summer 2008), (c) pumping from Lake Alexandrina to Lake Albert, which maintained water levels and acted as a successful management option to prevent rapid expansion of sulfuric materials, (d) and (e) after pumping ceased, the spatial distribution of sulfuric materials increased with the occurrence of ponded acidic water (pH <4) during rainfall events.

Minimise oxidation rate and isolate higher risk materials from exposure: (c) in Table 6-7

This may include covering ASS materials with soil or water to reduce oxygen availability and control the movement of water, or by controlling bacteria with bactericides or by applying other inhibitory treatments (e.g. alkalinity) through either physical or chemical means to reduce the oxidation rate. The amount of ASS requiring excavation and/or dewatering can be minimized through reconsideration of the design for a proposed development. This consideration will relate to an understanding of where exactly, both laterally and with depth, ASS is located on the site. Dewatering impacts can be more easily minimised through installation of hydraulic impediments to dewatering such as engineered 'curtains' (e.g. shoring), re-injection wells and galleries, infiltration basins, and wet excavations.

Case Study Example: The installation of a water flow regulator in the Paiwalla wetland has prevented soils with: (i) hypersulfidic materials from being further oxidised and (ii) monosulfidic materials from being further mobilized (Figure 15-2). This has enabled the wetland to be managed satisfactorily.

Controlled ponding in the wetland during the rewetting of moist hypersulfidic materials and monosulfidic materials by a flow regulator has minimised potential mobilisation and the return of salts, metals and monosulfidic material to the river [see Figure 15-2 showing predictive soil-regolith models that illustrate the current 2009 status and 2 post 2009 predictive scenarios, which includes: (i) continuation of drought conditions and (ii) rewetting or re-flooding scenario].

Contain acid drainage with or without treatment to minimise risk of significant offsite impacts: (d) in Table 6-7**)**

Acidity and oxidation products that cannot be retained on-site may be managed by other techniques such as acidity barriers or wetlands that intercept and treat contaminated water before it is discharged into rivers or estuaries. Typically, this would involve installing a leachate collection and treatment system (e.g. using limestone), a permeable reactive barrier (e.g. lime slot) to intercept and neutralize acidic water as it moves though the soil, or installing an impermeable barrier to locally confine acidic groundwater. In the simplest case, it may be the use of control structures to manage rewetting and discharge.

Case Study Example: The continued management of the Banrock Ramsar wetland involves the careful maintenance of water levels by controlling in-flows and out-flows (Figure 16-1 to Figure 16-9). Under this management scenario, sulfuric materials and metal contaminants will be contained in the wetland and flushed at appropriate times, thus allowing targeted and controlled management to occur to re-instigate and maintain wetland quality.

Neutralisation - Provide an agent to neutralise acid as it is produced: (e) in Table 6-7**)**

This option involves mixing the ASS material with an excess of limestone ($CaCO_3$) or other neutralising agent to buffer the pH of the soil. The amount of lime required depends on acidity already produced and potential for further production of acid. One of the issues with this option is the large amount of limestone (agricultural lime) that is sometimes required and the effects it could have on biota and surrounding ecosystems. Liming, as a substitute for reflooding, and application to dry soils, also poses a problem as the lime would need to be mixed in with the soils to be most effective. This would mean churning up soil/wetland beds causing further disturbance of the soils. However, surface application could effectively neutralise acid soil formed at the surface, which is the material most prone to erosion or to which animals and humans may be directly exposed.

Case Study Example: Applications of fine limestone have been applied to the upper Finniss River in the form of a barrier across the river below Wally's Landing jetty as shown in Figure 11-11 (May 2009) to neutralize potential acidic waters from the wetland and channel (Figure 11-1).

Case Study Example: Aerial dosing of fine agricultural limestone has been used for extensive coverage in Boggy Lake, which is connected to Lake Alexandrina to neutralize strongly acidic ponded water in May 2010 (see Figure 6-2).

Figure 6-2. Aerial application of limestone in Boggy Lake, SA (left hand side photo) and photos on right land side showing mechanism used to upload fine agricultural limestone into the aircraft in a nearby paddock.

If mulch or organic matter is applied on top of a wetland bed, it will break down and also act as a buffer to counteract the acidity of sulfuric materials.

Where feasible, controlled reflooding with freshwater (or seawater if available) can be used to neutralise acidity in sulfuric materials and dilute acidity, as well as reduce the concentration of dissolved metals, metalloids and non-metals (e.g. from sulfate-rich salt efflorescences). Seawater contains bicarbonate alkalinity of about 140 mg/L. However, the acids and any metals that would initially dissolve in the seawater should not be permitted to flush out to the ocean but should first be removed by natural processes (e.g. water ponding). If flushing is not possible, salinity and sulfides are likely to progressively accumulate in such areas (e.g. Lower Lakes) over time. Note that flooding with sea water also helps with the process of exclusion of oxygen, as mentioned above. Most dissolved metals also drop out of solution in alkaline water but will accumulate in bottom sediments where benthic feeders may introduce the metals into the food web. However, based on research by Hicks *et al.* (2009) it was found that seawater released acidity more rapidly than river water, because the saltier water was better at displacing acid stored in the soil. Separate laboratory studies were in agreement.

No further action - Minimum intervention option* – *erect warning signs and establish monitoring programs, Includes the uncontrolled rewetting of wetlands where the management option has been not to intervene: (f) in Table 6-7
Case Study Example: In Loveday Bay, at a remote area adjacent to Lake Alexandrina (see map Figure 5-2), water levels in summer remained low enough to keep this area disconnected from the main part of Lake Alexandrina and develop deep sulfuric soils. However, from July 2009 with winter rains, water flowed over and through the sulfuric soils and collected in the depression areas to form more than 200 ha of very acidic

water (pH 2.5 to 2.8) with the soils below this water remaining sulfuric and not reducing to sulfidic material (see Figure 12-7 and (Figure 12-8).

No management options were applied to remediate the acidic standing water over the Sulfuric subaqueous Soils and Sulfuric Soils. This no further action or minimum intervention option has been adopted because at this stage Loveday Bay has no apparent major risk to adjacent water bodies, wetlands, agricultural lands, stock or humans – due its inherent remote location. However, warning signs have been erected (e.g. Figure 6-3) and monitoring of water (i.e. monthly during the re-wetting phases when acidity and metal mobilisation are likely to occur) and acid sulfate soils (three monthly) is currently an essential strategy being applied.

Figure 6-3. Public notification of risk in Boggy Lake (background) adjacent to Lake Alexandrina, South Australia because of the widespread occurrence of both Acid Sulfate Soils with sulfuric materials (pH <2.5) on beaches and ponded acidic water (pH <4).

Separate sulfidic materials

This may include the use of mechanical separation, such as sluicing or hydrocyclone to separate sulfide minerals (e.g. pyrite crystals) from the sulfidic material, followed by treatment (e.g. liming) or disposal of the sulfide minerals in an anaerobic environment.

Hasten oxidation and collection and treatment of acidic leachate

This involves spreading the ASS materials in a thin layer on an impervious area to activate rapid oxidation. Rainfall or irrigation leaches the acid and this leachate is collected and treated (e.g. by liming).

Management of stockpiled Acid Sulfate Soil materials

It is important to minimise the quantity and duration of ASS storage, minimise the surface area that can be oxidised, cover the soil to minimise rainfall infiltration, control stormwater and erosion and to collect and treat runoff (leachate).

Planning and development controls

There are numerous planning and development controls for coastal ASS, which already exist, e.g. in South Australia through the Coast Protection Board (e.g. Fitzpatrick *et al.* 2008j) and in several other regions in Australia (e.g. Queensland and NSW).

Finally, we emphasise that within the above management strategies there is still a degree of risk, and that some may not suit the circumstances of a particular site. Innovative management strategies other than those listed may be considered, but sufficient information regarding their successful implementation, environmental impacts and scientific merit should be provided, before they can be considered.

Environmental management plan

If excavation or disturbance of acid sulfate soil material is unavoidable, the proponent is required to prepare an Environmental Management Plan (EMP) to the satisfaction of the local Environment Protection Authority (EPA), e.g. in accordance with the SA EPA Guideline: Environmental management of on-site remediation (e.g. www.epa.sa.gov.au/pdfs/guide_remediation.pdf'). The EMP should be a document that describes how the proponent will achieve acceptable environmental outcomes for the protection of soils, surface water and groundwater, the receiving environment and the community. The EMP should clearly:

- summarise the environmental condition of the site and adjacent areas and potential impacts of the work to be conducted
- summarise the proposed development and works
- describe the proposed acid sulfate soil management measures for all phases of construction and operation
- outline a monitoring program for soils, surface water, groundwater and air during construction and operations, including parameters, monitoring locations, monitoring frequency, laboratory analysis and reporting protocols
- summarise new technologies that are proposed and, if applicable, include results of trials
- demonstrate effectiveness of the procedures used
- describe contingency procedures to deal with unexpected events and failure of management measures and Remedial Management Plan (RMP)

The suitability of management measures will depend on the nature of the receiving environment and the characteristics of the acid sulfate soil. Management costs for acid sulfate soils may be reduced where it can be demonstrated that the subtypes of acid sulfate soils are self neutralising or there are other mitigating factors to prevent acid discharge to the environment. Finally, it is generally recommended that prior to submission of the EMP, the proponent should contact the EPA to discuss the contents of the plan and identify other information that may be required.

Table 6-6 Generalized range of management options for ASS (modified from Bowman *et al.* 1999)

	Capping	Chemical Neutralisation	Reflooding		Bioremediation
Objective	Seal to cut-off oxygen supply and limit leaching by compaction	Neutralise existing acidity and reduce further acidification	Decrease rate of pyrite oxidation and establish reducing conditions to generate alkalinity		Re-establish reducing conditions, stop oxidation & transform oxidation products
Treatment	Cover with clayey fill and load to seal and compress oxidised material	Incorporate limestone or other neutralizing agents Stabilise oxidation products by: Water table management Burial Removal	Structures or wetlands used to increase watertable height or duration of tidal or freshwater inundation Open System: Tidal/fluvial flushing Fluvial inputs Open or unmanaged wetland	Closed System: Controlled inputs Minimize exports Managed wetland	Controlled reflooding of closed bioreactor (no exports) Organic waste inputs Wetland stabilisation & treatment of leachate
Advantages	Established technology Easily costed Reclamation of land	Established technology Easily costed Reclamation of land (with burial)	Unlimited neutralising potential Low cost Low maintenance management	Minimize export of accumulated or ongoing oxidation products Good system control	A total environmentally acceptable solution because of *in-situ* microbial generation of neutralisation capacity Uses agricultural & urban organic wastes – “win/win solution” Good system control Toxic products complexed with organic matter
Disadvantages	Requires testing and management of fill if dredge spoil used Inflexible, static solution Cost and manageability of burial Acid production may continue after burial due to oxidation by Fe^{3+} Acid remains and is inaccessible if leaching continues Long term success not demonstrated as capping seal breaks down over time	Cost and manageability of lime incorporation More soluble and caustic reagents are required if flowing water is to be treated and sophisticated management is required to avoid the discharge of caustic waters Without burial: Continuation of oxidation & acid production because huge quantities of limestone is usually required (e.g. East Trinity site > 600 t/ha). Hence, this is an inflexible and static solution. With burial: Cost and manageability of burial Acid production may continue after burial due to oxidation by Fe^{3+} Problems with poor mixing efficiency with clays and peats	Potential for ongoing oxidation & acid production Export of accumulated/ongoing oxidation products No system control Established technique Long lead time Requires sophisticated management Questionable environmental acceptability Floodgate maintenance and monitoring Ongoing cost of dredging openings	Potential for ongoing oxidation & acid production Stored toxic oxidation products remain Neutralising capacity limited to initial charge Unproven technique Long lead time Requires sophisticated management Unstable endpoint	Unproven technique Requires costly trials Long lead time Requires sophisticated management
Outcome	Removal of oxygen supply, limiting discharge by loading (less permeable)	Chemical neutralisation of existing acidity (lime) & removal of oxygen supply (burial)	Reduction in acid discharge		Elimination of acid discharge / toxic products

Table 6-7. Summary of generalised Acid Sulfate Soil management principles applied in 36 case studies across Australia.

Geographical Areas	Map Location*	Case Study	†Process	§Management Principles Applied						
					a	b	c	d	e	f
Tributary streams and rivers	SA: Mount Lofty Ranges	D	6,5	D1 Finniss River..		x	x		x	
			6,5	D2 Currency Creak.		x	x		x	
			6,5	D3 Tookayerta Creak		x	x			
	Victoria: Burnt Creek	J	6	J1 Dunolly region	x	x				
Lakes and adjacent wetlands	SA: Lake Alexandrina	B	5,6	B1 Ewe Is barrage						x
			6,5	B2 Goolwa Channel		x	x			
			6,5	B3 Pt Sturt						x
			6,5	B4 Poltalloch						x
			6,5	B5 Loveday Bay						x
	SA: Lake Albert	C	5,6	C1 Campbell Park		x	x			
			5,6	C2 Meningie		x	x			
	Vic: Lake Bolac-Salt Ck	L	1,6	L1 Woorndoo	x	x	x			
	WA: Wheat Belt	M	5,6	M1 Dumbleyung drain		x		x	x	
			5,6, 1-3	M2 Green Lake & drain		x		x	x	
			5,6, 1-3	M3 MacPherson Lake		x		x	x	
Main river channels and adjacent wetlands also comprising numerous billabongs, swamps, disposal evaporation basins, drains and minor lakes (e.g. Lake Bonney)	SA: River Murray section below Blanchetown	E	5,6	E1 Swanport wetland						x
			6	E2 Ukee boat ramp						x
			6	E3 Jury swamp						x
			5,6	E4 Paiwalla wetland			x			
			6	E5 Morgans wetland						x
	SA: River Murray section above Blanchetown	F	5,6	F1 Banrock				x		
			5	F2 Loveday disposal basin			x			
			5	F3 Noora disposal basins						x
			5	F4 Nelwart swamp		x		x		x
			5,6	F5 Lake Bonney &						x
			6	F5 Gurra Gurra wetlands	x					
			5,1	F6 Groundwater SIS						x
	Victoria: Loddon River	K	5,6	K1 Below Loddon Weir	x	x				x
	NSW: River Murray		5	F7 Tareena billabong						x
Estuaries, River Mouth and Swamps with combined marine/freshwater influence	SA: Coorong and Murray Mouth	A	5,6,7	A1 Coorong & Murray mouth	x					x
	WA: Perth Coastal Plain	N	5,1,6,7	N1 Gnangara Mound	x	x		x		
Seepages overlying mineralized zones	SA: Eastern Mount Lofty Ranges	G	1–6	G1 Herrmanns & Dairy Ck catchments	x	x	x			
			1–6	G2 Mineral exploration regional	x	x	x			
	Victoria: Eastern Dundas Tablelands	I	1–6	I1 Merrifields	x	x	x			
			1–6	I2 Gatum	x	x	x			
Abandoned mines with waste rock stockpiles and tailings impoundments, which strongly impact on freshwater systems	SA: Pyrite and Cu/Zn mines	H	5	H1 Brukunga pyrite mine					x	

*Map location: Refer to Figure 5-2

†**Contributing processes:**

1 Removal of native vegetation.
2 Agriculture.
3 Improved farming systems using vegetation.
4 Erosion.
5 Engineering works.
6 Drought conditions.
7. Marine salts and groundwater flow patterns

§**Management principles – indicated by "x"**

(a) Minimise disturbance or drainage of ASS materials.
(b) Prevent oxidation of hypersulfidic material and/or reverse oxidation of sulfuric material including rewetting.
(c) Minimise oxidation rate and isolate higher risk materials from exposure.
(d) Contain acid drainage to minimise risk of significant offsite impacts (incl. rewetting).
(e) Provide an agent to neutralise acid as it is produced.
(f) No further action and/or minimum intervention including uncontrolled rewetting (erect warning signs, establish surveillance and monitoring programs).

Note: monitoring of soil and water is an essential component of all ASS management

6.7. Reporting and communication – Stage 7

Establishment of stakeholder and public engagement plans

It is important to establish and implement a stakeholder and public engagement plan to facilitate the timely distribution of obtained ASS information to a broad and relevant group of stakeholders and community groups. Such a communication or engagement plan should be structured to ensure that as information becomes available it is rapidly provided to all stakeholders and immediately applied to support best practice management. The wide range of target communication products should include all tiers of government, non-government bodies, land managers and the broader community (e.g. White *et al.* 2007). For example, successful communication products should include: (i) focussed presentations to advisory committees, (ii) material for conducting special field ASS training courses (see information sheets on ASS tailored for general community use, for example the colour Information Sheet entitled "Acid Sulfate Soils Along the Lower Murray" produced by CSIRO and the Department of Water, Land, and Biodiversity Conservation's communication group in 2007 in Appendix 8, Fitzpatrick *et al.* 2008i or can be downloaded from websites e.g. http://www.clw.csiro.au/acidsulfatesoils/. Workshops should also be conducted for community volunteers to teach them how to collect soil and water samples for ASS monitoring (Thomas and Fitzpatrick 2011).

Case Study: A manual was developed in consultation with farmers in the Eastern Mount Lofty Ranges in South Australia (Fitzpatrick *et al*. 1997; Fitzpatrick *et al.* 2003) and the Woorndoo district in Victoria (Cox *et al*. 1999) to assist them in recognising, mapping and managing inland ASS features on their properties. The two manuals include a diagnostic field key of visual indicators with on-farm management options and are designed to be useful tools to support farmers in assessment and decision making. ASS seminars and field days for farmers were held to build their capacity to effectively assess and manage ASS and to demonstrate how they could use the manuals in their own situations.

Case Study: ASS sampling protocols for monitoring changes in ASS conditions in the Lower Lakes region were developed for community volunteers by Thomas and Fitzpatrick (2011). In total, 6 ASS seminars and field days were held to build the capacity of 85 community group volunteers to effectively monitor ASS 4 times during 2009 and 2010 at 3 or more sites. This resulted in a total of 486 soil profiles and 1,458 soil layers being sampled and tested for pH in the field by community groups, and in the laboratory by CSIRO. The graphs showing pH changes and trends are available on ASRIS (Australian Soil Resource Information System), which also contains the Atlas of Australian Acid Sulfate Soils (AAASS).

Documentation

Where measures are required to manage drained ASS or to protect aquatic environments, these should be documented and lodged with an appropriate body. For example, unless approvals and compliance with licensing or legislation is documented, it may be difficult to manage future changes in imposed conditions.

The collection of site (or area) characterisation data is of limited benefit unless this complex information can be conveyed to stakeholders effectively. Stakeholders require information to be presented in a logical format that will enable them to make decisions regarding ASS hazard, ASS risk, management options and remediation methods. Important forms of data presentation that are likely to be beneficial in the ASS characterisation and reporting of drought triggered ASS (e.g. as demonstrated in the case studies presented) include:

1. **Simplified conceptual soil-regolith models**, which provide an easy referenced indication of the zones (e.g. surface features and layers at depth) related to the various

ASS materials (e.g. sulfuric and hypersulfidic materials) and ASS subtypes (e.g. subaqueous sulfuric soil).

Case Study: Generalised predictive soil-regolith models have been developed to describe and explain the formation of drought triggered ASS across the MDB (see Figure 5-3) and Figure 5-13). In addition, several more detailed predictive soil-regolith models have been developed for specific landscapes in the MDB such as Lake Alexandrina, Lake Albert, Finniss River, Currency Creek, Goolwa channel, River Murray below Lock 1 and Loddon River/Burnt Creek in Victoria (see 36 case studies discussed in sections 11 to 24 and in Table 6-7). These conceptual soil-regolith models illustrate relationships between landscape position, water level, and ASS forming processes. Specifically, these models:

- Explain the progression of various ASS subtypes in response to lowering water levels from Deep-water ASS → Subaqueous ASS → Waterlogged/saturated ASS (all containing sulfidic material with high sulfide concentrations and pH > 4) → Drained and unsaturated or dried ASS containing sulfuric material (pH< *4*) in the upper aerated soil layers. The models show conceptualised ASS processes dating from 5,500 BC to the extreme drought conditions of 2006 - 2008)
- Explain and predict occurrences of sulfide minerals in sulfidic material and sulfate-containing minerals in acidic salt efflorescences
- Indicate impacts of further drought on ASS formation and potential decline in water quality, especially during reflooding
- Help develop remediation and management options for specific ASS environments

2. Simplified ASS maps using Geographic Information Systems (GIS) have proved very useful for presenting the spatial distribution of the wide range of ASS subtypes (using legend developed for the National Atlas and uploaded to ASRIS). Using GIS has allowed ASS data to be presented in map layers that can be switched on and off to allow focus on certain aspects.

Case Study: Simplified predictive ASS maps were produced in 2007-2008 to help estimate the areal extent of various ASS subtypes in the Lower Lakes region (Fitzpatrick *et al.* 2008b; Figure 5-4, Figure 5-5, Figure 5-6). GIS was applied to the generalised predictive ASS model with lake bathymetry and predicted that for the Lower Lakes (93,466 ha), the aerial extent of sulfuric soils would increase from zero hectares before the drought in 2006 (+0.5 m AHD), to 1,039 ha (1%) in October 2008 (–0.5 m AHD), and will expand to 32,699 ha (35%) should the current drought persist and Lake levels continue to fall to -1.5 m AHD. These predictions were verified from field and laboratory investigations conducted in August 2009 when approximately 20,000 ha (20%) of sulfuric soils was identified by Fitzpatrick *et al.* (2010c) in Lake Alexandrina (-1.0 m AHD).

Monitoring

Similarly, unless ASS properties and groundwater levels/hydrogeochemistry and drain water quality are monitored and recorded, the efficacy of ASS and water management cannot be gauged and changes in acid and salt loads cannot be understood. Consequently, an effective documentation mechanism is essential and should be appropriate to manage the various potential risks and the assumptions made (e.g. see monitoring case studies conducted by: Baker *et al.* 2010; Fitzpatrick *et al.* 2011; Shand *et al.* 2009, 2010).

In accordance with the relevant environmental approval process for a development project, the environmental assessment of the project, incorporating the information on the risk management, should be forwarded to the relevant approving authority.

Both soil and water quality monitoring should be undertaken to detect changes in ASS quality and nature of effluent discharges, and to assess the potential impact of the discharge on the downstream environment. During the construction phases of drains or regulators, monitoring must be undertaken to determine whether site management practices and mitigation measures are successful in preventing ASS materials, waters or pollutants from entering drainage lines, groundwater and waterways (e.g. Fitzpatrick *et al.* 2011; Shand *et al*. 2009; 2010). The level of monitoring required is determined by evaluation of the nature of a threat from a discharge (i.e. via water or wind) and the level of protection required for the environment. Generally, the greater the potential environmental risk posed by a project, the more rigorous and complex the monitoring requirements become. The environmental monitoring program should identify the level of monitoring required (e.g. long term monitoring conducted by Baker *et al.* 2010).

7. REFERENCES

Ahern, CR, McElnea, AE & Sullivan, L (2004). *Acid sulfate soils laboratory methods guidelines*. In 'Queensland Acid Sulfate Soils Manual 2004'. Department of Natural Resources, Mines and Energy, Indooroopilly, Queensland, Australia. http://www.nrw.qld.gov.au/land/ass/pdfs/lmg.pdf (Accessed 2 October 2007).

Ahern CR, Ahern MR & Powell B (1998). *Guidelines for sampling and analysis of* lowland acid sulfate soils (ASS) in Queensland. Queensland Acid Sulfate Soils Investigation Team (QASSIT), Department of Natural Resources, Resource Science Centre, Indooroopilly, Queensland.

Anon (2009) *Strategic Framework for the List of Wetlands of International Importance*, edition 2009. The Ramsar Convention on Wetlands. 1971, amended 1982 and 1987, published 1994. Third edition, as adopted by Resolution VII.11 (COP7, 1999) and amended by Resolutions VII.13 (1999), VIII.11 and VIII.33 (COP8, 2002), IX.1 Annexes A and B (COP9, 2005), X.20 (COP10, 2008) and posted on web 2009 at http://www.ramsar.org/key_guide_list2009_e.htm confirmed 22 July 2009)

Appleyard SJ & Cook T (2008). Reassessing the management of groundwater use from sandy aquifers: acidification and base cation depletion exacerbated by drought and groundwater withdrawal on the Gnangara Mound, Western Australia. *Hydrogeology Journal* 17:579–588.

Appleyard SJ, Wong S, Willis-Jones B, Angeloni J & Watkins R (2004). Groundwater acidification caused by urban development in Perth, Western Australia: source, distribution and implications for management. *Australian Journal of Soil Research* 42:579–585.

Appleyard SJ, Angeloni J & Watkins R (2006). Arsenic-rich groundwater in an urban area experiencing drought and increasing population density, Perth, Australia. Applied Geochemistry 21:83–97.

Baldwin DS, Hall KC, Rees GN & Richardson AJ (2007). Development of a protocol for recognising sulfidic sediments (potential acid sulfate soils) in freshwater wetlands. *Ecological Management and Restoration* 8, 56–60.

Baker AKM, Fitzpatrick, RW, Shand, P, Simpson SL, Merry RH, & Thomas M (2010). Temporal variations in representative Acid Sulfate Soil environments around Lakes Alexandrina and Albert, South Australia. Prepared for The Murray Darling Basin Authority and South Australian Murray Darling Basin Natural Resources Management Board. Client Report R-325-8-2, CSIRO: Sustainable Agriculture Research Flagship, 250 pp. http://www.clw.csiro.au/publications/science/2010/SAF-Lakes-Alexandrina-Albert-sulfate-soils-temporal.pdf

Baker AK & Fitzpatrick R (2008). A New Web-Based Approach for the Acquisition, Collation and Communication of Complex Inland Acid Sulfate Soils Data. In *Inland Acid Sulfate Soil Systems Across Australia* (Eds. RW Fitzpatrick & P Shand). pp 162-168. CRC LEME Open File Report No. 249. (Thematic Volume) CRC LEME, Perth, Australia.

Baker AK and Fitzpatrick RW (2011). A web-based approach to improve collation and communication of complex soil-landscape data with examples relating to agricultural production, environmental degradation and mineral exploration. *Soil Use and Management* **27**, 550-559. DOI: 10.1111/j.1475-2743.2011.00370.x

Barnett SR (1992) Regional hydrogeology of the Cooke Plains - Coomandook area, Murray Basin. Department of Mines and Energy South Australia Report 92/14. 43 pp.

Berne RA (1984) Sedimentary pyrite formation: an update. *Geochimica et Cosmochimica Acta* 48, 605–615.

Bigham JM & Nordstrom DK (2000) Iron and aluminium hydroxysulfates from acid sulfate waters. pp. 351–403. *In* Alpers, C.N. Jambor, J.L. & Nordstrom D.K (Eds.). *Sulfate minerals: Crystallography, geochemistry, and environmental significance. Rev. Miner. Geochem*. Vol. 40. Miner. Soc. Am., Washington, D.C.

Bigham JM, Schwertmann U Carlson L & Murad E (1990) A poorly crystallized oxyhydroxysulfate of iron formed by bacterial oxidation of Fe(II) in acid mine waters. *Geochim. Cosmochim. Acta* 54, 2743–2758.

Bigham JM, Fitzpatrick RW & Schulze DG (2002) Iron Oxides. pp. 323–366. *In* Dixon J.B. & Schulze D.G. (Eds.). *Soil Mineralogy with Environmental Applications.* Soil Science Society America Book Series No 7. SSSA, Madison, Wisconsin.

Bigham JM, Schwertmann U, Traina SJ, Winland RL. & Wolf M (1996). Schwertmannite and the chemical modelling of iron in acid sulfate waters: *Geochimica et Cosmochimica Acta*, v. 60, 2111–2121.

Blöschl G, Ardoin S, Bonel, M, Doringer M, Goodrich D, Gutnecht, D, Matamoros D, Merz B, Shand P & Szolgay J. (2007) At what scales do climate variability and land cover change impact on flooding and low flows? Invited commentary, *Hydrological Processes*, 21(9), 1241-1247.

Bowman GM, Hicks WS, Fitzpatrick RW & Davies PJ (1999). Remediation options for acid sulfate soil "hotspot" at East Trinity Inlet, Cairns, North Queensland. Proceedings of Workshop on Remediation and Assessment of Broadacre Acid Sulfate Soils. (Ed. P.G. Slavich). Southern Cross University, Lismore, 31 August to 2 September, 1999. Acid Sulfate Soil Management Advisory Committee (ASSMAC), Australia. p.130-145.

Bradley MP, & Stolt MH (2003) Subaqueous soil-landscape relationships in a Rhode Island estuary. *Soil Sci. Soc. Am. J.* 67:1487-1495.

Burton ED, Bush RT & Sullivan LA (2006a) Reduced inorganic sulfur speciation in drain sediments from acid-sulfate soil landscapes. *Environ. Sci. Technol*. 40, 888–893.

Burton ED, Bush, RT & Sullivan LA (2006b) Acid-volatile sulfide oxidation in coastal floodplain drains: iron-sulfur cycling and effects on water quality. *Environmental Science & Technology* 40, 1217–1222.

Burton ED, Bush RT, Sullivan LA, Hocking RK, Mitchell DRG, Johnston SG, Fitzpatrick RW, Raven M, McClure, S & Jang LY (2009) Iron-monosulfide oxidation in natural sediments: Resolving microbially mediated S transformations using XANES, electron microscopy, and selective extractions. *Environmental Science and Technology* 43: 3128–3134.

Bush RT, Fyfe D. & Sullivan LA (2004) Occurrence and abundance of monosulfidic black ooze in coastal acid sulfate soil landscapes. *Aust. J. Soil Res*. 42, 609–616.

Cook T, Watkins R, Appleyard S & Vogwill R (2006) Acidification of groundwater caused by a falling water table in a sandy aquifer in the Perth Region, Western Australia. In: Proceedings of the 18th World Congress of Soil Science. Philadelphia, Pennsylvania, USA. 9-15 June 2006.

Coram JE, Dyson PR, Houlder PA & Evans WR (2001) *'Australian Groundwater Flow Systems contributing to Dryland Salinity'.* A Bureau of Rural Sciences Project for the National Land and Water Resources Audit's Dryland Salinity Theme. 77 pp.

Cox JW, Fitzpatrick RW, Mintern L, Bourne J & Whipp G (1999) *Managing waterlogged and saline catchments in south-west Victoria: A soil-landscape and vegetation key with on-farm management options.* Woorndoo Land Protection Group Area Case Study. Catchment Management Series No. 2. CSIRO Publishing, Melbourne.

Cox JW, Fritsch E & Fitzpatrick RW (1996) Interpretation of soil features produced by ancient and modern processes in degraded landscapes: VII. Water duration. *Australian Journal of Soil Research* 34, 803–824.

Creeper N, Fitzpatrick R, Shand P & Kingham R (2010) A systematic analysis procedure incorporating the chip-tray incubation method for the hazard assessment of Acid Sulfate Soils in the Murray Darling Basin. In: RJ Gilkes & 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 9-12.

Dear SE, Moore NG, Dobos SK, Watling KM. & Ahern CR (2002) Soil Management Guidelines. In *Queensland Acid Sulfate Soil Technical Manual: (version 3.8).* Department of Natural Resources and Mines, Queensland. http://www.nrw.qld.gov.au/land/ass/pdfs/soil_mgmt_guidelines_v3_8.pdf

DEC (2008) Department of Environment and Conservation WA An initial Assessment of Groundwater Acidification on the Gnangara Mound. DEC website. Date viewed: 18th May 2009; http://www.water.wa.gov.au/Waterways+health/Groundwater/Gnangara+Mound/default.aspx

Degens B Proposed guidelines for treating acidic drain water in the Avon catchment, Western Australia: adapting acid mine drainage treatment systems for saline acidic drains, Western Australia, Salinity and land use impacts series, SLUI 54, Department of Water, 140p.

Degens B, Shand P, Fitzpatrick R, George RG, Rogers S & Smith M (2008a) Avon Basin, WA Wheatbelt: An Overview of Geochemical Risks of Saline Acidic Discharge from Deep Drains Used to Manage Dryland Salinity in Western Australia. In *Inland Acid Sulfate Soil Systems Across Australia* (Eds. Rob Fitzpatrick and Paul Shand). pp 169-175. CRC LEME Open File Report No. 249. (Thematic Volume) CRC LEME, Perth, Australia.

Degens B, Fitzpatrick R & Hicks W (2008b) Avon Basin, WA Wheatbelt: Acidification and Formation of Inland ASS Materials in Salt Lakes by Acid Drainage and Regional Groundwater Discharge. In *Inland Acid Sulfate Soil Systems Across Australia* (Eds Rob Fitzpatrick and Paul Shand). pp 176-189. CRC LEME Open File Report No. 249. (Thematic Volume) CRC LEME, Perth, Australia.

Degens BP, Fitzpatrick RW & Raven MD (2010) Hydric halitic sulfuric soils in secondary salinised landscapes of Southwest Western Australia. *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.

Degens B, McIntosh K and Shand P (2008c). Farm-Based Treatment of Acid Drainage Waters Coupled with Inland Acid Sulfate Soil Materials in Western Australia. In *Inland Acid Sulfate Soil Systems Across Australia* (Eds Rob Fitzpatrick and Paul Shand). pp 205-210. CRC LEME Open File Report No. 249. (Thematic Volume) CRC LEME, Perth, Australia.

Degens B & Wallace-Bell P (2009). Acid sulfate soil survey of shallow regolith on the Scott Coastal Plain. Department of Water, Government of Western Australia, Hydrogeological record series, report no. HG24.

Degens B and Shand P (editors) (2010) Assessment of acidic saline groundwater hazard in the Western Australian Wheatbelt: Yarra Yarra, Blackwood and South Coast. CSIRO: Water for a Healthy Country National Research Flagship. 152 pp..

http://www.clw.csiro.au/publications/waterforahealthycountry/2010/wfhc-WA-acid-saline-groundwater-hazard.pdf

Demas GP & Rabenhorst MC (1999) Subaqueous soils: Pedogenesis in a submersed environment*. Soil Science Society of America Journal*. 63, 1250–1257.

Dent DL (1986) Acid Sulphate Soils: a Baseline for Research and Development. I.RI Pub. No. 39. International Institute for Land Reclamation & Improvement. Wageningen.

Dent DL & Pons LJ (1995) A world perspective on acid sulfate soils. *Geoderma* 67, 263-276.

DEWHA (2009) Emergency response for the crisis management of Acid Sulfate Soils in the Goolwa Channel, Finniss River and Currency Creek, South Australia. Referral of proposed action document (Department of the Environment, Water, Heritage and the Arts). The *Environment Protection and Biodiversity Conservation Act 1999* EPBC Reference Number 2009/4833 - Emergency response for the crisis management of Acid Sulfate Soils in the Goolwa Channel, Finniss River and Currency Creek, South Australia. http://www.environment.gov.au/cgi-bin/epbc/epbc_ap.pl?name=referral_detail&proposal_id=4833. (Accessed 16 September 2009).

DWLBC (2008) River Murray telemetry data, accessed 16 September 2008 via URL http://data.rivermurray.sa.gov.au/#b < http://data.rivermurray.sa.gov.au/>

de Mooy CJ (1959) Soils and land use around Lakes Alexandrina and Albert, South Australia. CSIRO Soils and Land Use Series No. 29. CSIRO Division of Soils, Melbourne, 84 pp.

Dogramaci S & Degens B, (2003). Review of Engineering and Safe Disposal Options, Western Australia. Water and Rivers, Report No. SLUI 20. Government of Western Australia.

EPHC & NRMMC (2011) *National guidance for the management of ASS in inland aquatic ecosystems*, Environment Protection and Heritage Council, and Natural Resource Management Ministerial Council, Canberra, ACT. www.environment.gov.au/water/publications/quality/guidance-for-management-of-acid-sulfate-soils.html

Fanning DS (2002) Acid sulfate soils.. In *Encyclopedia of Soil Science (Ed R Lal).* pp 11–13 Marcel Dekker, New York.

Fanning DS & Fanning MCB (1989) Soil: Morphology, genesis and classification. pp395 John Wiley & Sons, New York.

Fawcett J, Fitzpatrick R & Norton R (2008). Inland Acid Sulfate Soils of The Spring Zones Across the Eastern Dundas Tableland, South Eastern Australia. In *Inland Acid Sulfate Soil Systems Across Australia* (Eds. Rob Fitzpatrick and Paul Shand). pp 268-280. CRC LEME Open File Report No. 249. (Thematic Volume) CRC LEME, Perth, Australia.

Fitzpatrick RW (1991) How rising water-tables cause productive soils to alter to saline mangrove swamp like-soils. *CSIRO Division of Soils Technical Report* No. 16/1991. 6pp. http://www.clw.csiro.au/publications/divisionofsoils/techmemos/s-tm-16-1991.pdf

Fitzpatrick RW (2004) Classification Systems: Australian. In *Encyclopedia of Soils in the Environment (Editor-in-Chief Daniel Hillel*). pp. 211–216. Elsevier Ltd., Oxford, U.K. © 2005. ISBN (Set): 0-12-348530-4

Fitzpatrick RW (2008) Soils and Natural Resource Management. pp. 307–339 (colour plates: pp 172–174). *In* Scott, K.M & Pain, C.F. (Eds.). *Regolith Science.* (Chapter 12) CSIRO Publishing (Australia) and Springer.

Fitzpatrick R**,** Degens B, Baker A, Raven M, Shand P, Smith M, Rogers S & George R (2008a) Avon Basin, WA Wheatbelt: Acid Sulfate Soils and Salt Efflorescences in Open Drains and Receiving Environments. In *Inland Acid Sulfate Soil Systems Across Australia* (Eds. Rob Fitzpatrick and Paul Shand). pp 189-204. CRC LEME Open File Report No. 249. (Thematic Volume) CRC LEME, Perth, Australia.

Fitzpatrick R, Degens B, Hicks W & Fordyce I (2010a) Acidic sediment chemistry in acidified lakes – case studies. *In* Degens B and Shand P (eds.) Assessment of acidic saline groundwater hazard in the Western Australian Wheatbelt: Yarra Yarra, Blackwood and South Coast. CSIRO: Water for a Healthy Country National Research Flagship. p. 91–101. http://www.clw.csiro.au/publications/waterforahealthycountry/2010/wfhc-WA-acid-saline-groundwater-hazard.pdf

Fitzpatrick RW, Cox JW & Bourne J (1997) *Managing Waterlogged and Saline Catchments in the Mt Lofty Ranges, South Australia: a soil-landscape and vegetation key with on-farm management options.* Catchment Management Series No. 1. CSIRO Publishing, Melbourne.

Fitzpatrick RW, Cox JW, Munday B & Bourne J (2003a) Development of soil - landscape and vegetation indicators for managing waterlogged and saline catchments. *Australian Journal of Experimental Agriculture* 43, 245–252.

Fitzpatrick RW, Fritsch E & Self PG (1996) Interpretation of soil features produced by ancient and modern processes in degraded landscapes. V. Development of saline sulfidic features in non-tidal seepage areas. *Geoderma* 69, 1–29.

Fitzpatrick RW, Grealish G, Shand P, Simpson SL, Merry RH & Raven MD (2009a) Acid Sulfate Soil Assessment in Finniss River, Currency Creek, Black Swamp and Goolwa Channel, South Australia. CSIRO Land and Water Science Report 26/09. CSIRO, Adelaide, 213 pp. http://www.clw.csiro.au/publications/science/2009/sr26-09.pdf

Fitzpatrick R, Grealish G, Shand P, Merry R, Creeper N, Thomas M, Baker A, Thomas B, Hicks W & Jayalath N (2010b) Chip-tray incubation – a new field and laboratory method to support Acid Sulfate Soil Hazard Assessment, Classification and Communication. 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 28-31.

Fitzpatrick RW, Grealish G, Chappell A, Marvanek S, & Shand P (2010c). Spatial variability of subaqueous and terrestrial Acid Sulfate Soils and their properties, for the Lower Lakes, South Australia. Report prepared for the SA Department for Environment and Natural Resources, South Australia (DENR). Client Report R-689-1-15: CSIRO Sustainable Agriculture National Research Flagship 122 pp. http://www.clw.csiro.au/publications/science/2010/SAF-Lower-Lakes-SA-sulfate-soils.pdf

Fitzpatrick RW, Grealish GH, Shand P, & Creeper NL (2011a) Monitoring and Assessment of Reflooded Acid Sulfate Soil Materials in Currency Creek and Finniss River Region, South Australia. Prepared for the South Australia Department of Environment and Natural Resources (DENR), Adelaide. Client Report R-325-8-6. CSIRO: Sustainable Agriculture Research Flagship, 103 pp. http://www.clw.csiro.au/publications/science/2011/SAF-monitoring-ASS-Currency-Creek.pdf

Fitzpatrick RW, Hudnall WH, Self PG & Naidu R (1993) Origin and properties of inland and tidal saline acid sulfate soils in South Australia. pp. 71–80. *In* Dent, D.L. & van Mensvoort M.E.F. (Eds.). *Selected papers of the Ho Chi Minh City Symposium on Acid Sulfate Soils*. International Institute for Land Reclamation and Development Publication 53.

Fitzpatrick RW, Marvanek S, Shand P, Merry RH, Thomas M & Raven M (2008b) 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 RW, Marvanek S, Powell B. & Grealish G (2010d) 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 & Merry RH (1999) Pedogenic Carbonate Pools and Climate Change in Australia p.105-119. In: R. Lal, J.M. Kimble, H. Eswaran & B.A. Stewart (eds.). “Global Climate Change and Pedogenic Carbonates”. CRC Press Lewis Publishers. Boco Raton. FL.

Fitzpatrick RW & Merry RH (2002) Soil-regolith models of soil-water landscape degradation: development and application. In *Regional water and soil assessment for managing sustainable agriculture in China and Australia.* (Eds TR McVicar, L Rui, RW Fitzpatrick and L Changming) pp. 130–138. Australian Centre for International Agricultural Research 84, Canberra.

Fitzpatrick RW, Merry RH & Cox JW (2000a). What are saline soils? What happens when they are drained? *Journal of the Australian Association of Natural Resource Management* (AANRM). Special Issue (June 2000), 26–30.

Fitzpatrick RW, Merry RH, Cox JW, Rengasamy P & Davies PJ (2003b) Assessment of physico-chemical changes in dryland saline soils when drained or disturbed for developing management options. *CSIRO Land and Water Technical Report* 02/03. CSIRO, 56pp.

Fitzpatrick RW, Merry RH, Raven MD & Shand P (2008c) 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, Raven MD, McClure S & Shand P (2008d) Geochemistry and Mineralogy of Sulfidic Drains in Tilley Swamp, South Australia. pp. 262–267. *In* Fitzpatrick R.W. & Shand P (Eds.). *“Inland Acid Sulfate Soil Systems Across Australia”.* CRC LEME Open File Report No. 249. (Thematic Volume) CRC LEME, Perth, Australia.

Fitzpatrick RW, Merry RH, Williams J, White I, Bowman G & Taylor G (1998) Acid Sulfate Soil Assessment: Coastal, Inland and Minespoil Conditions. National Land & Water Resources Audit Methods Paper. pp.18. http://lwa.gov.au/files/products/national-land-and-water-resources-audit/pn21357/pn21357.pdf

Fitzpatrick RW, Naidu R & Self PG (1992) Iron deposits and microorganisms occurring in saline sulfidic soils with altered soil water regime in the Mt. Lofty Ranges, South Australia. pp. 263–286. *In* Skinner HCW & Fitzpatrick RW (Eds.) “*Biomineralization Processes of Iron and Manganese - Modern and Ancient Environments*”. Catena Supplement 21. Catena, Reiskirchen, Germany.

Fitzpatrick RW, Powell B, McKenzie NJ, Maschmedt DJ, Schoknecht N & Jacquier DW (2003c) Demands on Soil Classification in Australia. pp. 77–100. *In* Eswaran, H., Rice, T., Ahrens, R. & Stewart B.A. (Eds) *Soil Classification: A Global Desk Reference.* CRC Press LLC Boco Raton. FL.

Fitzpatrick RW, Powell B & Marvanek S (2008e) Atlas of Australian Acid Sulfate Soils. pp. 90–97. *In* Fitzpatrick R.W. & Shand P (Eds.) *Inland Acid Sulfate Soil Systems Across Australia.* CRC LEME Open File Report No. 249. (Thematic Volume) CRC LEME, Perth, Australia.

Fitzpatrick RW, Raven M, Self PG, McClure S, Merry RH & Skwarnecki M (2000b) Sideronatrite in acid sulfate soils in the Mt. Lofty Ranges: First occurrence, genesis and environmental significance. pp. 109–110. *In* Adams J.A. & Metherell A.K. (Eds.) *New Horizons for a New Century.* Australian and New Zealand Second Joint Soils Conference Volume 2: Oral Papers. December 2000, Lincoln University, New Zealand Society of Soil Science.

Fitzpatrick RW & Self PG (1997) Iron oxyhydroxides, sulfides and oxyhydroxysulfates as indicators of acid sulphate surface weathering environment. pp. 227–240. *In* K. Auerswald, Stanjek H. & Bigham J.M. (Eds.) *Soils and Environment: Soil Processes from Mineral to Landscape Scale.* Advances in GeoEcology 30. Catena Verlag, Reiskirchen, Germany.

Fitzpatrick RW & Skwarnecki MS (2005) Mount Torrens, eastern Mount Lofty Ranges, South Australia: Regolith Models of Soil-Water Landscape Degradation. pp. 220–225. *In* Anand R.R. & de Broekert P. (Eds.) *Regolith Landscape Evolution Across Australia: A compilation of regolith-landscape case studies and landscape evolution models*. CRC LEME, Perth.

Fitzpatrick RW & Shand P (2008) Inland Acid Sulfate Soils: Overview and conceptual models. pp. 6–73. *In* Fitzpatrick, R.W. & Shand, P. (Eds.). *Inland Acid Sulfate Soil Systems Across Australia*. CRC LEME Open File Report No. 249 (Thematic Volume) CRC LEME, Perth, Australia.

Fitzpatrick RW, Shand P, Grealish G, Thomas M, McClure S, Merry RH, Raven R & Baker A (2010e). 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 (2008f) 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, 167. pp. http://www.clw.csiro.au/publications/science/2008/sr46-08.pdf

Fitzpatrick RW, Shand P & Merry RH (2009b) Acid sulfate soils. pp. 66–110. *In* Jennings, JT (Ed.) *Natural History of the Riverland and Murraylands.* Royal Society of South Australia.

Fitzpatrick RW, Shand P, Thomas M, Merry RH, Raven, MD & Simpson SL (2008g) Acid sulfate soils in subaqueous, waterlogged and drained soil environments of nine wetlands below Blanchetown (Lock 1), South Australia: properties, genesis, risks and management. Prepared for South Australian Murray-Darling Basin Natural Resources Management Board. *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, Shand P, Merry RH & Raven MD (2008h) 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 http://www.clw.csiro.au/publications/science/2008/sr21-08.pdf

Fitzpatrick RW, Shand P, Merry RH, Thomas B, Marvanek S, Creeper N, Thomas M, Raven MD, Simpson, SL, McClure S & Jayalath N (2008i) Acid sulfate soils in the Coorong, Lake Alexandrina and Lake Albert: properties, distribution, genesis, risks and management of subaqueous, waterlogged and drained soil environments. Prepared for Department of Water, Environment, Heritage and Arts. CSIRO Land and Water Science Report 52/08. CSIRO, Adelaide, 167. pp. http://www.clw.csiro.au/publications/science/2008/sr52-08.pdf

Fitzpatrick, RW, Thomas B P. & Merry R.H (2008j) Acid Sulfate Soils in Gulf St Vincent. pp. 106-120. *In* Shepherd, S.A., S. Bryars, I.R. Kirkegaard, P. Harbison & J.T Jennings (Eds.). *Natural History of Gulf St Vincent*. Royal Society of South Australia (Inc.) Adelaide, South Australia.

Fritsch E & Fitzpatrick RW (1994) Interpretation of soil features produced by ancient and modern processes in degraded landscapes. I. A new method for constructing conceptual soil-water-landscape models. *Australian Journal of Soil Research* 32, 880–885, 889–907.

George RG, Speed RJ, Simons JA, Smith RH, Ferdowsian R, Raper GP and Bennett DL, (2008). *Long-term groundwater trends and their impact on the future extent of dryland salinity in Western Australia in a variable climate.* Proceedings: “2nd International Salinity Forum”, Adelaide 31st March - 3rd April, 2008.

Hall KC, Baldwin DS, Rees GN & Richardson AJ (2006) Distribution of inland wetlands with sulfidic sediments in the Murray-Darling Basin, Australia. *Science of The Total Environment* 370, 235–244.

Hicks W & Fitzpatrick RW (2008) Greenhouse Emissions and Toxic Gas Emissions from Soil Organic Matter and Carbonates Associated with Acid Sulfate Soils. pp. 125–135. *In* Fitzpatrick, R.W. & Shand, P. (Eds.). *Inland Acid Sulfate Soil Systems Across Australia*. CRC LEME Open File Report No. 249. (Thematic Volume) CRC LEME, Perth, Australia.

Hicks WS, Creeper N, Hutson J, Fitzpatrick RW. Grocke S & Shand P (2009) The potential for contaminant mobilisation following acid sulfate soil rewetting: Field Experiment. Prepared by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Land and Water for the SA Department of Environment and Natural Resources, Adelaide. 113 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

Hill E (1969) (First published in 1937) *Water Into Gold*. Walkabout paperback edition, Sydney, 296pp.

Hipsey M, Busch, B, Coletti J & Salmon S (2010). Geochemical and hydrological modelling of acid sulfate soil impact on the River Murray Lower Lakes, University of Western Australia.

Hingston FJ & Gailitis V. (1976) The geographic variation of salt precipitated over Western Australia. *Australian Journal of Soil Research* 14, 319-335.

Horwitz P & Sommer B (2005) Water quality responses to fire, with particular reference to organic-rich wetlands and the Swan Coastal Plain: a review. Journal of the Royal Society of Western Australia 88, 121-128

Horwitz P, Sommer B & Calvert T (2007) Water chemistry and invertebrate responses to fire in wetlands with pyritic organic rich soils on the Swan Coastal Plain. Consortium for Health and Ecology Edith Cowan University, Joondalup WA 6027 (Department of Water, Albany) Final Report to the Western Australian Department of Water March 2007.

Hollingsworth ID, Fitzpatrick RW & Hudnall WH (1996) Distribution and properties of soils in an experimental sub-catchment with altered soil water regimes near Cooke Plains, South Australia. CSIRO Division of Soils Divisional Report No. 126; 42 pp. (ISBN 0 643 05863X).

Isbell RF and CSIRO (2002) *The Australian soil classification*. CSIRO, Publishing, Melbourne.

Jensen HI (1914) Soils of New South Wales. Department of Agriculture, New South Wales, Sydney, Australia.

Johnston S, Kroon F, Slavich P, Cibilic A & Bruce A (2003) Restoring the balance: Guidelines for managing floodgates and drainage systems on coastal floodplains. (NSW Agriculture: Wollongbar, Australia).

Johnston S, Slavich P & Hirst P (2004). The acid flux dynamics of two artificial drains in acid sulfate soil backswamps on the Clarence River floodplain, *Australia. Australian Journal of Soil Research* 42:623–637.

Johnston S, Slavich P & Hirst P (2005). The effects of controlled tidal exchange on improving drainage water quality in acid sulfate soil backswamps. *Agricultural Water Management* 73:87–111.

Kjøller C Postma D and Larsen F (2004) Groundwater acidification and the mobilization of trace metals in a sandy aquifer. *Environmental Science and Technology* 38, 2829-2835.

Kingwell R & Cook S, (2007). Farmers' attitudes and investment intentions regarding land drainage in a salinising Australian landscape. The International Journal of Interdisciplinary Social Science 2, 169-185.

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.* CSIRO Land and Water, Technical Report 28/04. CSIRO, CSIRO Land and Water Technical Report No. 28/04. CRC LEME Open File Report 165. August 2004. 65pp.

Lamontagne S, Hicks WS, Fitzpatrick RW & Rogers S (2006) Sulfidic materials in dryland river wetlands. *Marine and Freshwater Research* **57,** 775–788.

Mack D (1958-2003) Irrigation Settlement: some historic aspects in South Australia on the River Murray 1838–1978. Published by the Cobdogla Irrigation and Stream Museum in association with The Cobdogla Steam Friends Society. P.O. Box 208, Berri South Australia, 5343. pp 389.

McDonald RC, Isbell RF, Speight JG, Walker J, & Hopkins MS (1990) Australian Soil and Land Survey Field Handbook, 2nd Edition, Inkata Press, Melbourne. pp. 87–183.

McRea A (2004) Perth's groundwater mounds under pressure – agricultural irrigation factor. In: Proceedings of the Irrigation Association of Australia Biennial National Conference, Adelaide, Australia, 11-13 May 2004.

MDBC (2006a) *The Lower lakes, Coorong and Murray mouth icon site environmental management plan 2006-2007*. Murray-Darling Basin Commission. Living Murray, MDBC Publication. 34/06, 115 pp.

MDBC (2006b) The River Murray Channel icon site environmental management plan (2006–2007). Murray Darling Basin Commission. MDBC Publication No. 35/06, 119 pp.

MDBA (Murray–Darling Basin Authority) 2009, Acid sulfate soils field guide — A field guide for the identification of wetlands at risk of acid sulfate soils in the Murray–Darling Basin, Murray–Darling Basin Authority, Canberra.

MDBA (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. MDBA Publication 57/10. ISBN 978-1-921557-67-5. 58 pp.

MDBA (2011) Acid sulfate soils in the Murray–Darling Basin. Murray–Darling Basin Authority MDBA Publication 147/11. ISBN 978-1-921914-10-2.

Milnes AR, Fitzpatrick RW, Self PG, Fordham AW & McClure SG (1992) Natural iron precipitates in a mine retention pond near Jabiru, Northern Territory, Australia. p. 233-261. *In* Skinner HCW & Fitzpatrick RW (Eds.). Biomineralization Processes of Iron & Manganese - Modern and Ancient Environments. *Catena Supplement* 21. Catena Verlag, Reiskirchen, Germany.

National Working Party on Acid Sulfate Soil (2000) *'National Strategy for the Management of Coastal Acid Sulfate Soils'.* NSW Agriculture, Wollongbar Agricultural Institute, Wollongbar, NSW. http://www.dpie.gov.au/dpie/armcanz/pubsinfo/ass/ass.html

Ngarrindjeri Tendi, Ngarrindjeri Heritage Committee & Ngarrindjeri Native Title Management Committee (2007) Ngarrindjeri Nation Sea Country plan: Caring for Ngarrindjeri country and culture. Ngarrindjeri Land and Progress Association, Camp Coorong, Meningie, South Australia, 5264. Email: nlpa@bigpond.com.

Nordstrom DK & Alpers CN (1999) Geochemistry of acid mine waters. pp. 133–160. *In* Plumlee, G.S. & Logsdon, M.J., (Eds.) *The environmental geochemistry of mineral deposits*, *Part A.: Processes, techniques, and health issues*. Society of Economic Geologists, Inc., *Reviews in Economic Geology*, vol. 6A.

Northcote KH, Beckmann GG, Bettenay E, Churchward HM, Van Dijk DC, Dimmock GM, Hubble GD, Isbell RF, Mcarthur WM, Murtha GG, Nicholls KD, Paton TR, Thompson CH, Webb A.A &Wright MJ (1960-68) Atlas of Australian Soils. Sheets 1-10 with explanatory booklets. CSIRO, Publishing, Melbourne, Australia. Soil maps may be purchased at AUSLIG Sales, PO Box 2, Belconnen, ACT 2616.

NRMMC (2006) Natural Resource Management Ministerial Council (2006) – Glossary of terms Page 50. Commonwealth of Australia Department of the Environment and Heritage, Canberra, ACT. National Cooperative Approach to Integrated Coastal Zone Management: Framework Implementation Plan. ISBN 0642550514.

IOCI (2002) Climate variability and change in south west Western Australia. Indian Ocean Climate Initiative. Perth September, 2002. 34 pp http://www.ioci.org.au/pdf/IOCI_TechnicalReport02.pdf

Pons LJ (1973) Outline of the genesis, characteristics, classification and improvement of acid sulphate soils. pp. 3–27. *In* Dost H. (Ed.) *Proceedings of the 1972 (Wageningen, Netherlands) International Acid Sulfate Soils Symposium, Volume 1*. International Land Reclamation Institute Publication 18. Wageningen, Netherlands.

Prescott JA (1931) The soils of Australia in relation to vegetation and climate. CSIR Bulletin 52.

Phillips W & Muller K (2006) Ecological Character of the Coorong, Lakes Alexandrina and Albert Wetland of International Importance. South Australian Department for Environment and Heritage.

Prakongkep N, Gilkes RJ, Singh B & Wong S (2010) The morphology and composition of pyrite in sandy podosols on the Swan Coastal Plain. In: *Proceedings of the 19th World Congress of Soil Science* Brisbane, Australia, August 2010.

Prescott JA (1931) The soils of Australia in relation to vegetation and climate. CSIR Bulletin 52.

Salama RB, Otto CJ & Fitzpatrick RW (1999) Contributions of groundwater conditions to soil and water salinisation. *Hydrogeology Journal* 7, 46–64.

Salama RB, Otto CJ & Fitzpatrick, RW (1999) Contributions of groundwater conditions to soil and water salinisation. *Hydrogeology Journal* 7, 46–64.

Schoeneberger, PJ, Wysocki DA, Benham EC & Broderson WD (editors) (2002) Field book for describing and sampling soils, Version 2.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Schwertmann U & Fitzpatrick RW (1992) *Iron Minerals in Surface Environments*. p 7-30. In H.C.W. Skinner and R.W. Fitzpatrick (eds.) Biomineralization Processes of Iron and Manganese -Modern and Ancient Environments. Catena Supplement 21. Catena Verlag, Reiskirchen, Germany.

Searle JA McHugh SL Paton AC and Bathols GR (2010) Perth Shallow Groundwater Investigations: Lake Mariginiup. Western Australia Department of Water Hydrogeological Reprt No HG 36.

Shand P & Degens B (Eds.), (2008). Avon Catchment acid groundwater – geochemical risk assessment, CRC LEME Open File Report 191.

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, Fitzpatrick RW & Merry R (2008e) Development of a methodology and protocol for sampling and rapid risk assessment of acid sulfate soils in subaqueous and sub-aerial environments of the Murray Darling Basin In, 6th International Conference on ASS and AMD. China. 301-302.

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, James-Smith J, Hodgkin T, Fitzpatrick RW, McClure S, Raven M, Love A, Stadter M & Hill T (2008a) Ancient Acid Sulfate Soils in Murray Basin Sediments: Impacts on Borehole Clogging by $Al(OH)_3$ and Salt Interception Scheme Efficiency. *In* Fitzpatrick, R.W. & Shand, P. (Eds.). pp 117–124. *Inland Acid Sulfate Soil Systems Across Australia*. CRC LEME Open File Report No. 249. (Thematic Volume) CRC LEME, Perth, Australia.

Shand P, Merry RH, and Fitzpatrick, RW (2008b) 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 & Fitzpatrick RW (2008c) Acid sulfate soil assessment of Noora Basin, South Australia Prepared for Murray-Darling Basin Board. CSIRO Land and Water Science Report 41/08. CSIRO, Adelaide, 69 pp. http://www.clw.csiro.au/publications/science/2008/sr41-08.pdf

Shand P, Degens B & Rogers S (2008d) The geochemistry of acid-saline waters and drainage sediments in the Avon Catchment, Western Australian Wheatbelt. Explore, 140, 1-11.

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

Simpson SL, Apte SC & Batley GE (1998) Effect of short-term resuspension events on trace metal speciation in polluted anoxic sediments. *Environmental Science and Technology* 32, 620–625.

Simpson S, Angel B, Spadara D,. Fitzpatrick RW, Shand P, Merry RH & Thomas M (2008) Acid, Metal and Nutrient Mobilisation Following Rewetting of Acid Sulfate Soils in the Lower Murray. Prepared for the South Australian Environmental Protection Agency. CSIRO Land and Water Science Report 27/08. CSIRO, Adelaide, 150. pp. http://www.clw.csiro.au/publications/science/2008/sr27-08.pdf

Simpson SL, Fitzpatrick RW, Shand P, Angel BM, Spadaro DA & Mosley L (2010) Climate-driven mobilisation of acid and metals from acid sulfate soils Seasonal trends in soil electrical conductivity to better distinguish salinity types in the Mount Lofty Ranges, South Australia. *Marine and Freshwater Research* Volume: 61, Issue: 1, 2010, pp. 129 - 138

Skwarnecki MS & Fitzpatrick RW (2008) Geochemical Dispersion in Acid Sulfate Soils: Implications for Mineral Exploration in the Mount Torrens-Strathalbyn area, South Australia. pp. 86–107. *In* Fitzpatrick, R.W. & Shand, P. (Eds.). *Inland Acid Sulfate Soil Systems Across Australia*. CRC LEME Open File Report No. 249. (Thematic Volume) CRC LEME, Perth, Australia.

Skwarnecki MS & Fitzpatrick RW (2003) Regional geochemical dispersion in materials associated with acid sulfate soils in relation to base-metal mineralisation of the Kanmantoo Group, Mt Torrens-Strathalbyn region, eastern Mt Lofty Ranges, South Australia. Cooperative Research Centre for Landscape Environments and Mineral Exploration. CRC LEME Restricted Report No 185R; 193pp; Reissued in 2008 as: CRC LEME Open File Report No 205; 193 pp.

Skwarnecki MS, Fitzpatrick RW & Davies PJ (2002) Geochemical dispersion at the Mount Torrens lead-zinc prospect, South Australia, with emphasis on acid sulfate soils. Cooperative Research Centre for Landscape Environments and Mineral Exploration. CRC LEME Restricted Report No 174. pp. 68 (volume 1) (plus 13 appendices: volumes 2 and 3). Reissued in 2008: Open File Report No 204 68pp (Volume 1) (plus 13 appendices: volumes 2 and 3).

Sommer B & Horwitz P (2001) Water quality and macroinvertebrate response to acidification following intensified summer droughts in a Western Australian wetland. J*ournal of Marine and Freshwater Research* 52, 1015-1021.

Sommer B & Horwitz P (2009) Macroinvertebrate cycles of decline and recovery in Swan Coastal Plain (Western Australia) wetlands affected by drought-induced acidification. *Hydrobiologica* 624, 191-203.

Soil Survey Staff (1999) *Soil Taxonomy - a basic system of soil classification for making and interpreting soil surveys. 2nd edn.* United States Department of Agriculture, Natural Resources Conservation Service, USA Agriculture Handbook No. 436. 869 pp.

Soil Survey Staff, (2003) *Keys to Soil Taxonomy. 9th edn.* United States Department of Agriculture, Soil Conservation Service, Blacksburg. http://soils.usda.gov/technical/classification/tax_keys/

Soil Survey Staff (2010) Keys to Soil Taxonomy, 11th ed. USDA-Natural Resources Conservation Service.

Soil and Land Information (2004) Land Use Mapping of South Australia: Murray Darling Basin. [CD ROM]. Department of Water, Land and Biodiversity Conservation, South Australia.

Stauber J, Chariton A, Binet M, Adams M, Simpson SL, Batley G, Durr M, Bentley K, Fitzpatrick RW & Shand P (2008) Water quality screening risk assessment of Acid Sulfate Soil Impacts in the Lower Murray, SA. Prepared for the South Australian Environmental Protection Agency CSIRO Land and Water Science Report 45/08. CSIRO, Adelaide, 133 pp. http://www.clw.csiro.au/publications/science/2008/sr45-08.pdf

Stephens CG (1952, 1956, 1962) *A manual of Australian Soils*. CSIRO, Melbourne. 1st, 2nd, 3rd Editions.

Stolt MH (2006) *Glossary of terms for subaqueous soils, landscapes, landforms, and parent materials of estuaries and lagoons.* Department of Natural Resources Science, University of Rhode Island, Kingston, RI. http://nesoil.com/sas/glossary.htm (accessed 6/6/06).

Sturt C (1849) Selected texts from the book entitled “To the Inland Sea: Charles Sturt's Expedition 1844-1845” by Edward Stokes (1986) Century Hutchinson Australia Pty Ltd. Victoria.

Sullivan LA, Bush RT & Fyfe D (2002) Acid sulfate soil drain ooze: Distribution, behaviour and implications for acidification and deoxygenation of waterways. pp. 91–99. *In* Lin, C., Melville, M.D. & Sullivan, L.A. (Eds.). *Acid sulfate soils in Australia and China*. Science Press, Beijing.

Sullivan LA, Fitzpatrick RW, Bush RT, Burton ED, Shand P & Ward NJ (2010) Modifications to the classification of acid sulfate soil materials. Southern Cross GeoScience Technical Report No. 310. Southern Cross University, Lismore, NSW, Australia. 12 pp.

Sullivan LA, Ward NJ, Bush RT, Burton ED (2009) Improved identification of sulfidic soil materials by a modified incubation method. *Geoderma* 149, 33 – 38.

Sullivan LA (2011) Introduction to Acid Sulfate Soil Materials. *In* Clay C. (Ed.). Professional Short Course Acid Sulfate Soils Identification, Assessment and Management South Australian Course Notes: May 2011.

Taylor JK & England HN (1929) A soil survey of Block E (Renmark) and Ral Ral (Chaffey) irrigation areas. CSIR Australia Bulletin 42.

Taylor JK & Poole HG (1931a) A soil survey of the swamps of the lower Murray River. CSIR Aust. Bull. 51.

Taylor JK & Poole HG (1931b) Report on the soils of the bed of Lake Albert, South Australia. Journal of the Council for Scientific and Industrial Research 4, 83–95 + plates.

Teakle LJH & Southern B (1937). The peat soils and related soils of Western Australia, II. A soil survey of Herdsman Lake. *Journal of Agriculture Western Australia* 14, 404–424.

Technical Committee for Hydric Soils - NTCHS (1985) Hydric soils of the United States United States Department of Agriculture, Soil Conservation Service, Washington, DC.

Thomas BP, Merry RH Creeper NL, Fitzpatrick RW, Shand P, Raven MD & Jayalath N (2009) Acid Sulfate Soil Assessment of the Lower Loddon River and Burnt Creek, Central Victoria. CSIRO Land & Water Science Report CLW 18/09. http://www.clw.csiro.au/publications/science/2009/sr18-09.pdf

Thomas B, Fitzpatrick R, Merry R & Hicks W (2003). Acid sulfate soil technical manual: coastal acid sulfate soils management guidelines, Barker Inlet, SA. CSIRO Land and Water.

Thomas BP, Fitzpatrick RW, Shand P, Simpson S & Jayalath N. (2011) Assessment of Acid Sulfate Soil materials in Ramsar wetlands of the Murray Darling Basin: Banrock Station Wetland Complex. Water for a Healthy Country Flagship Report series ISSN: 1835-095X. Report to Murray-Darling Basin Authority, February 2011.

Thomas M & Fitzpatrick RW (2011) Community monitoring of Acid Sulfate Soils in the Lower Lakes, South Australia: Four surveys between August 2009 and June 2010. Prepared for the SA Department for Environment and Natural Resources (DENR). Client Report R-325-8-4. CSIRO Sustainable Agriculture National Research Flagship 240 pp.

Tulau M (2000). Acid sulfate soils remediation guidelines. New South Wales Department of Land and Water Conservation.

United States Environmental Protection Agency (US EPA) (1995) Ground water Issue – Light Nonaqueous Phase Liquids.

van Tol G, van Dobben HF Schmidt P and Klap JM (1998) Biodiversity of Dutch forest ecosystems as affected by receding groundwater levels and atmospheric deposition. *Biodiversity and Conservation* 7, 221-228.

Vogwill R (2004) Groundwater Modelling for the Eat Wanneroo Land and Water use Re-evaluation. Western Australian Department of Environment Technical Report No 217.

Wallace L, McPhail B, Fitzpatrick RW, Welch S, Kirste D, Beavis S & Lamontagne S (2008a) Sulfur and Carbonate Mobility During Changes in Water Regime in an Inland Sulfidic Wetland, Lower Murray Floodplains, South Australia. pp 209–228. *In* Fitzpatrick, R.W. & Shand, P. (Eds.). *Inland Acid Sulfate Soil Systems Across Australia*. CRC LEME Open File Report No. 249. (Thematic Volume) CRC LEME, Perth, Australia.

Wallace L, McPhail B, Fitzpatrick RW, Welch S, Kirste D., Beavis S. & Lamontagne S (2008b) Spatial Variability in the Storage of Sulfur, Carbon and Acid Generation Potential in an Inland Saline Sulfidic Wetland, Lower Murray River Floodplains, South Australia. pp 229–253. *In* Fitzpatrick, R.W. & Shand, P. (Eds.). *Inland Acid Sulfate Soil Systems Across Australia*. CRC LEME Open File Report No. 249. (Thematic Volume) CRC LEME, Perth, Australia.

Walker PH (1972) Seasonal and stratigraphic controls in coastal floodplain soils. *Australian Journal of Soil Research* 10, 127–142.

Ward J (2009) Modelling the rate of groundwater acidification and trace metal mobility in aquifer profiles at the Gnangara mound, Western Australia. Honours Thesis University of New South Wales.

Ward J, Andersen M, Appleyard S & Clohessy S (2010) Acidification and trace metal mobility in soil and shallow groundwater on the Gnangara Mound, Western Australia. In: Proceedings of the 19th World Congress of Soil Science Brisbane, Australia, August 2010.

Wells CB & Prescott JA (1983) The origins and early development of soil science in Australia. In `Soils: an Australian viewpoint', 3 - 12 pp. CSIRO: Melbourne/Academic Press: London.

Woodward HP (1914) Investigation into the cause of the mineralisation of the “seven-mile” swamp at grassmere, near Albany, South-West Division. Western Australia Dep. of Mines, Annual Report.

White,I, Melville MD, Macdonald BCT, Quirk RG, Hawken R, Tunks M, Buckley D, Beattie R, Williams J, Heath L, (2007). From conflicts to wise practice agreement: Cooperative learning and coastal stewardship in estuarine floodplain management, Tweed River, eastern Australia. . Journal of Cleaner Production 15, 1522-1528

Willett I (2008) Case Study: Acid Sulfate Soils of the Magela Creek Plain, East Alligator River, N.T. In *Inland Acid Sulfate Soil Systems Across Australia* (Eds Rob Fitzpatrick and Paul Shand). CRC LEME Open File Report No. 249. pp 294-300 (Thematic Volume) CRC LEME, Perth, Australia.

Yesertner C (2002) Declining water levels on the Gnangara Mound. Western Australian Water and Rivers Commission Technical Report.

Websites for ASS:

Australian Government Acid Sulfate Soil website

http://www.environment.gov.au/water/topics/acid-sulfate-soils.html

http://www.environment.gov.au/archive/coasts/cass/index.html

CSIRO Land and Water: http://www.clw.csiro.au/acidsulfatesoils/

- Atlas of Australian Acid Sulfate Soils (CSIRO): www.asris.csiro.au/index_ie.html
- ABC Catalyst story on acid mud: http://www.abc.net.au/catalyst/stories/2232992.htm

MDFRC: www.mdfrc.org.au

NSW Department of Primary industries: http://www.dpi.nsw.gov.au/agriculture/resources/soils/ass

- ASSAY-national newsletter: http://www.dpi.nsw.gov.au/aboutus/resources/periodicals/newsletters/assay

Queensland ASS: http://www.derm.qld.gov.au/land/ass/pdfs/soil_mgmt_guidelines_v3_8.pdf

Southern Cross Geosciences - http://www.scu.edu.au/geoscience/index.php/4/

South Australia (DENR):

http://www.environment.sa.gov.au/Conservation/Rivers_wetlands/Coorong_Lower_Lakes_Murray_Mouth/The_environment/Acid_sulfate_soils AND

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

Tasmania: - http://www.dpipwe.tas.gov.au/acidsulfatesoils

Victoria: http://www.dpi.vic.gov.au/dpi/vro/vrosite.nsf/pages/soil_acid_sulfate_soils

Western Australia: http://www.dec.wa.gov.au/ass

8. GLOSSARY

Acid Sulfate Soil environments

- **Coastal environments** or modern-day coastal zones - those areas landwards of the coastal waters influenced by processes or activities that affect the coast and its values - as defined by NRMMC (2006) comprising “coastal ASS” in estuarine systems such as the River Murray Mouth estuary and Coorong.
- **Inland environments** – those areas, which occur inland of modern-day coastal zones (as defined by NRMMC (2006) comprising “inland ASS” in upland systems such as the Mount Lofty Ranges.
- **Minespoil environments**– those areas, which occur in: (i) waste rock stockpiles and tailing impoundments (e.g. Milnes *et al.* 1992; Fitzpatrick *et al.* 1998) and (ii) mine retention ponds (Fitzpatrick & Self 1997; Nordstrom & Alpers, 1999) - comprising “mine spoil ASS” and “acid–rock drainage’ – related but not dealt with in this report.

Acid Sulfate Soil materials (modified from Sullivan *et al.* 2010)

- **Sulfuric material** –pH less than 4 (Isbell 1996).
- **Sulfidic material*** – soil materials containing detectable sulfide minerals (containing greater than or equal to 0.01% sulfidic S). The intent is for this term is to be used in a descriptive context (e.g. sulfidic soil material) and to align with general definitions applied by other scientific disciplines such as geology and ecology (e.g. sulfidic sediment). _*This term differs from previously published definitions in various soil classifications (e.g. Isbell, 1996)._
- **Hypersulfidic material** – 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 or less (1:1 by weight in water, or in a minimum of water to permit measurement) when a 2 - 10 mm thick layer is incubated aerobically at field capacity. The duration of the incubation is either: a) until the soil pH changes by at least 0.5 pH unit to below 4, or b) until a stable** pH is reached after at least 8 weeks of incubation.
- **Hyposulfidic material** – Hyposulfidic material is a sulfidic material that (i) has a field pH of 4 or more and (ii) does not experience a substantial* drop in pH to 4 or less (1:1 by weight in water, or in a minimum of water to permit measurement) when a 2 - 10 mm thick layer is incubated aerobically at field capacity. The duration of the incubation is until a stable** pH is reached after at least 8 weeks of incubation.

  *A substantial drop in pH arising from incubation is regarded as an overall decrease of at least 0.5 pH unit.

  **A stable pH is assumed to have been reached after at least 8 weeks of incubation when either the decrease in pH is < 0.1 pH unit over at least a 14 day period, or the pH begins to increase.
- **Monosulfidic material** – soil materials with an acid volatile sulfur content of 0.01%S or more. Monosulfidic materials are subaqueous or waterlogged organic-rich materials that contain appreciable concentrations of monosulfides (e.g. Sullivan *et al.* 2002; Bush *et al.* 2004; Burton *et al.* 2006a, 2006b). Monosulfidic black oozes are specific materials characterised by their gel-like consistence. Monosulfidic materials have a field pH of 4 or more, commonly > pH 7–8, but may not become extremely acidic (pH < *4*) when drained. Recognition of the occurrence and importance of monosulfides in soil materials led to inclusion of monosulfidic materials as a distinguishing property in the legend of the Australian Atlas of Acid Sulfate Soils (Fitzpatrick *et al.* 2008a).

Acid Sulfate Soil minerals

In inland systems, the combination of sulfide oxidation with high rates of evaporation has led to the formation of an extremely wide range of surface mineral efflorescences or evaporites (e.g. Fitzpatrick *et al.* 2008e,f,g,h; 2009a,b,c). Many of these were extremely rare, until the lowering of water levels during the drought (2006 to 2010), but have now been documented over wide areas. A number of mineral combinations have been identified in different local pH environments in soils (e.g. Bigham *et al.* 1990, 1996, 2000, 2002, Fitzpatrick *et al.* 2000b; Fitzpatrick and Shand 2008; Fitzpatrick and Self 1997; Schwertmann and Fitzpatrick 1992):

- pH < 2.5: Sideronatrite [$Na_2Fe(SO_4)_2.OH.3H_2O$], metavoltine [$K_2Na_6Fe^{2+}Fe^{3+}{}_6(SO_4)_{12}O_2.18H_2O$], alunogen, tamarugite [$Na_2Al(SO_4)_2.OH.3H_2O$],, copiapite, epsomite, hexahydrite, botryogen, pickeringite, redingtonite, halotrichite, tschermigite and gypsum in often sandy or organic-rich sulfuric materials.
- pH 3.5: Natrojarosite [$NaFe_3(SO_4)_2(OH)_6$], jarosite [$KFe_3(SO_4)_2(OH)_6$] and plumbojarosite [$NaFe_3(SO_4)_2(OH)_6$] usually in often clay-rich sulfuric materials.
- pH 3.5-4.5: schwertmannite [$Fe_8O_8(OH)_6SO_4$], (reddish-yellow or orange-yellowish) in sandy or clay-rich sulfuric materials.
- pH 5 to 6: poorly-crystalline Al oxyhydroxide precipitates (white)
- pH 6 to 7: lepidocrocite (orange), akaganéite (reddish-yellow or reddish-orange)
- pH >7 ferrihydrite (reddish-brown)

The formation of these complex suites of sulfate and oxyhydroxysulfate salts (of Fe, Al, Na, Pb, Ca, As, Zn) and Fe oxides are indicative of extreme and often rapidly changing local environments and variations in Eh (redox), pH and availability of Fe, S and other elements (e.g. Bigham *et al.* 2002, Fitzpatrick & Self 1997, Skwarnecki & Fitzpatrick 2003). If the affected site is not managed properly, the minerals may become a problem when dissolved during re-flooding, or have potential to be windblown when dry. Farm stock should be prevented from ingesting these salts (similar to Epsom salts) because this is likely to lead to scouring. Magnesium sulfate, also present, may become toxic when ingested.

Atlas of Australian Acid Sulfate Soils (AAASS) (modified from Fitzpatrick *et al.* 2008d)

- **Web-based hazard assessment tool** with a nationally consistent legend, which provides information about the distribution and properties of both coastal and inland ASS across Australia. This tool is available on ASRIS (Australian Soil Resource Information System: www.asris.gov.au) and every polygon or mapping unit is attributed with information pertaining to: (i) classes of "probability of occurrence", (ii) levels of confidence relating to the quality of data source, and (iii) additional descriptors such as desiccation cracks. The Atlas is a constantly evolving national map of available ASS information, which also includes priority case studies at a range of localities across Australia. (e.g. http://www.clw.csiro.au/acidsulfatesoils/index.html).
- **Types and Subtypes of Acid Sulfate Soils used in AAASS legend–** Australia's current national soil classification system is the Australian Soil Classification (ASC; Isbell 1996). This is based on several internationally recognized systems and allows international technology transfer, because similar soils anywhere in the world can be identified and successful management practices can be copied or correlated without need for extensive local trials. However, the Australian Soil Classification and other internationally recognised classification systems such as Soil Taxonomy (Soil Survey Staff 1999, 2003) require considerable expertise and experience. More importantly, these classification systems do not yet incorporate the following new terminologies: subaqueous soils, monosulfidic material, hypersulfidic material, hyposulfidic material. Therefore, the simplified Soil Identification Key (see Fitzpatrick *et al.* 2009a) specific for inland ASS was developed, initially for ASS in the River Murray and Lower Lakes systems to identify and classify the various subtypes of ASS and non-ASS. The key was designed to assist users who are not experts in soil classification systems to easily identify types and subtypes of ASS used in the AAASS legend. The key uses a collection of plain language names for ASS types and subtypes in accordance with the legend for the AAASS and separates out the same soil classes as would occur if the ASC or Soil Taxonomy was to be used. It recognises 5 Soil Types and 17 Soil Subtypes (Fitzpatrick *et al.* 2009a; 2010c,d). This key is based on easily observable soil features and simple tests (e.g. subaqueous, measured pH). 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. hypersulfidic material, and the depths at which they occur or change in the soil profile. Hence, it has the potential to deliver soil-specific land development and soil management packages to advisors, planners and engineers.

  The key consists of a systematic arrangement of soils into 5 Soil Types, each of which can be further divided into up to 16 Soil Subtypes. The key layout is bifurcating, being based on the presence or absence of particular soil profile features (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 soil types and subtypes in the Soil Identification Key are largely in the same order as occurs in the AAASS Legend. A collection of plain language soil type and subtype names was developed. The 5 ASS types in the Key (Fitzpatrick *et al.* 2009a; 2010c,d) are: (i) Subaqueous Soils, (ii) Organic Soils, (iii) Cracking Clay Soils, (iv) Sulfuric Soils and (v) Hypersulfidic Soils. These are further sub-divided into 17 subtypes based on occurrence of monosulfidic material, hypersulfidic material, sulfuric material and clayey or sandy layers. The key permits easy identification of ASS types and subtypes, which describe practical, surrogate methods to assist users to estimate treatment categories and risk classes (High, medium, low and very low).

Alluvial – deposited by a river

Anaerobic – Without oxygen as a part of the environment. The opposite of aerobic.

Arid – Dry, like a desert.

Aquifer – water bearing rock unit

Bedrock – Mass of solid rock beneath the soil. Can be parent material if it is close enough to the surface to weather into soil.

Blocky – A soil structure. Soil particles are arranged into shapes that resemble small cubes with sharp or rounded edges.

Classification soil – the systematic arrangement of soils into groups or categories on the basis of their characteristics. Broad groupings are made on the basis of general characteristics and subdivisions on the basis of more detailed differences in specific properties. For complete definitions of taxa (Soil Survey Staff 2000).

Clay – The smallest-sized soil particles. Often have plate-like shapes. Feels sticky when wet. Also refers to a soil texture that consists of at least 40% clay particles.

CLORPT – The five factors that influence what type of soil forms: **cl**imate, **o**rganisms, **r**elief (landscape), **p**arent material, and **t**ime.

Columnar – A soil structure. Soil particles are arranged into tall vertical shapes or columns often with rounded tops.

Compounds – The combination of two or more elements. For example, hydrogen and oxygen combine to make water.

Conceptual soil-regolith model – model based on simplified and condensed geomorphological, geological, hydrological, soil, regolith, geochemical information.

Conceptual site model – "---- The interpretation and assimilation of all site-related information into assumptions and hypotheses regarding contamination sources, subsurface contaminant distribution, and dominant transport/fate processes" (US EPA 1995), which can be presented in graphical and/or written form.

Confined flow – groundwater flow that is restricted by overlying rocks and is consequently under pressure

Decompose (Decomposition) – To break down a compound into simpler compounds. Often accomplished with the help of micro-organisms.

Deficiency – Lacking in something important. A deficiency of nutrients in a plant, for example, can stunt its growth.

Developed soil – A soil that has had a long time to form, such as most tropical soils. A mature soil.

Discharge – flow of groundwater from the saturated zone to the earth surface

Drained Soils – soils in environments where the soil was previously saturated with water and the water level has lowered allowing air instead of water to fill the soil pore spaces.

Eluviated horizon (E horizon) – A horizon from which minerals, clay, and/or organic matter have been leached.

Erode (Erosion) – To wear away, or remove, rock or soil particles by water, ice, and/or gravity.

Estuary – A semi-enclosed body of water with a source of fresh water and an outlet to the ocean.

Fertility – The ability of a soil to supply essential nutrients to plants.

Fertilizer – A substance added to soil that contains plant nutrients such as nitrogen, phosphorus, and potassium.

Granular – A soil structure. Soil particles are arranged into shapes that resemble granola. Has lots of pores.

Groundwater – Water that collects underground in the pore spaces of soil and rock. An important source of drinking water.

Groundwater flow system classification - To understand inland ASS processes, it is useful to know how groundwater systems respond to changes in recharge. Groundwater systems across Australian landscapes differ and therefore their contribution to inland ASS also differs. A catchment classification approach to categorise Australia's groundwater flow systems, has been developed by Coram (1998; Coram *et al.* 2001). Groundwater Flow Systems are based on recharge and flow behaviour and the approach identifies groundwater flow systems where particular management activities will lead to similar responses. Groundwater flow systems can be classified as local, intermediate or regional:

- Local groundwater flow systems respond rapidly to increased groundwater recharge and can also respond relatively rapidly to ASS management practices.
- Intermediate groundwater flow systems take longer to 'fill' following increased recharge. They present much greater challenges for inland ASS management than local groundwater flow systems.
- Regional groundwater flow systems take more than 100 years to 'fill' after clearing the native vegetation. These systems require widespread community action and major land use change to secure improvements.

Horizon – A layer of soil with properties that differ from the layers above or below it.

Humus – Organic matter such as highly decomposed leaves.

Holocene – a period of time from about 10 000 years ago to the present, an epoch of the Quaternary period.

Hydraulic conductivity – the rate at which water is transmitted

Hydraulic gradient – the change in ground water level elevation over the distance at which the change occurs

Hydrochemical – relating to the chemistry of water

Hydrogeological – relating to groundwater

Hydrological – relating to surface water

Impermeable – relatively impervious to the passage of water

Infiltration – the unsaturated movement of water through the soil and regolith

Leaching – The removal of minerals and nutrients from a soil or a horizon as water passes through it.

Loam – A soil texture with moderate amounts of sand, silt, and clay, sometimes in nearly equal proportions. Good texture for farming and gardening.

Macronutrients – Nutrients needed by organisms in relatively large quantities.

Massive – A soil that has no structure. Soil particles are completely stuck together.

Microbes – Microscopic organisms, such as bacteria and fungi. Microbes represent the most abundant soil organisms.

Minerals – The inorganic particles in soils that weather from rocks.

Mottles (Mottling) – Spots or blotches of colour(s) in a soil that differ from that soil's dominant colour.

Lacustrine – derived from a lake

Leachate – the soil constituent that is washed out from a mixture of soil solids

Mobilise – situation where the naturally occurring metals in soil or sediment are changed from an insoluble to a soluble state.

Nitrogen (N) – Macronutrient essential to living things like plant growth and building proteins. Often added to agricultural and garden soils.

Nutrients – Elements or compounds that nourish organisms. Essential for growth and reproduction.

Organic matter – Material derived from the decay of plants and animals. Always contains compounds of carbon and hydrogen.

Organisms – Living things such as bacteria, fungi, plants, or animals.

Oxidised – process of chemical change involving the addition of oxygen following exposure to air

Numerical model – computer model based on mathematics

Palaeodrainage – drainage lines that existed in the geological past

pH – a measure of the acidity of alkalinity of a soil of water body on a logarithmic scale of 0 to 14; a pH < 7 is acid, pH 7 is neutral, and pH > 7 is alkaline. Note that one unit change in pH is a tenfold change in acidity

Parent material – The material from which a soil formed. Can be bedrock or materials carried and deposited by wind, water, glaciers, and/or gravity. The C horizon in a soil profile.

Peat – Partially decayed organic matter that accumulates in environments that stay wet.

Ped – The structural unit formed when soil particles (sand, silt, and clay) bind together.

Pedologist – A scientist who studies soils.

Perennials – Plants that live for more than two years as opposed to annuals that grow each year from seeds or biennials that live for only two years.

Perched aquifer – a hydraulically conductive rock with saturated groundwater flow that is underlain by an unsaturated zone

Permeable – able to transport water

Platy – A soil structure. Soil particles are arranged into shapes that resemble flat plates.

Pores – The space between soil particles, which can be filled with water or air. A **porous** soil has lots of pores.

Prismatic – A soil structure. Soil particles are arranged into shapes that resemble columns.

Productive – A term used to describe a soil that has the capacity to grow an abundance of crops.

Pyritic framboids - from the French " framboise" meaning raspberry.

Recharge – infiltration of water from the earth surface to the saturated zone

Relief – The shape of the land surface created by features such as hills and valleys.

Runoff – Water from precipitation or irrigation that does not soak into the soil but flows off the land and reaches streams and rivers.

Salinisation – The build-up of salts in soil. Often occurs in arid environments.

Sand – The largest-sized soil particles. Sand feels gritty. Also refers to a soil texture that consists of at least 85% sand particles.

Sediment – Any particle of soil or rock that has been deposited by water, wind, glaciers, or gravity.

Silt – Soil particles in between sand and clay in size. Silt feels like flour (smooth and velvety). Also refers to a soil texture that consists of at least 80% silt particles.

Single–grained – A soil that has no structure. Soil particles are not bound to each other in any way, such as beach sand.

Slope – A landscape, or surface, that is tilted or inclined.

Sod – Grass and the soil beneath it, held together by roots. Can be cut into blocks and used as a building material.

Soil – A mixture of minerals, organic matter, water, and air, which forms on the land surface and includes shallow permanently flooded environments with water not deeper than 2.5 m. Can support the growth of rooted plants.

Soil profile – A section of the soil that has been cut vertically to expose all its horizons, or layers.

Soil structure – The arrangement of soil particles into clusters, called peds, of various shapes that resemble balls, blocks, columns, or plates.

Soil texture – The relative proportions of sand, silt, and clay particles.

Subaqueous Soils – soils in shallow permanently flooded environments covered by less than 2.5 m water, which is not too deep for the growth of rooted plants (Stolt 2006); (e.g. Figure 5-13).

Subsoil (B horizon) – The soil horizon rich in minerals that eluviated, or leached down, from the horizons above it. Not present in all soils.

Topsoil (A horizon) – Mostly weathered minerals from parent material with a little organic matter added. The horizon that formed at the land surface.

Topographic gradient – steepness of the ground surface

Transmissivity – ability to transmit water, reflecting both the hydraulic conductivity and the area of the rock

Transform – To change from one thing into another or from one state into another, like a liquid into a gas.

Weather (Weathering) – To break down rocks and minerals at or near Earth's surface into smaller particles and soil.

Wetland – An area of land where the soil is saturated with water, such as a marsh, swamp, or bog.

Unconfined flow – groundwater flow that is not restricted by overlying rocks and which is consequently at atmospheric pressure

Unconformity – a plane that separates older rocks below from younger rocks above, and represents a break in deposition

Unconsolidated – loosely compacted; uncemented

Unsaturated zone – the zone above the water table that is not saturated in water

Watertable – portion of the ground saturated with water; often used specifically to refer to the upper limit of the saturated ground

Waterlogged Soils – soils in environments where there is sufficient water to fill the soil pore space but not pond above the soil surface for any length of time.

Weathering – the process by which rocks are decomposed

Wetland Classification – Wetlands are defined by the Ramsar Convention (Anon 2009) as "- - areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salt, including areas of marine water the depth of which at low tide does not exceed six metres" (Article 1.1). In this report both Inland and man-made wetlands are included (e.g. see examples listed in Figure 5-13).

9. HISTORICAL BACKGROUND

This brief and selective historical background provides a synopsis of inland ASS in Australia but makes no claim to be comprehensive or to have recorded all useful individual contributions, but rather presents a broad overview.

9.1. Aboriginal peoples

Aboriginal peoples of Australia record creation stories about the remarkable changes that occurred both when the sea level began rising ca. 18,000 years ago and when the current sea level stabilised about 5,000 years ago. At the same time, rainfall and inland lake levels were initially low followed by cycles of brief highs and extended dries. By 5000 years ago, rainfall was marginally higher than it is today. During wetter periods, lake levels filled, while dune-building dominated in dry periods (Bowler *et al.* 1976). The creation stories and oral traditions of indigenous people have been passed down from generation to generation, especially about the detailed knowledge of the nurseries i.e. wetlands (reed beds were much more extensive in the past), many of which contain inland ASS. For example, the Ngarrindjeri people believe the land and water is a living body and that they are a part of its existence (Ngarrindjeri Tendi *et al.* 2007). In the Ngarrindjeri Nation *Yarluwar-Ruwe* plan (Ngarrindjeri Tendi *et al.* 2007) it is stated: "The land and waters must be healthy for the Ngarrindjeri people to be healthy. We say that if wetlands/nurseries die, our *Ngartji* (totem or special friend) die, then Ngarrindjeri will surely die."

9.2. Early explorers

The first European explorers possessed great skills of observation. The early explorers were usually not trained scientists as their primary concerns were to delineate the major terrain features of the interior and to survive. Moreover, many of the early explorers originated or worked in environments quite different from Australia. Using mainly horses for transport, early explorers' observations and reports on soils had mainly to do with pastoral or agricultural potential rather than with the natural history of wetlands or back swamps. Nevertheless, the following observations remain of interest with regard to past and current known occurrences of inland ASS:

Captain Charles Sturt was one of the earliest recorders of soil information in southern Australia. Following his previous experience along the Murrumbidgee, Murray and Darling rivers from 1828 to 1829, Sturt explored from Cawndilla near the Menindee Lakes westward into the north-east deserts of South Australia in 1844-46. His journals (Sturt 1849) reveal him to be an observant and inquisitive explorer. The following quotations from his published journals reveal a few of his perceptions about the possible natural occurrences of inland ASS in wetlands: Sturt was the first known European to have travelled down the Murray River to its mouth in 1830 when he noted the following in his journal that ***"the shores of the lakes were densely covered with fresh water reeds in one continuous belt as far as the eye could see"*** (these are suitable conditions for the formation of sulfidic material because of the considerable build-up of organic matter in the dense reeds in waterlogged soils). As he passed across the region of the South Australian border he records "… we travelled over firm and open plains of clay and sand, similar to the soil of the plains of the Murray". *Sunday, August 17th 1845 (Page 156):* "For the last six miles the country has fallen off greatly, the flats are broader and of a white clay with but little grass upon them. The sand hills are very high and the sand as red as brick, and from their summits the view to the NW is as dreary as can be imagined.... Surface water is becoming very scarce, and what we are obliged to use is ***as thick as a puddle and looks like a mixture of Magnesia and Rhubarb***. ***The pools in truth are not more than two inches deep, and as it blows more or less violently every day the mud gets so mixed that it will not settle***. I may say that we have not had a drop of wholesome water since

November......". *Sunday September 7th 1845 (Page 180):* "Its channel was white as the driven snow and it was flanked by sand banks on which the marks of flood were 12 feet high. ***There was no water in the bed where we struck it, but the bed was too soft for us to cross with the horses*** so that we turned up it northerly, passing a long sheet of water on which the ***salt was coated like ice***. Tracing it upwards at a mile we crossed a high sand ridge, and beneath us saw the dry basin of this creek surrounded by samphire. Crossing it we took up our old course, and traversed flats of salt formation between sandy ridges dark with samphire bushes excepting where there were white patches thinly coated with salt, the shallow receptacles for water. ***The bottoms of these were spongy and soft.*** The mineral salts in the waterholes such as this cause the clay sediments to settle, and also ***produce foul-smelling mud*** under the white crust". (This is likely to have been sulfidic mud rich in hydrogen sulfide or rotten egg small gas).

Edward John Eye, the explorer, "***The Founder of the First Irrigation Settlement***" in South Australia (1841) and Government Official at Moorundie near Blanchetown, noted the possibilities of "***rich alluvial soils***" in wetlands adjacent to the River Murray during his overland journey of 1838 when he passed through Moorundie (Mack 1958-2003).

Ernestine Hill (1969; first published 1937) from "*Water Into Gold*" noted (page 12) "In the late 1830s Lake Bonney was described as a fine lake of fresh water about 30 miles in diameter (e.g. Figure 4-8). Thousands of ducks were on the water" and (page 15): "In marked contrast, in 1841 ***a sulphurous silence lay over Lake Bonney. The bed of the lake was as dry as a bone***".

9.3. The early engineers and scientists

According to Pons (1973), Acid Sulfate Soils were recognised in Europe over 250 years ago. However, the early soil scientists and pedologists who produced soil maps of Australia were often unaware of, and thus did not consider ASS (e.g. Prescott, 1931; Stephens, 1952, 1956, 1962; Northcote *et al.* 1960-68). A plausible explanation for this may be found in the following statement by Fanning and Fanning (1989): "….perhaps this was because most soil scientists lived and worked primarily in the centres of large continents, upon the extensive soils used for agriculture and forestry in those areas, rather than near seacoasts where ASS are more common, extensive and important". In general, soil scientists have only become more aware of ASS processes since 1973 when the first international symposium on ASS was held (Pons 1973), and in Australia, the comprehensive studies by Woodward (1914) and Walker (1972) identified this issue and specifically warned of the dangers of continuing to drain sulfidic materials.

South Australia

Field survey investigations of Australian soils were first commenced by Taylor and England (1929) in the Renmark Irrigation District on the River Murray (Wells and Prescott 1983). By 1940, all then existing irrigation areas in SA had been investigated and/or mapped, including the irrigated, drained Phragmites swamps on the lower Murray River (Taylor and Poole 1931a) between Murray Bridge and Wellington (Figure 5-2). Significantly, these soil survey investigations also included the bed of Lake Albert, which was being considered for drainage and development as an irrigated pasture/cropping area similar to the swamps (Taylor and Poole 1931b). An occurrence of inland ASS was recognised as a potential problem as early as 1929 by Taylor and Poole (1931b) in Lake Albert. This soil survey required subaqueous soil inspections and novel sampling techniques. At that time, they noted the presence of what we now call Inland ASS, one soil having a pH of 3.9, and they successfully argued that the lake should not be drained for agriculture. Their original soil samples were retrieved from the CSIRO Land and Water soil archive in Canberra, and analysed for pH for comparison with the original measurements made 78 years previously. The original, 1930s pH values (pH 8.5) and the low 2007 pH values (pH 2 to 4) are in effect a long-term incubation experiment, which confirmed the acidifying effects of exposure of the soils to the atmosphere (Fitzpatrick *et al.* 2008e).

New South Wales

The early reports on soils (1898 to 1922) in NSW were mostly concerned with their qualities for crop production, which also culminated in the publication by Jenson (1914) entitled “Soils of New South Wales”, but there was no mention of the occurrences of inland ASS. However, Jenson (1914) identified blue coloured coastal soils in swamps that contained iron sulfide, which formed by reduction of sulfate and iron, and became acidic after being drained.

Western Australia

An occurrence of inland Acid Sulfate Soil was recognised as a potential problem as early as 1914, following drainage of the “Seven Mile Swamps and land below it in Western Australia (Woodward 1914): “… during the early years this swamp land was very productive; now, however, the lower lying portions have become so highly saturated with mineral solutions as to tender it perfectly infertile …. leaving a red-brown encrustation after the subsidence, and thus it is claimed was the primary cause of the damage.…. the whole trouble can be directly attributed to the decomposition of pyrite which is present in soil and subsoil of the swamp itself in considerable quantity……the decomposition of the pyrites is, however brought about by either, or rapidly by both, of the following conditions: firstly, by the drainage of the land which permits the access of the air into the soil, and secondly, by cultivation, which opens up the soil, thus exposing pyrites to the atmosphere”. Teakle and Southern (1937) also recognised sulfide-bearing soils in the Herdsman Lake in Western Australia.

10. REPRESENTATIVE CASE STUDIES IN AUSTRALIA (Figure 5-2)

Thirty-six selected case studies are presented below in order to improve our understanding of key factors that will contribute to the successful management of Inland ASS, including issues related to change in land management. Based on these 36 wide ranging case studies it is clear that we have not permanently solved Inland ASS problems. However, the old adage that prevention is better than cure certainly holds with regard to Inland freshwater ASS i.e. we need to keep soils saturated and in an anaerobic state to prevent oxidation of sulfides.

Clearing of vegetation in recent times and the rising of saline ground water levels has led to the formation of saline Acid Sulfate soils with hypersulfidic material. However, subsequent lowering of near surface perched water levels due to tree planting and the installation of surface drains (i.e. soil drainage) has led to the formation of sodic soils because of salt flushing, which has also cause erosion gullies to form. These processes have proved to be the major cause of oxidation of sulfides in soils and the consequent formation of sulfuric materials (e.g. Fitzpatrick *et al.,* 1996; Cox *et al.* 1996; Salama *et al.* 1999). From these case studies, it is clear that implementing actions that prevent further build up of sulfuric material in ASS, and returning to a more natural cycle may not be achievable for a whole range of reasons. In one case study (Loveday Bay in the Lower Lakes), which is being actively monitored, the only feasible strategy currently being adopted as “acid soil and water management” is “living with Inland ASS” because the 200 ha. area affected occupies a remote and isolated region in Lake Alexandrina.

Soil scientists and other professionals working in agriculture and water resources have a “duty of care” with respect to the provision of advice on processes affecting or affected by Inland ASS. There is a major need for soil scientists, biogeochemists and wetland ecologists to work closely with other scientists (hydrogeologists, geologists, plant physiologists, agricultural scientists, etc) to encourage a multi-disciplinary approach. The results of investigations need to be discussed with landholders, and communicated to the community and politicians. This will encourage implementation of new management techniques by farmers at the local scale and communities at the catchment and regional scale. Ideally, landholders and community groups need to be included at an early stage of ASS investigation to assist in ASS identifying, monitoring and mapping. For example, the development by Thomas and Fitzpatrick (2011) of ASS sampling protocols for monitoring changes in ASS conditions in the Lower Lakes region for community volunteers (see also several other *case studies* listed above in Section 6.7).

These case studies, collectively, summarise the properties and extent of a variety of subtypes of ASS and the management options being applied in South Australia, Victoria and Western Australia.

11. River Murray tributaries from the eastern Mount Lofty Ranges (Area D in Figure 5-2)

11.1. Background and Environmental Setting

These case studies, collectively, summarise the properties and extent of the various subtypes of ASS present and the ASS management options being applied in the tributaries of the Lower Murray (Fitzpatrick *et al.* 2009a,b; 2011). They describe the circumstances that have developed over time in the lower reaches of Finniss River, Currency Creek, Black Swamp and Goolwa Channel region (see area D in Figure 5-2).

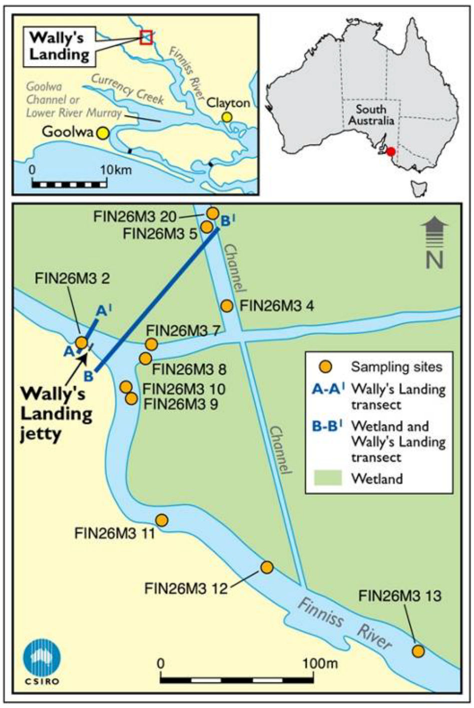


Figure 11-1. Locality map of upper Finniss River area showing localities of two cross sections (A–A' and B – B') and for water and soil profile sites monitored during rewetting from winter rainfall.

11.2. Acid Sulfate Soil Processes and Hazards

Changes in water level in the Finniss River at Wally's Landing (Figure 11-1) are shown in Figure 11-2. The August 2007 photograph shows the river with benign hypersulfidic subaqueous clay under 80 cm of water at the end of the jetty. Benign hypersulfidic organic clay was sampled in the *Phragmites* reeds four metres from the bank or water's edge. The November 2008 photograph shows substantial lowering of water levels to produce mainly waterlogged benign hypersulfidic cracking clay (end of jetty). The February 2009 photograph shows further lowering of water levels to expose a dry clay river-bed with cracks and salt efflorescences (sulfuric cracking clay). The red square shown in the February 2009 photograph in Figure 11-2 indicates the location of white fluffy acidic salts adjacent to *Phragmites* reeds. This is shown in close-up on the lower right hand side photograph.

In summary, more than 91% of the 39 representative sites examined in November 2008 had a high, very high, or extra high ASS hazard classification. It was found that 37 of the 39 sites (94%) investigated had sufficient net acidity that, if disturbed, would be a major concern (Fitzpatrick *et al.* 2009a).

Acid Generating Potential
The combined standard methodologies of: (i) soil morphology, (ii) field pH testing, (iii) pH peroxide testing, (iv) acid-base accounting (Ahern *et al.* 2004), (v) soil incubation (ageing) and (vi) mineralogical analyses has confirmed that these soils either contain sulfuric acid (sulfuric material, pH ≤ 4), or have the potential to oxidise and form sulfuric acid when exposed to air (oxygen) because of high concentrations of sulfide minerals (hypersulfidic material). This potential is being realised in many areas along the Murray River and the associated Lower Lakes. However, the risk of soil acidification would be significantly lower if water levels were kept at a level high enough to maintain saturated anaerobic conditions.

Figure 11-2. Wally's Landing (Figure 11-1), showing changes in water level and soil pH (pH < 2.5 along edge near Phragmites) during August 2007, November 2008 and February 2009.

Metals and Mobilisation

Metal mobilisation is likely to be significant in sulfide-containing soils that have undergone oxidation (Fitzpatrick *et al.* 2009a; 2011). Sulfide minerals scavenge trace metals, which may be released during oxidation. During 24 hour laboratory mobilisation tests on ASS, the water pH generally became similar to that measured for the soils (Simpson *et al.* 2008, 2009). Metal release was rapid in sulfuric materials producing high dissolved concentrations of Al, Cd, Co, Cu, Cr, Mn, Ni, V and Zn. Greater concentrations of metals were released from the more clay-rich Finniss River soils than from the sandy soils in Currency Creek. In general, the concentrations of metals released increased greatly at water pH < 5. Tests demonstrated that the rewetting of dried acid sulfate soils has the potential to release significant quantities of environmentally degrading substances (Fitzpatrick *et al.* 2009a; 2011). However, the release of nitrate and phosphate from the dried soils was low. Dissolved metal concentrations are likely to decrease through co-precipitation and adsorption to aluminium and iron oxyhydroxide phases as acidic, metal-rich waters mix with more neutral or alkaline water.

Mineralogy

At several sites, abundant minerals were recorded in salt efflorescences and sub-surface horizons by Fitzpatrick *et al.* (2009a). In the bright yellowish green and orange surface salts (e.g. Figure 11-2 to Figure 11-5), and pale yellow mottles in subsoils (Figure 11-3 to Figure 11-5) X-ray diffraction analyses identified sideronatrite, schwertmannite and jarosite/natrojarosite minerals, respectively. The pH values of the bright yellowish green surface efflorescences was very acidic (pH < 2) and the orange and pale yellow minerals were acidic (pH < 3 to 4). The presence of all these minerals indicates high contents of iron sulfides (principally pyrite) in the original subaqueous soils. It is predicted that large quantities of sulfuric acid will be produced in the hypersulfidic, subaqueous soils if the river levels continue to drop significantly and the adjacent wetland soils are allowed to dry. Where winter rainfall has rewet previously identified sandy sulfuric soils with pH values of 1.6 to 2.5, the mineral tamarugite [$NaAl(SO_4)_2.6H_2O$], with traces of sideronatrite were subsequently identified with extremely acidic pH values ranging from 0.5 to 0.8 during slight rewetting of the mineral surfaces.

Hydrogeochemistry

Water in some soil pits of the dry river-beds and wetlands of Currency Creek and Finniss River had acidic pH values ranging from 3.4 to 3.9. Some river waters sampled in Currency Creek and Black Swamp in November 2008 still contained moderate to low concentrations of alkalinity (< 117 mg/L and 31 mg/L respectively as HCO_3^-). The alkalinity of Lake Alexandrina (> 250 mg/L) has helped to maintain the alkalinity of the remnant Currency Creek and Finniss River waters whilst these are still connected, along with local contributions from alkaline ground waters and evaporation. Acid sulfate soil impacts are most likely to have an effect where net acidities are high and surface water alkalinities are low, such as in Currency Creek, where alkalinities are lower than in Lake Alexandrina (currently 200 to 250 mg/L).

The data from Wally's Landing in May 2009 showed that the pH in the flowing river was circumneutral following rewetting from recent winter rainfall. However, water in cattle pugs close to the river was found to be very acidic (pH 3.2). In a major anabranch of the Finniss River, the flowing stream water was found to produce acidic pulses (pH 3.3. to 4.0) with relatively high specific electrical conductance (SEC) of 13300 µS cm^{-1} (reflecting the presence acidic sulfate salts).

Finniss River explanatory soil-regolith model for clays (Site D1 in Figure 5-2)

The explanatory soil-regolith model shown in Figure 11-3 for a wetland adjacent to the Finniss River clearly shows the relationship between various clayey soils sampled and how the underlying layers and ASS materials vary across the landscape (Fitzpatrick *et al.* 2009a). The model highlights large cracks in the subsoil that formed columns during drying. The columns were extremely hard and the sides coated with various minerals including jarosite (FIN 20), schwertmannite (FIN 23), sideronatrite (FIN 23) and other soluble Al-Fe-Mg-Na sulfates. These clay columns overlay a black soft organic rich clay layer that varied in thickness and proximity to the surface. Underlying this was a black, very soft clay. The hard upper columnar layer was classified as sulfuric material and the underlying soft clay as hypersulfidic material. When these ASS materials were sampled in November 2008, the sulfuric material in the cracking clay (FIN 20) had thick soft layers (pale yellow mottles/ precipitates) of jarosite in the cracks (pH 3.3) and the water in the large cracks had a pH of 3.5 (Fitzpatrick *et al.* 2009a).

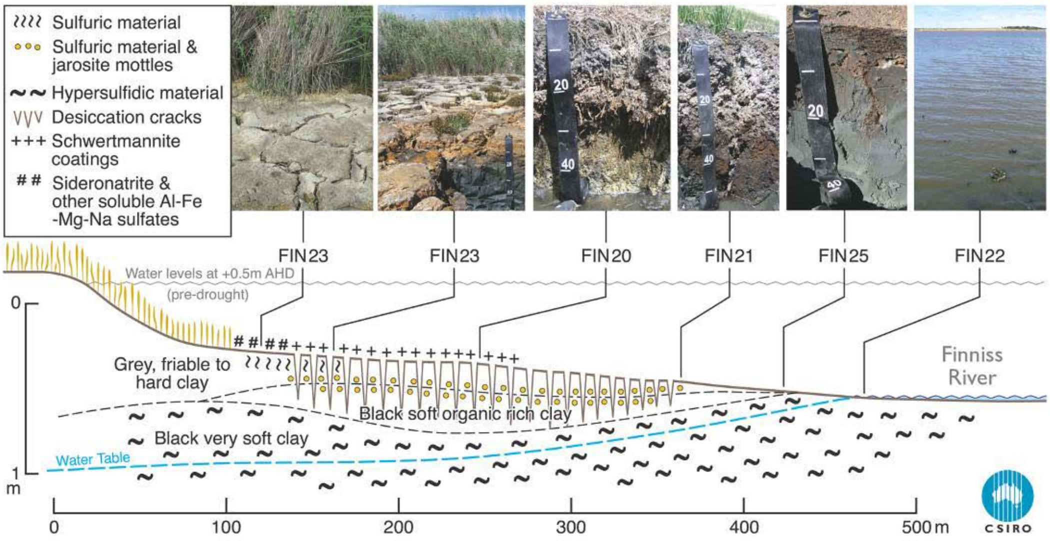


Figure 11-3. Explanatory soil-regolith toposequence model for profiles FIN20 to 25, located on the west side of Finniss River (site D1 in Figure 5-2) (from Fitzpatrick *et al.* 2009a).

Currency Creek explanatory soil-regolith model for sands (Site D2 in Figure 5-2)

The explanatory soil-regolith model shown in Figure 11-4 was characterised by sandy surface materials to a depth of 50 cm.

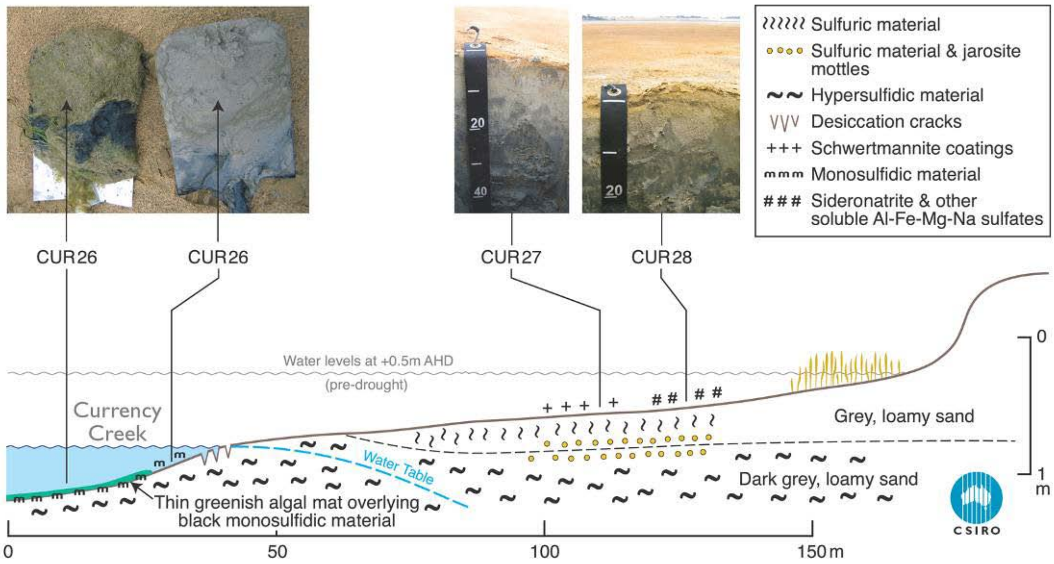


Figure 11-4. Descriptive soil-regolith toposequence model for profiles CUR27 to 28, located on the north-eastern side of Currency Creek (site D2 in Figure 5-2) (from Fitzpatrick *et al.* 2009a).

Bright yellowish, 2 to 5 mm thick, sandy friable crusts were observed at site CUR28. These layers contained mainly precipitates of the mineral sideronatrite, which occurred as rosettes and platelets on the soil surface in sulfuric material (< pH 2.5). Sideronatrite in the yellowish crusts dissolved and re-precipitated as orange coloured schwertmannite (CUR27) in immediately adjacent zones where the pH was slightly more alkaline, to display distinct orange patches or areas on the soil surface, and orange mottles to a depth of 2 to 10 cm (CUR27).

This mineral forming process occurs during rainfall events and drying cycles, which causes water to dissolve sideronatrite and transport ferrous Fe and sulfate ions to adjacent “micro-ponds”, where schwertmannite rapidly crystallises (Fitzpatrick & Shand 2008). The formation of these minerals is indicative of local geochemical environments that are rapidly changing due to variations in pH and rates of Fe, S and Na mineralisation. Thick layers (0 to 30 cm) of monosulfidic material also occur below thin algal mats in the subaqueous acid sulfate soil soils in Currency Creek (e.g. profile CUR26).

Goolwa Channel explanatory soil-regolith model for sands (Site B2 in Figure 5-2)

The explanatory soil-regolith model shown in Figure 11-5 was characterised by a firm brownish grey sandy surface with pockets of black fibrous organic material (e.g. CUR17). Underlying this was sandy clay, which in turn overlay yellowish clay containing calcrete (e.g. CUR18). The sandy dry surface near the landward end had prominent thin layers of sideronatrite on the surface.

Mid-way along the toposequence transect, sulfuric material with prominent mottles and streaks of natrojarosite in the upper soil layers (e.g. CUR18) were present. The lower dark grey layers all contained hypersulfidic material.

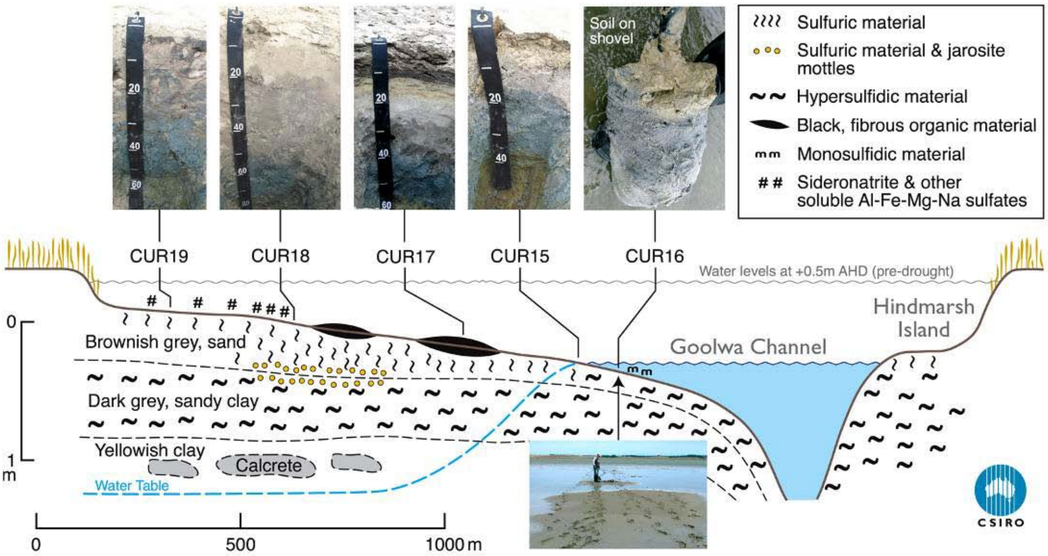


Figure 11-5. Descriptive soil-regolith toposequence model, north-eastern side of Goolwa Channel (site B2 in Figure 5-2) (from Fitzpatrick *et al.* 2009a)

Finniss River predictive soil-regolith models (Site D1 in Figure 5-2)
Predictive soil-regolith models illustrating the formation and transformation of hypersulfidic material were constructed for the Finniss River and adjacent wetlands in the area near Wally's Landing (Figure 11-1 and Figure 11-2). These models provide an understanding of how the nature of the soil materials have changed over time. Based on field investigations and historical soils knowledge of the Finniss River wetlands, a sequence of eleven conceptual models have been reconstructed (Fitzpatrick *et al.* 2009a) in (Figure 11-6, Figure 11-7 and Figure 11-8. This is elaborated on in the following text.

(i) **5,500 BC to 1930s. Following stabilisation of sea level to about its present position (5,500 BC),** the lower Finniss River cycled between natural wetting and flushing, and partial drying conditions in response to seasonal and climatic cycles occurring in the upper Murray-Darling Basin and its own catchment. During wetter periods, the river accumulated sulfidic materials from sulfate contained in surface waters and groundwaters. However, during periods when river flows were lower (Figure 11-6 - lower panel), the river and adjacent wetlands partially dried causing oxidation of sulfidic materials, especially on the dry margins with the potential formation of sulfuric materials. In wetter times and during floods, the acidic material was resubmerged causing dilution or neutralisation of acidity, entrainment of soluble materials in the river waters or the reformation of sulfidic material. The build-up of sulfidic materials in the Finniss River was thus regularly kept in check by oxidation and removal during scouring floods.

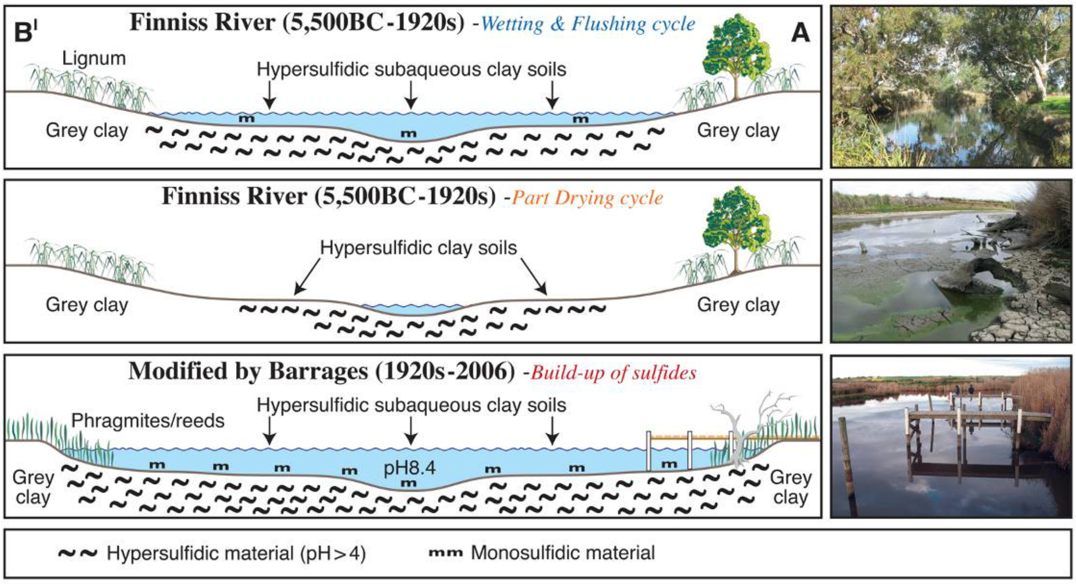


Figure 11-6. Predictive soil-regolith models for Finniss River (A – A' transect in Figure 11-1) illustrating natural wetting and flushing (upper panel), and partial drying (lower panel) cycles during the time prior to major pre-European development (5,000 BC to 1880s). The first picture taken upstream of Wally's Landing to represent its possible original condition.

(ii) From the 1930s to 2006. Since the 1930s water levels in Lake Alexandrina and Finniss River have been managed using locks and barrages and this continues to the present, with seawater exclusion being their main function. The installation of locks and barrages has allowed considerable build-up of sulfidic, hypersulfidic and monosulfidic material in the lower lakes and tributaries due to: firstly the evaporative concentration of sulfate from river nutrient and salt loads during periods of stable pool levels and from groundwater sources, and secondly, the lack of scouring and seasonal flooding. This has led to the formation of subaqueous ASS (i.e. Hypersulfidic subaqueous clayey soils) with ultra-fine monosulfidic material accumulating in low-flow backwaters and along the vegetated edges of the wetlands.

(iii) From 2006 to November 2008. During this drought period, partial drying of the river and adjacent wetlands took place (Figure 11-7 and Figure 11-8), and the river and lake levels continued to decrease (Figure 4-2). The subaqueous ASS (Hypersulfidic subaqueous clayey soils) transformed to waterlogged ASS (Hypersulfidic clayey soils).

(iv) From November 2008 to February 2009. During the period from November 2008 to February 2009, extreme drying of Lake Alexandrina and adjacent wetlands took place (Figs. 17 & 18) due to the extended drought conditions and lower lake levels (Lake Alexandrina had almost reached –1.0m AHD; see Figure 4-2). Most wetlands adjacent to Lake Alexandrina effectively became hydraulically disconnected from the lake. These conditions also permitted oxidation of sulfides due to increased soil aeration from deepening of desiccation cracks (> 50cm), especially in areas that were organic-rich (> 10 % organic carbon) and clayey (> 35 % clay).

This resulted in the formation of sulfuric material up to 50 cm into the subsoil (Sulfuric clayey soils). Under these low pH conditions, acid dissolution of the layer silicate soil minerals caused the release of substantial amounts of soluble Fe, Al, Mg, Si (and other elements) (Figure 11-7 and Figure 11-8). The continued drying of the Finniss River and the adjacent wetlands caused further desiccation, and the precipitation of sulfate-rich salt efflorescences in desiccation cracks and on the sandy edges of the river (Figure 11-7 and Figure 11-8). Areas with monosulfidic materials continued to dry out, with the formation of desiccation cracks in the fine textured material.

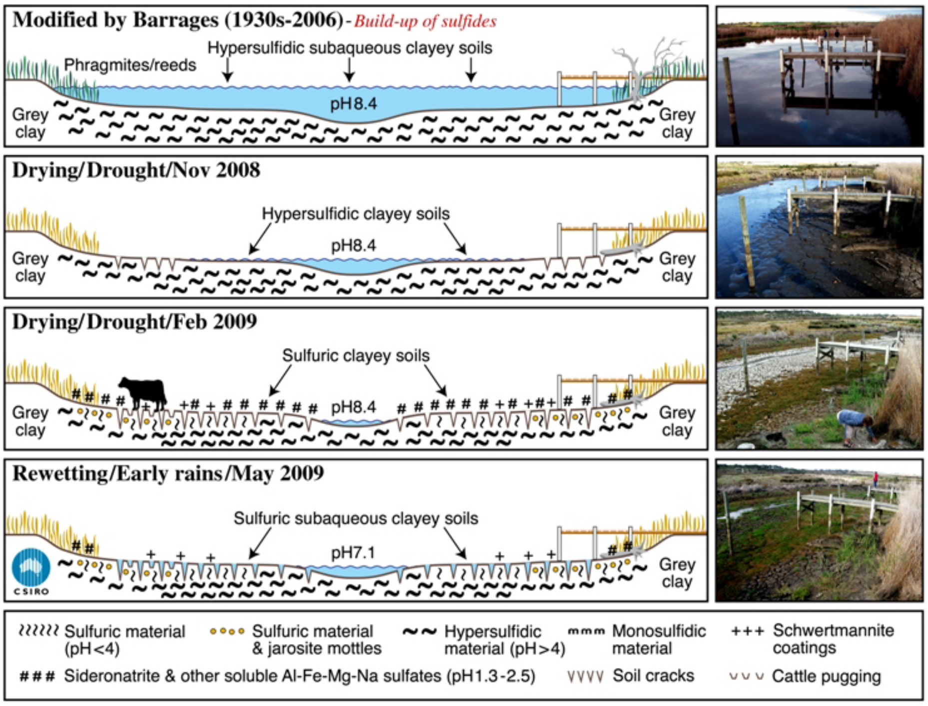


Figure 11-7: Predictive soil-regolith models for the Finniss River at Wally's Landing (A – A' transect in Figure 11-1) illustrating modification of water levels by barrage installations causing the build up of sulfides under continuous subaqueous ASS conditions from 1930s-2006 followed by progressive drying (middle two panels), and finally a rewetting phase in May 2009 (lower panel) resulting in acidic waters in the cracks and cattle pugs, and in running waters in adjacent wetlands.

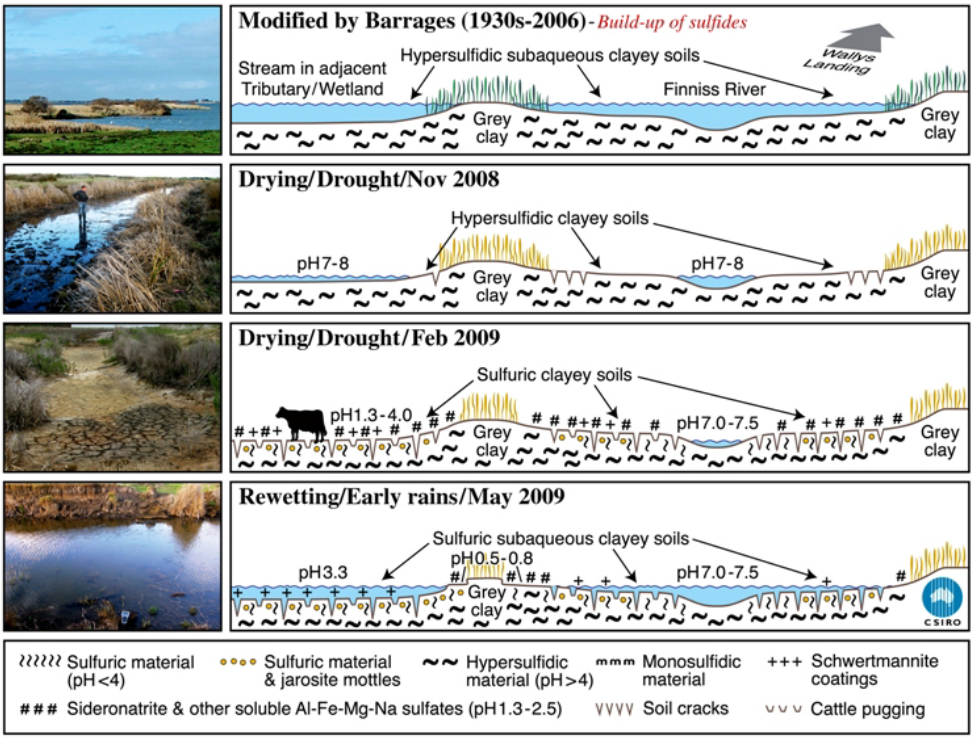


Figure 11-8. Predictive soil-regolith models across the Finniss River and adjacent wetland (B – B' transect in Figure 11-1) illustrating modification of water levels and progressive drying (middle upper panels), and finally a rewetting phase in May 2009 (lower panel) resulting in acidic pools and running water (pH 3.3. to 4) in the cracks and cattle pugs (pH 0.5 to 0.8).

(v) **May 2009** (Figure 11-7 and Figure 11-8 – lower panels)**.** During May 2009, the river and adjacent wetlands (cracks and areas pugged by cattle) were rewet. This caused sulfate-rich salt efflorescences to dissolve and wash into cracks and cattle pugs (pH 1.3 to 2.5). Rewetted soil surfaces with extremely low pH values (pH 0.5 to 0.8) were also recorded. The river channel water had a pH of 7.1 (Figure 11-7). The higher river pH values on the southern side were likely partly maintained by the discharge of alkaline groundwater. However, at the same time strongly flowing extremely acidic water (pH 3.3) was observed in the adjacent anabranches and wetlands draining former channels of the lower alluvial plain (Figure 11-8).

11.3. Distribution of Acid Sulfate Soils

The ASS maps of the Finniss River, Currency Creek and Goolwa Channel areas (area D in Figure 5-2) shown in Figure 11-9 show the likely extent of sulfuric and sulfidic soil materials with:

(a) water levels at -0.5 m AHD (February, 2008) when these soils were originally mapped using limited available data (Fitzpatrick *et al.* 2008a),
(b) previously predicted occurrence at -1.0 m AHD, and
(c) predicted occurrence for a future scenario of –1.5 m AHD (Fitzpatrick *et al.* 2008a).

The predicted distribution at -1.0 m AHD [Figure 11-9 (b)] closely approximates the extent of all ASS materials identified in late November 2008 (Fitzpatrick *et al.* 2009a) when the water level was -0.7 m AHD and closely relates to the data displayed in the explanatory and predictive soil-regolith toposequence models (e.g. Figure 15-1 Figure 11-8).

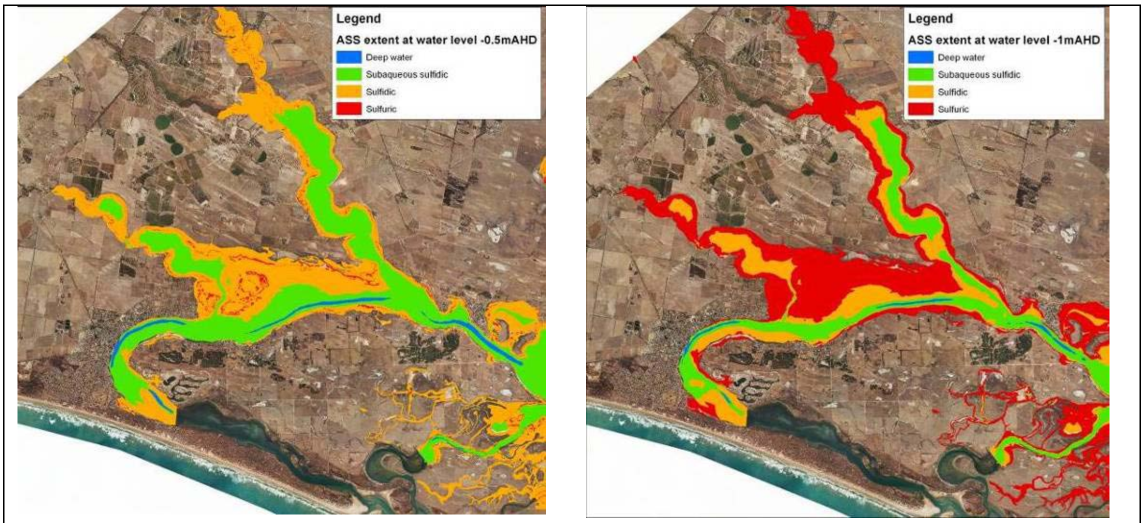
11.4. Management of Acid Sulfate Soils and water levels

Monitoring acidity

Monitoring of ASS properties and river water chemistry was undertaken as an essential component of ASS assessment in this region, especially during the winter rewetting phases when acidity, metal mobilisation and widespread occurrences of salt efflorescences were observed (Figure 11-7 and Figure 11-8 – lower panels; Fitzpatrick *et al.* 2009a). The risk of unmanageable acidic conditions triggered the application of fine limestone to the lower Finniss River (and Currency creek) during the winter rainfall rewetting period. This was aimed at neutralising the acidic waters flowing from the wetland and channel to maintain pH above the critical level of 4.0 (Figure 11-10).

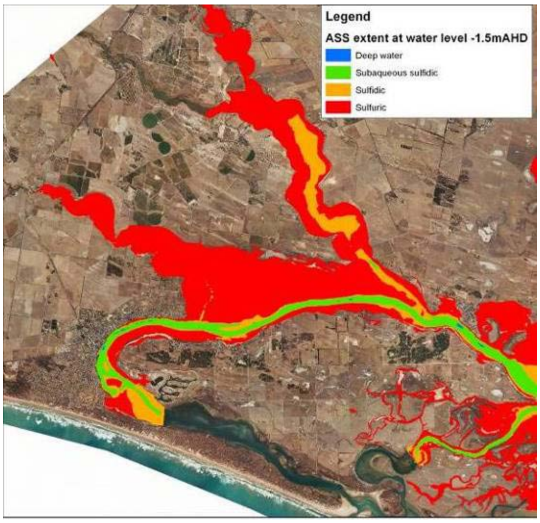
As a consequence of the widespread occurrence of sulfuric material (Figure 11-9) and acidic waters in the Goolwa Channel, Finniss River and Currency Creek areas, the Federal government, in response to a Referral under the Environment Protection and Biodiversity Conservation Act, gave approval for the South Australian Government to undertake a set of emergency actions to undertake management measures to mitigate Acid Sulfate Soils (DEWHA 2009).

A temporary flow regulator across the Goolwa Channel at Clayton was constructed (Figure 11-11) to allow water levels in the Goolwa Channel, Finniss River and Currency Creek to be raised. This aimed to saturate the recently exposed sulfuric and hypersulfidic materials (Figure 11-9) to minimise further sulfide oxidation and to allow the early season flows (which would have mobilised acid and heavy metals) to be held back, allowing in-situ bioremediation to proceed. The constructed height of the regulator was approximately +2.5 m AHD (to allow sufficient freeboard), but the water level was managed to a maximum level of +0.7m AHD. The pool level was initially raised to +0.7m AHD by pumping water from Lake Alexandrina. This action required approximately 20 GL of water. In addition, a low-level regulator (0 m AHD) has been constructed across the mouth of Currency Creek to permit continued saturation of sulfidic, hypersulfidic and sulfuric materials.



(a) February, 2008

(b)



(c)

Figure 11-9. Maps of various acid sulfate soil subtypes in the Goolwa channel, Currency Creek and Finniss River area for: (a) water levels at -0.5 m AHD (February, 2008); (b) predicted occurrence at -1.0 m AHD, which closely approximates ASS subtypes found in late November 2008; and (c) predicted occurrence for of -1.5 AHD (modified from Fitzpatrick *et al.* 2008b).

Figure 11-10: Applications of fine limestone in the Finniss River below Wally’s Landing jetty to acidic waters flowing from the wetland and channel (Figure 11-1) in May 2009.

Figure 11-11. Main temporary flow regulator across the Goolwa Channel at Clayton Bay was completed in early August 2009 allowing water levels in the Goolwa Channel, Finniss River and Currency Creek to be raised and to saturate the existing exposed sulfuric material (map (c) in Figure 11-9). The regulator is about 400 metres long and 40 metres wide, and constructed as an earth-fill embankment.

12. Lake Alexandrina and adjacent wetlands (Area B in Figure 5-2)

12.1. Background and Environmental Setting

Lake Alexandrina (Area B in Figure 5-2) is a large freshwater lake that receives water principally from River Murray flows but also from the Eastern Mount Lofty Ranges via the Finniss River and Currency Creek. This interconnected freshwater lake has been physically segregated from the estuarine environments of the Coorong and Murray Mouth by a series of five barrages, which were completed in the 1940's and are constructed to a height of approximately +0.83 mAHD (Figure 3-2). According to Phillips & Muller (2006) they have a target maximum fill level of +0.75 mAHD. Prior to European settlement, Lake Alexandrina experienced brief periods of seawater intrusion during severe drought periods, but generally the lake remained mainly fresh, or at worst, brackish.

12.2. Acid Sulfate Soil Processes and Hazards

Based on soil investigations (Fitzpatrick *et al.* 2008e,h) and historical and palaeo-pedological knowledge, a series of 8 conceptual models have been constructed that illustrate how various ASS materials in subaqueous, waterlogged (saturated) and dried soils have sequentially changed, and will change over time in the Coorong and Lower Lakes. To illustrate these sequential changes, a soil-regolith model was constructed for Lake Alexandrina using cross-sections (Lake Alexandrina cross section A-A' is shown in Figure 3-2) covering the periods:

(i) before the 1880s (approximately 5,500 BC to the 1880s), when Lake Alexandrina cycled between natural wetting and flushing, and partial drying conditions,

(ii) from the 1880s to the 1930s when the river and lake systems were modified for irrigation purposes,

(iii) from the 1930s to 2006, when Lake Alexandrina was managed using locks and barrages,

(iv) during 2006 to 2007 when partial drying of wetlands and the margins of Lake Alexandrina took place, and during 2007 to 2008 when complete drying of the margins around Lake Alexandrina and adjacent wetlands took place. This was unprecedented since the installation of the barrages.

(v) during 2008 to 2009 assuming no pumping from Lake Alexandrina occurred and extreme drought conditions continue, and

(vi) during 2008, when pumping water from Lake Alexandrina to Lake Albert took place to maintain water levels to prevent further oxidation of sulfidic material and rewetting of sulfuric materials.

Lake Alexandrina predictive soil-regolith model (Area B in Figure 5-2)

(i) Before the 1880s (5,500 BC to the 1880s). Lake Alexandrina cycled between partial natural wetting and flushing (Figure 12-1, upper panel) as described above for the tributaries area (Figure 11-7). It underwent partial drying conditions in response to seasonal (i.e. winter/summer) and climatic (e.g. drought/wet) cycles occurring in the upper MDB. Lake Alexandrina accumulated sulfidic materials from sulfate contained in surface waters and groundwaters, with occasional partial intrusion of sea water. However, during dry periods such as droughts (Figure 12-1) when river flows were lower, the margins of Lake Alexandrina and adjacent wetlands dried, causing oxidation of sulfidic materials. Pyrite in the sulfidic material was oxidised with the possible formation of sulfuric acid and potentially the formation of sulfuric materials. In wetter times and during floods, the acidic material was submerged in the water column, with dilution/neutralisation of acidity, entrainment of oxidation products in the water and the reformation of sulfidic material. The build-up of sulfidic materials in Lake Alexandrina was regularly kept in check by oxidation and removal through episodic floods.

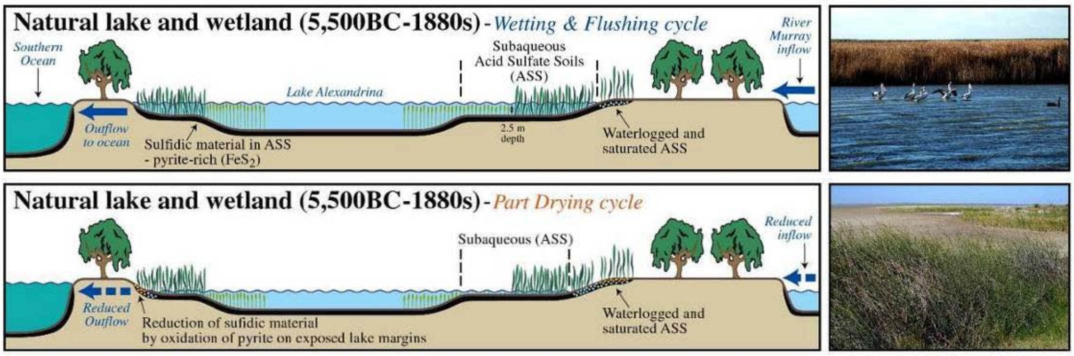


Figure 12-1. Predictive soil-regolith models (A-A'; Figure 3-2) for Lake Alexandrina; illustrating natural wetting and flushing (upper panel), and partial drying (lower panel) cycle conditions during pre-colonial times (5,000 BC–1880s).

(ii) From the 1880s to the 1930s. European colonists moderated the flows of the River Murray and Lower Lakes by extraction upstream for irrigation and by the construction of locks from the 1920s to ensure reliable navigation and irrigation (Figure 12-2). During this period, Lake Alexandrina was "managed for flood irrigation" (e.g. mainly dairy farming).

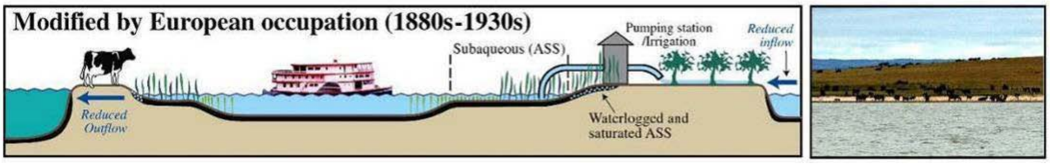


Figure 12-2. Predictive soil-regolith model (A-A'; Figure 3-2) for Lake Alexandrina; illustrating modification of water flows by European occupation (1880s–1930s).

(iii) From the 1930s to 2006. Lake Alexandrina was managed using locks and barrages (Figure 12-3). The installation of locks and barrages allowed considerable build-up of sulfidic and monosulfidic material in the Lower Lakes (subaqueous sulfidic materials) due to: (i) the evaporative concentration of sulfate-containing nutrient/salt loads under stable pool levels and from groundwater sources, (ii) the lack of scouring and seasonal flooding. Monosulfidic material also accumulated in low-flow backwaters and along the vegetated edges of the wetland.

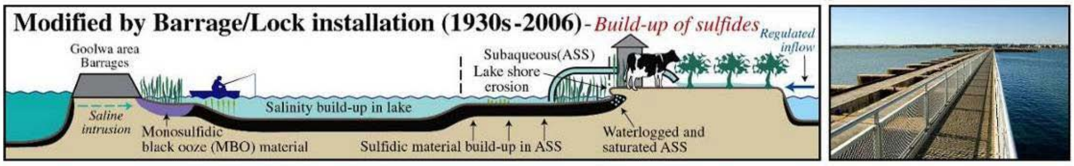


Figure 12-3. Predictive soil-regolith model (A-A'; Figure 3-2) for Lake Alexandrina; illustrating modification of water flows by barrage (and lock) installations causing the build up of sulfides under subaqueous ASS conditions from 1930s–2006.

(iv) From 2006 to 2007. Partial drying of wetlands and beaches surrounding Lake Alexandrina took place (Figure 12-4) due to the drought conditions from 2006 to 2007 when river and lake levels continued to drop. During this period, subaqueous ASS transformed to waterlogged ASS (i.e. ASS that are wet or saturated long enough to produce periodically anaerobic conditions).

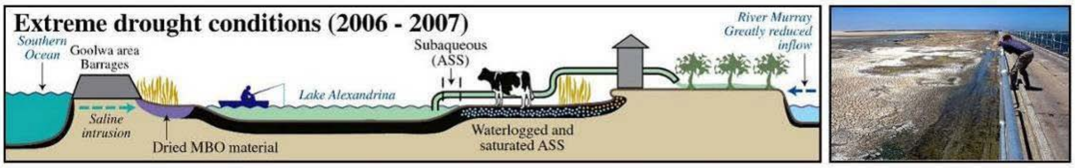


Figure 12-4. Predictive soil-regolith model (A-A'; Figure 3-2) for Lake Alexandrina, illustrating extreme drought conditions in 2006– 2007 where subaqueous ASS transform to waterlogged ASS (i.e. ASS that are wet or saturated long enough to produce periodically anaerobic conditions, thereby influencing the growth of plants: e.g. hydric soils with sulfidic material).

(v) From 2007 to 2008. Drying of extended beaches surrounding Lake Alexandrina and adjacent wetlands took place (Figure 12-5). Most wetlands adjacent to Lake Alexandrina effectively became hydraulically disconnected from the lake. This resulted in the formation of sulfuric material with depths up to 75 cm. These conditions have also permitted deepening of desiccation cracks (> 50 cm), especially in areas that are organic-rich (> 10% organic carbon) and clayey (> 35% clay). The continued drying of Lake Alexandrina and the adjacent wetlands caused further desiccation, and the precipitation of a wide range of sulfate-rich salt efflorescences in desiccation cracks and on the sandy beaches surrounding the lake. Areas with monosulfidic material continued to dry out, causing desiccation cracks to develop in the fine textured material (Figure 12-5).

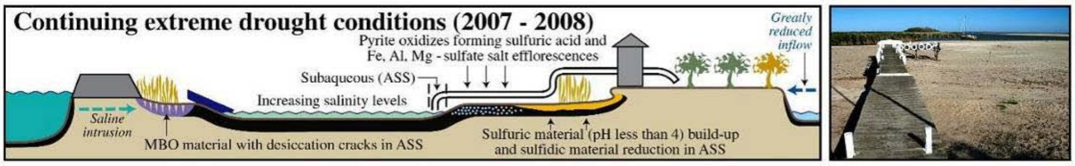


Figure 12-5. Predictive soil-regolith model (A-A'; Figure 3-2) for Lake Alexandrina; illustrating the formation of: (i) sulfuric material (pH < *4*) by oxidation of sulfides in sulfidic material, (ii) sulfate-rich salt efflorescences and (iii) deep desiccation cracks; due to continued lowering of water levels under persistent extreme drought conditions during 2007–2009.

(v) Rewetting scenario post 2008 (Figure 12-6) illustrating the various rewetting scenarios of initial acidification, metal and salt mobilisation during low water flows, followed by metal dilution, immobilisation and flocculation during sustained increased water flows and ponding (Figure 12-6).

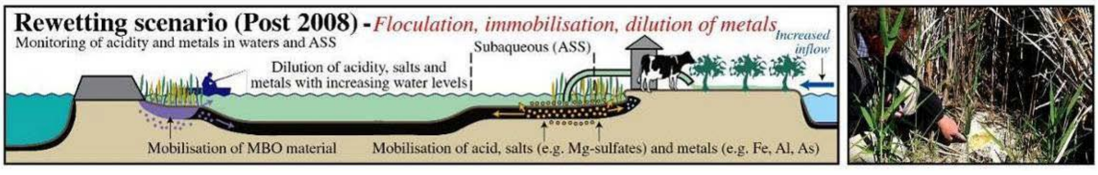


Figure 12-6. Generalised conceptual cross section (A-A'; Figure 3-2) soil-regolith model for Lake Alexandrina; illustrating the various rewetting scenarios of initial metal and salt mobilisation during low water flows followed by metal dilution, immobilisation and flocculation during sustained increased water flows and ponding.

Loveday Bay predictive soil-regolith model (Area B5 in Figure 5-2)

In September 2009, CSIRO (Fitzpatrick *et al.* 2010a) identified an area of more than 200 ha of acidic surface water (pH 2.5 to 2.8) in Loveday Bay adjacent to Lake Alexandrina (Figure 12-7). Due to lowering water levels, this area became disconnected from the main lake water body, surface water evaporated and the saturated Hypersulfidic soils became unsaturated and oxidised to form sulfuric soils [panel (b) in Figure 12-8]. Water levels remained low enough to keep the area disconnected from the main lake water body, and with winter rains, water flowed over and through the sulfuric soils and collected in the depression areas (which covered more than 200 ha). The consequence of this, observed during the August 2009 mapping survey described in Fitzpatrick *et al.* (2010a), which was areas of very acidic water (pH 2.5 to 2.8) and soils below this water remaining sulfuric and not reducing to hypersulfidic material (i.e. soils remained as "sulfuric subaqueous soils"). Interestingly, the ASS subtype on the edge of the acidic water had a high amount of monosulfidic material (i.e. Hypersulfidic soil with monosulfidic material) while most of the exposed beach areas comprised Sulfuric Soil with abundant highly acidic salt efflorescences, comprising mostly sideronatrite. In summer 2008, Loveday Bay dried out completely leaving a vast area comprising predominantly sulfuric soil (see Figure 12-8; Fitzpatrick *et al.* 2010c).

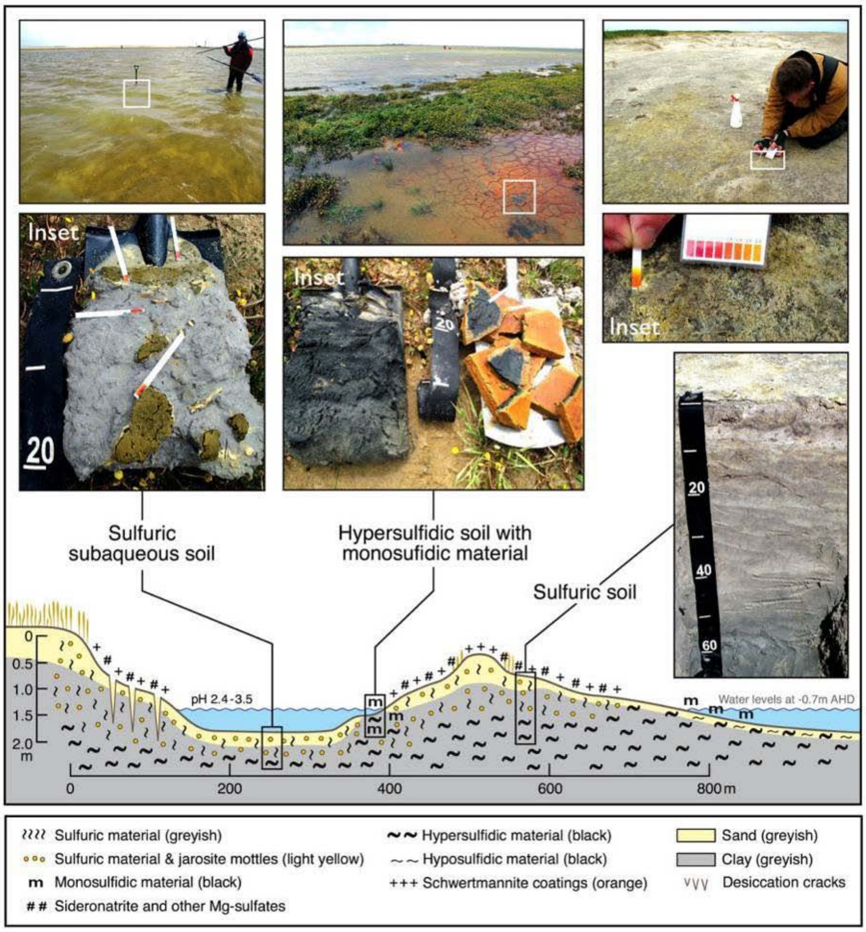


Figure 12-7. Descriptive soil-regolith model, for Loveday Bay adjacent to Lake Alexandrina (site B5 in Figure 5-2)

12.3. Distribution of Acid Sulfate Soils

Combined bathymetry, soil and vegetation mapping in a GIS was used to construct ASS maps to help predict the distribution of the various subtypes of ASS according to three scenario maps (Fitzpatrick *et al.* 2008a,d,e,h), which depict sequential changes in ASS materials at different water levels in Lake Alexandrina of +0.5 m AHD (pre-drought), -0.5 m (approximate level during early 2008), and for -1.5 m AHD (an extreme case, should very low lake inflows persist). These are presented schematically for Lake Alexandrina in a series of simplified maps in Figure 12-9 [more detailed maps are available in reports by Fitzpatrick *et al.* (2008a,e,h)]. The maps show the distribution of different subtypes of ASS (deeper than 2.5 m; subaqueous sulfidic; sulfidic and sulfuric) as lake water levels drop, and soils de-water.

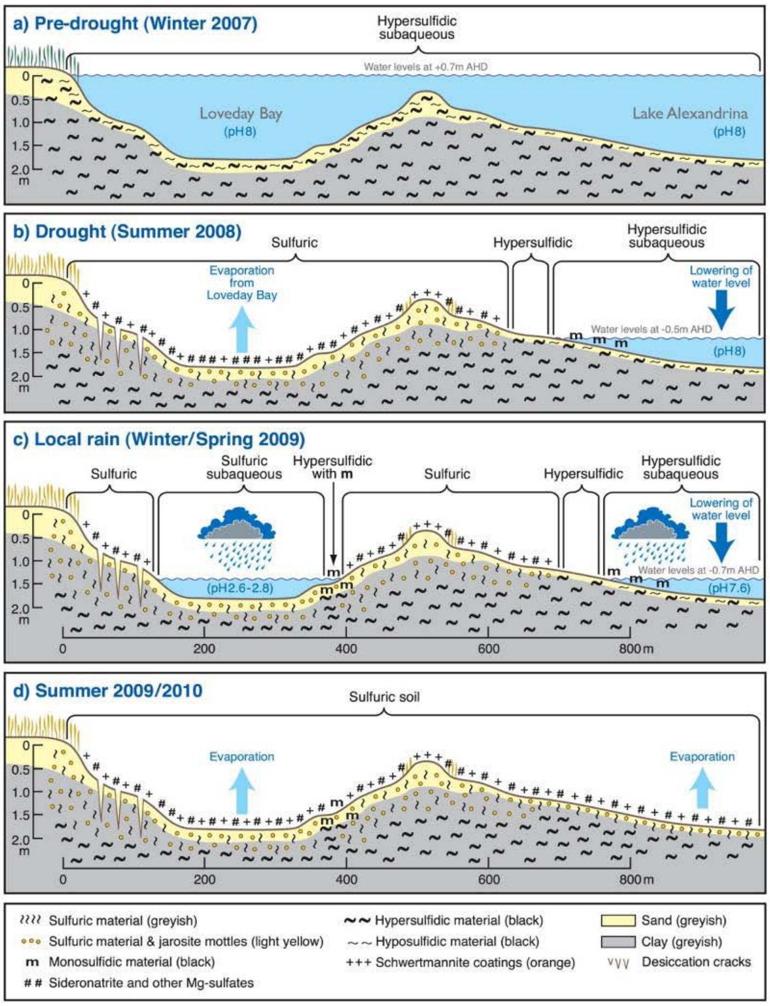


Figure 12-8. Predictive soil-regolith model for Loveday Bay (site B5 in Figure 5-2)

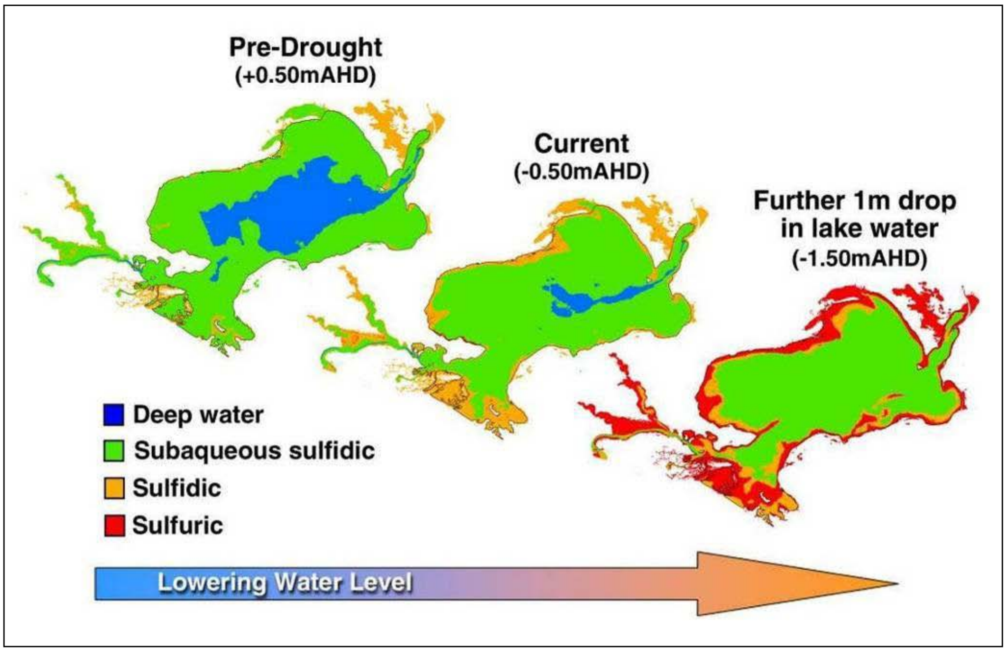


Figure 12-9. Predictive scenario maps depicting changes in acid sulfate soil materials at different water levels in Lake Alexandrina (+0.5 m AHD, -0.5 m AHD and -1.5 m AHD) (from Fitzpatrick *et al.* 2008a,e,h.) Finniss River, Currency Creek and Goolwa Channel are the three extensions occurring on the left side of Lake Alexandrina.

12.4. Management options

The CSIRO reports, which include ASS maps have added to a growing body of acid sulfate soil research being conducted that has informed the decisions of senior environmental managers (e.g. DENR 2011). Management decisions included: (a) pumping water from Lake Alexandrina into Lake Albert to maintain water levels to arrest the formation of acid sulfate soils on Lake Albert shores and (b) initiating research on bioremediation of the shores and bed of Lake Albert.

No management options were applied to remediate the strongly acidic standing water overlying the Sulfuric subaqueous Soils and Sulfuric Soils in Loveday Bay as indicated in Figure 12-8. This “no further action or minimum intervention option” was adopted because in 2009 and 2010, Loveday Bay posed no apparent major threat to adjacent water bodies, wetlands, agricultural lands, stock or humans, due its remote location. However, monitoring of water (i.e. monthly during the re-wetting phases when acidity and metal mobilisation are likely to occur) and acid sulfate soils (six monthly) continues as an essential part of the management strategy (Baker *et al.* 2010). Warning signs have also been erected (Figure 6-3).

It is recommended that the careful long-term monitoring of soils (Baker *et al.* 2010). and water in the Lower Lakes be continued in order to establish robust ‘trigger values’ for soil and water to guide future management decisions or interventions. Monitoring is based on the approach and indicators identified using selected representative sites featured in CSIRO ASS studies (e.g. Baker *et al.* 2010, Fitzpatrick *et al.* 2010c; MDBA 2010). Finally, based on field investigations and historical and palaeo-pedological knowledge of Lake Alexandrina, a series of conceptual soil-regolith models were constructed that illustrate how various ASS materials have sequentially changed under subaqueous, waterlogged (saturated) and dried conditions, and have further changed, because of re-wetting by winter rainfall and reflooding events in 2010 and 2011 (Figure 5-13).

Monitoring is an essential component of acid sulfate soil assessments not only during drought conditions, but also during the re-wetting phases when acid formation and metal mobilisation are likely to occur.

Workshops have been conducted for community volunteers to teach them how to collect soil and water samples for ASS monitoring (see Fitzpatrick and Thomas 2011). The first half of each workshop provided the general theory of acid sulfate soil formation, particularly as this relates to present day conditions in the Lower Lakes. The presentation included the chemistry of ASS formation, the distribution in lake landscapes, the possible environmental issues, and management options. The second half of the workshop presented field survey and sampling protocols, which were adapted from the MDBA rapid assessment protocol (MDBA 2010). Information was given on how to select a suitable survey area that represented a ‘typical’ hydrosequence, and then selection of three survey sites within the area: Site 1, in shallow water; Site 2, just above the current waterline; and Site 3, halfway between the current waterline and the pre-drought waterline. Sampling procedure and data collection were outlined. Samples were collected at 0-5, 5-30 and >30 cm depth increments, and the pH of each sample was measured using Merck indicator strips. Description of key morphological features of the depth increments, placement of depth increment samples into a chip tray with proper labelling for laboratory incubation, and storage of samples were all included in the program. All information was recorded on field data sheets.

At least 85 volunteers conducted surveys at 486 well-distributed soil profiles around the Lower Lakes. Immediately after sampling was complete, chip trays (containing soil samples) and 70 ml jars containing water samples were frozen and transferred to the CSIRO laboratory. At the CSIRO laboratory the sealed 70 ml jars were placed in a freezer for long-term storage and potential future analyses. The chip trays were thawed and pH and pH incubation measurements were undertaken. The results are presented via the Australian Soil Resource Information (ASRIS) portal (www.asris.csiro.au) and a GoogleEarth interface to enable wide public access to the community data.

13. Lake Albert and adjacent wetlands (Area C in Figure 5-2)

13.1. Background and Environmental Setting

Lake Albert (Area C in Figure 5-2) is a large freshwater lake that receives water principally from River Murray flows but also via Lake Alexandrina from the Eastern Mount Lofty Ranges via the Finniss River and Currency Creek. This interconnected freshwater lake has also been physically segregated from the estuarine environments of the Coorong and Murray Mouth by a series of five barrages in Lake Alexandrina, which were completed in the 1940’s and are constructed to a height of approximately +0.83 m AHD (Figure 3-2). According to Phillips & Muller (2006) they have a target maximum fill level of +0.75 mAHD. Prior to European settlement, the Lake Albert experienced brief periods of seawater intrusion during severe drought periods, but generally it would have remained fresh, or at worst, brackish.

13.2. Acid Sulfate Soil Processes and Hazards

Descriptive soil-regolith model

To aid in understanding the spatial heterogeneity of acid sulfate soil property variation, soil landscape cross-sections were constructed from the data and surveyor knowledge. Descriptive soil-regolith models are presented for the Campbell Park area in Lake Albert for Pre-drought (winter 2007), Drought (Summer) 2008 and Winter-Spring 2009) conditions (see Figure 13-1, Figure 13-2, Figure 13-3, and Figure 13-4).

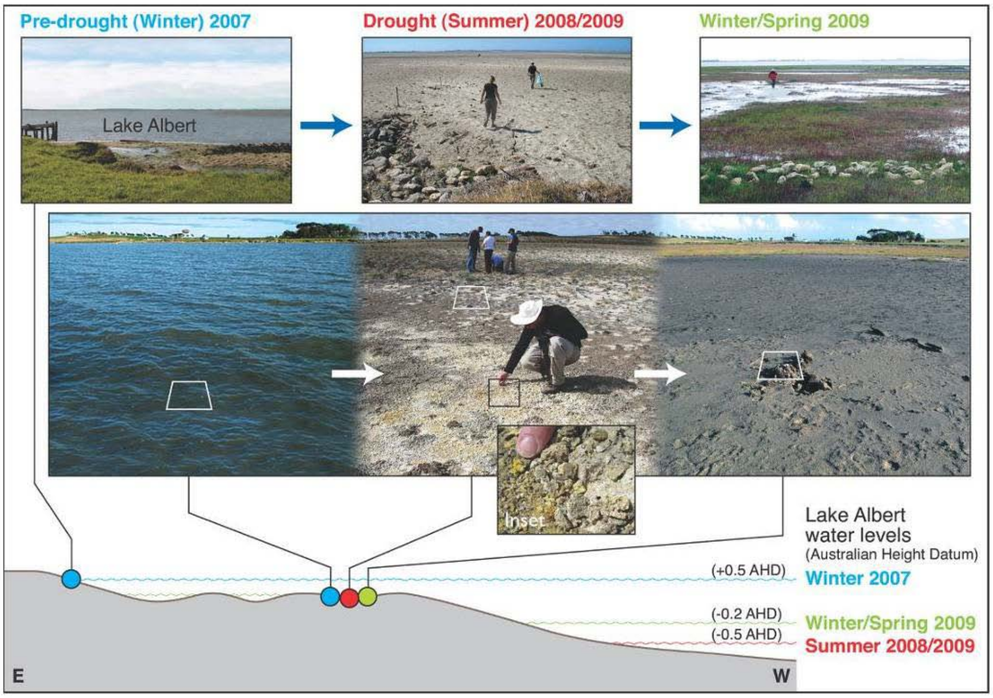


Figure 13-1. Descriptive toposequence model for an area near Campbell Park in Lake Albert showing variation of acid sulfate soil features in Pre-drought (winter) 2007, Drought (Summer) 2008 and Winter-Spring 2009).

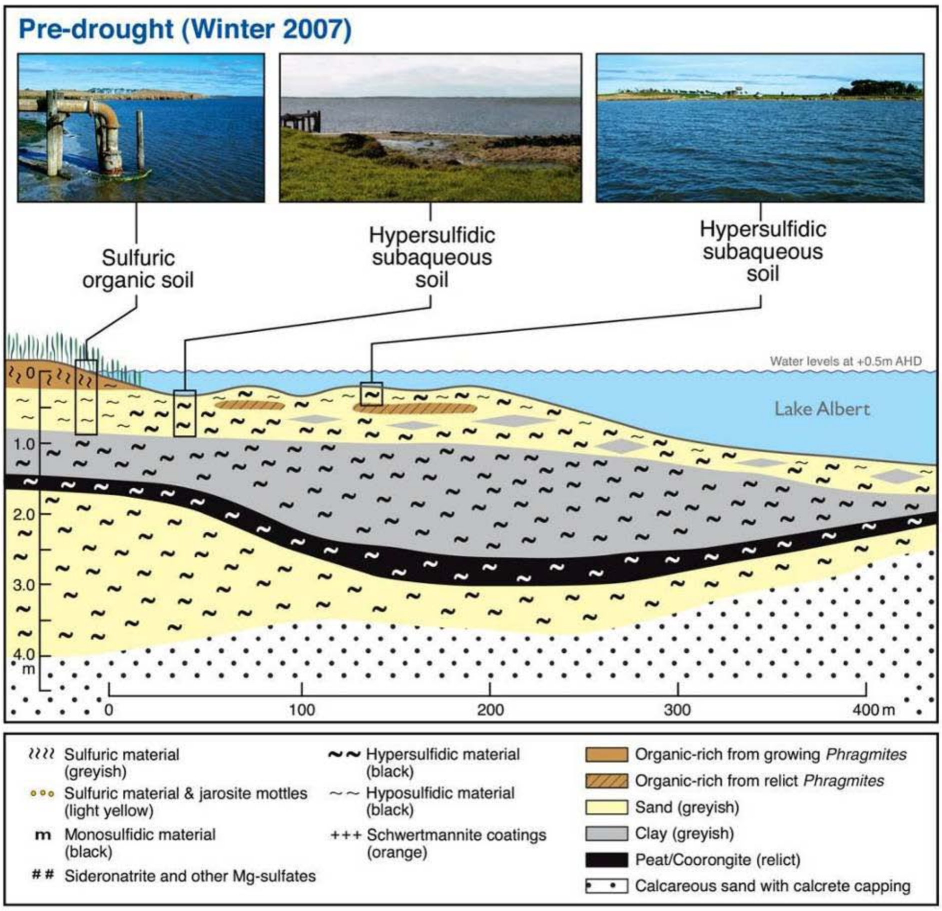


Figure 13-2. Descriptive soil-regolith model for an area near Campbell Park in Lake Albert showing spatial variation of acid sulfate soil materials in Pre-drought (winter 2007).

These soil-regolith models clearly show in cross-section the spatial heterogeneity of the wide range of ASS materials and other features (e.g. salt efflorescences). They all show the location and transition of hypersulfidic, sulfuric and monosulfidic materials occurring in the unsaturated sands, hypersulfidic material on the water margins, and subaqueous hypersulfidic material occurring below water.

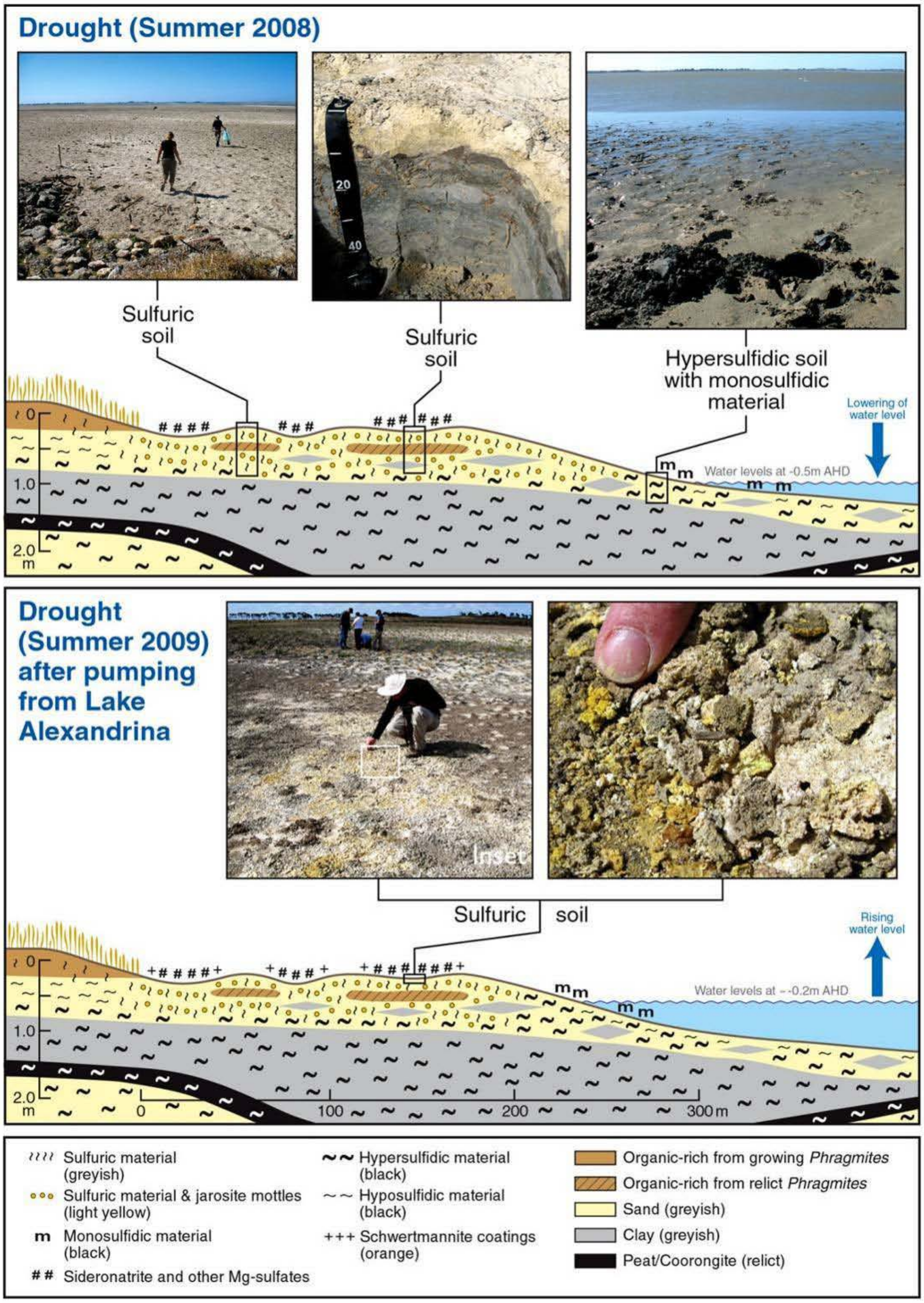


Figure 13-3 Descriptive soil-regolith model for an area near Campbell Park in Lake Albert showing spatial variation of acid sulfate soil materials (summer 2008).

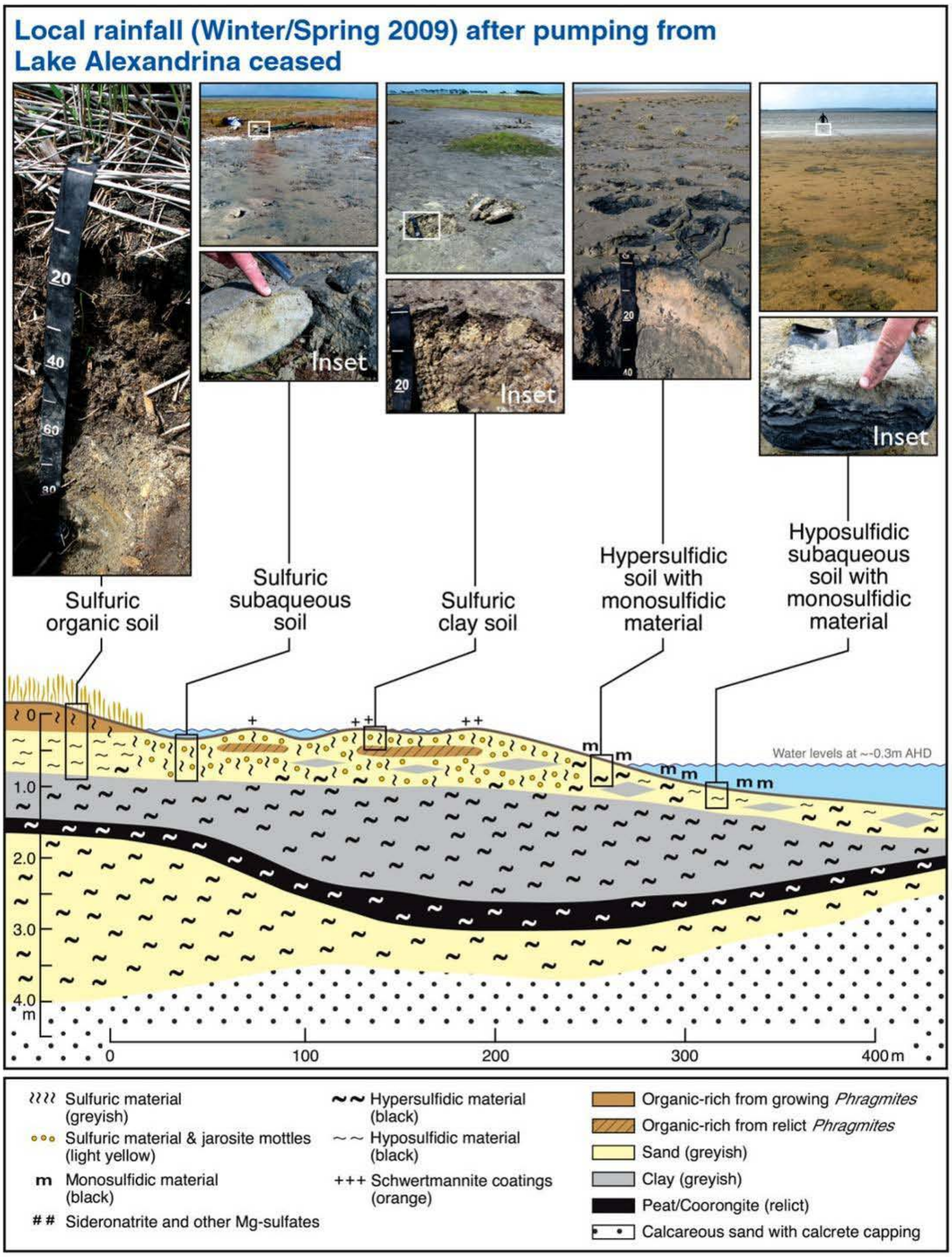


Figure 13-4. Descriptive soil-regolith model for an area near Campbell Park in Lake Albert showing spatial variation of acid sulfate soil materials (winter / spring 2009) (Area C5 in Figure 5-2).

An important finding of this case study was the occurrence of shallow sulfuric subaqueous soils, and that they occurred over significant areas during the winter-spring period in 2009. In the Lake Albert toposequence shown in Figure 13-1, these subaqueous soils occurred where there were isolated pools of water that formed in shallow surface depressions.

Based on soil investigations (Fitzpatrick *et al.* 2008e,h) and historical and palaeopedological knowledge, a series of 8 conceptual soil-regolith models were also constructed to illustrate how various ASS materials in subaqueous, waterlogged (saturated) and dried conditions have sequentially changed, and will change over time in Lake Albert. To illustrate these sequential changes, a predictive soil-regolith model was constructed for Lake Albert using cross-sections covering the different periods.

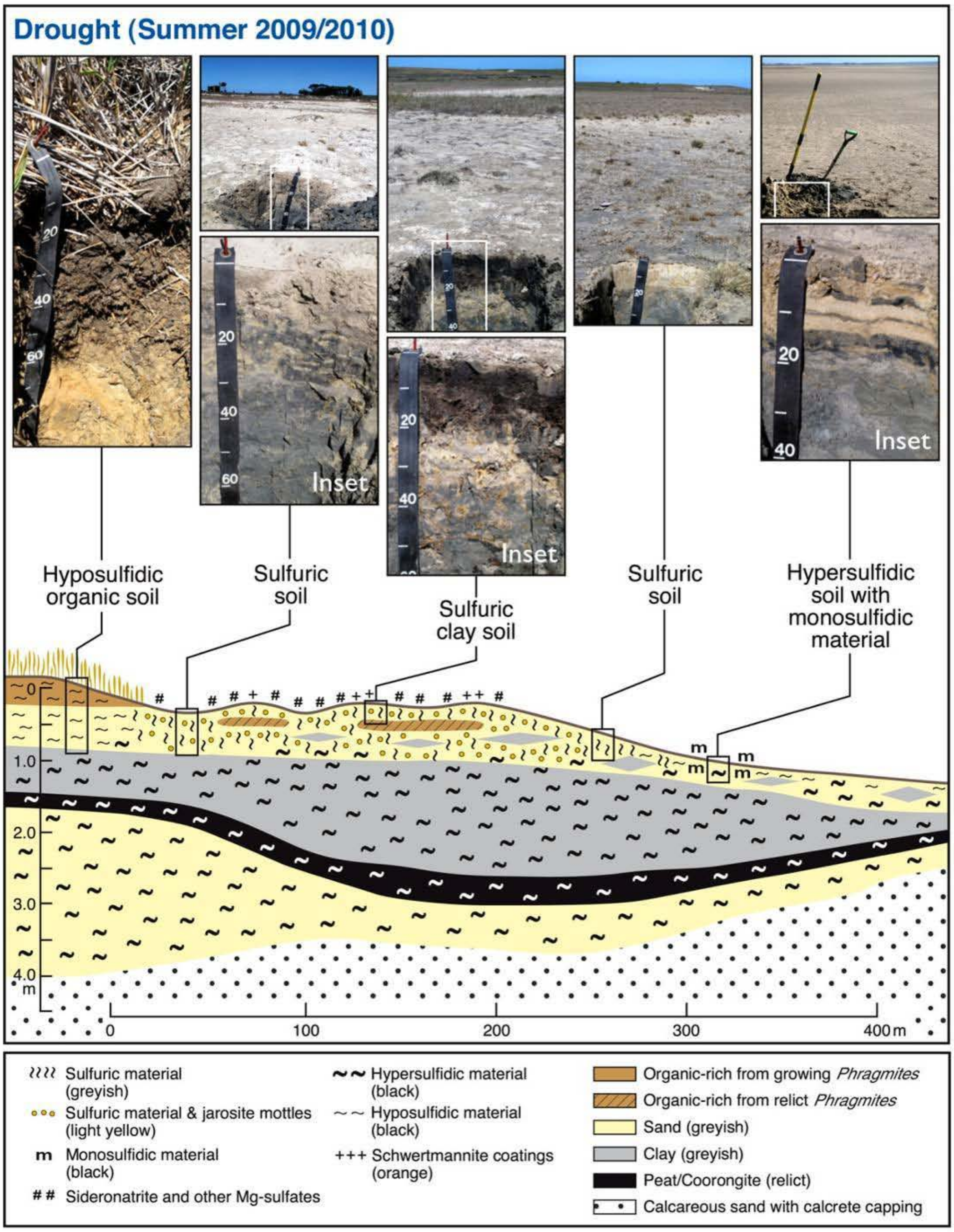


Figure 13-5. Descriptive soil-regolith model for an area near Campbell Park in Lake Albert showing spatial variation of acid sulfate soil materials at the end of summer and after discontinuation of water pumping from Lake Alexandrina to Lake Albert (March 2010)

13.3. Distribution

The maps for Lake Albert and for Lake Alexandrina (see also Figure 12-9) were combined and calculations of the acid sulfate soil transitions from the wetter to drier subtypes made. A summary of predicted aerial extents is shown in Table 13-1. The data shows that with the lowering of the water level there is predicted to be a major shift from Subaqueous Sulfidic at +0.5m AHD to Sulfidic at -0.5m AHD and then a massive shift to Sulfuric at -1.5m AHD. This highlights that significant acidification is present and that this is also likely to increase to become a significant management burden if water levels continue to fall.

Table 13-1. Summary of predicted aerial extents (ha) of acid sulfate soil types coverage's for Lake Alexandrina and Lake Albert combined under water levels of +0.5m, -0.5m and -1.5m AHD.

	Predicted aerial extent, ha (% value)		
Acid Sulfate Soil type	**+0.5 m AHD (previous, pre-drought)**	–0.5 **m AHD (current, drought)**	–1.5 **m AHD (future, persistent drought)**
Sulfidic, deeper than 2 m	16,912 (18%)	3,061 (3%)	32 (0%)
Subaqueous sulfidic	67,584 (72%)	64,790 (69%)	42,492 (45%)
Sulfidic	8,970 (10%)	24,575 (26%)	18,253 (20%)
Sulfuric	0 (0%)	1,039 (1%)	32,699 (35%)

13.4. Management options

The management option chosen for preventing more sulfidic material in Lake Albert oxidising to form sulfuric material was to pump water from Lake Alexandrina to Lake Albert to maintain water levels (Figure 13-6 and Figure 13-7). This option was based on:

- Identification of abundant sulfuric and underlying hypersulfidic materials in Lake Albert when water levels were -0.3 m AHD (Figure 13-3)

- Predicted formation of abundant sulfuric materials if water levels dropped further due to extreme drought conditions in the Lower Lakes (See ASS maps in Fitzpatrick *et al.* 2008a,e,h)

- The absence of satisfactory environmental flows resulting in restoration of water levels in the lower lakes. The South Australian and Australian Federal governments maintained water levels in Lake Albert at approximately -1.5 to -0.3 m AHD by pumping water at a rate of 400 ML/day from Lake Alexandrina to Albert.

This option prevented the water level in Lake Albert from dropping below -0.6 m AHD (Figure 13-6 and Figure 13-7), to minimise the risk of extreme soil and water acidification. Lake Albert was disconnected from Lake Alexandrina after the construction of an earthen bank (see photograph in Figure 13-6 and Figure 13-7) before pumping commenced in early 2008. However, pumping ceased in Winter 2009 [see panel (d) in Figure 13-7].

The predictive soil-regolith model shows that pre-drought [panel (a) in Figure 13-7] water levels were higher and connected to the main Lake water body; the soils were covered with water and were considered to be subaqueous hypersulfidic soils. Due to lowering water levels, wetland areas at the lake margin became disconnected from the main lake water body, surface water evaporated and the saturated hypersulfidic soils became unsaturated and oxidised to form sulfuric soils [panel (b) in Figure 13-7].

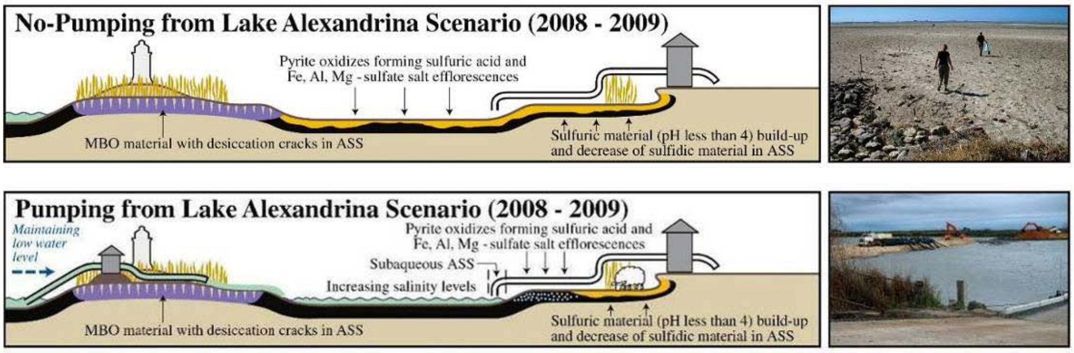


Figure 13-6. Soil-regolith models for Lake Albert showing: (a) the formation of sulfuric materials on the edges of the lake – “no management or no pumping scenario” (upper panel) illustrating the widespread formation of: (i) sulfuric material (pH < *4*) by oxidation of sulfides in sulfidic material, (ii) sulfate-rich salt efflorescences and (iii) deep desiccation cracks; due to continued lowering of water levels under persistent extreme drought conditions during 2008–2009, and (b) management by protecting sulfidic materials from oxidation using partial water inundation - “pumping of water from Lake Alexandrina scenario” (lower panel) where an earthen bank between Lake Albert and Lake Alexandrina was constructed in early 2008, which disconnected Lake Albert from Lake Alexandrina.

Water levels remained low enough to keep the areas disconnected from the main lake water body, and with winter rains, water flowed over and through the sulfuric soils and collected in small depression areas [panel (d) in Figure 13-7]. As a consequence of this, in October 2009 areas of very acidic water (pH 2.5 to 2.8) were found, with soil materials below this water remaining as sulfuric material and not reducing to sulfidic material.

Interestingly, the acid sulfate soil subtype on the edge of the acidic water had a high amount of monosulfidic material (i.e. Hypersulfidic soil with monosulfidic material) while most of the exposed beach areas comprise Sulfuric Soil with abundant highly acidic salt efflorescences (comprising mostly sideronatrite).

Also, note the location of the Hypersulfidic soils that are adjacent to the main lake water bodies and how their position shifts with time due to the fluctuating water conditions [see panels (b) to (d) in Figure 13-7]. This confirms that mapping of these soil subtypes at these soil locations changes and is highly dependent on the water level at the time of field survey. This clearly demonstrates that ASS materials and subtypes vary both spatial and temporally. As our knowledge and understanding improves, soil-regolith models can be prepared to illustrate ASS potential changes in the future.

The ASS maps together with the conceptual soil-regolith toposequence models can be used to predict acid sulfate soil changes and generate “interpretive maps” and data sets to support management and planning. To extract value from these maps, data sets and soil-regolith models, professionals with knowledge and an understanding of the maps and acid sulfate soil process should be consulted. Depending on the situation it is likely that additional information would need to be collected to be incorporated.

While the ASS maps and data produced are static for the time when the field work for such studies are conducted (e.g. Fitzpatrick *et al.* 2009a; 2010a), there is a very good opportunity to extract and provide information from ASS maps, which can be used to support decision making.

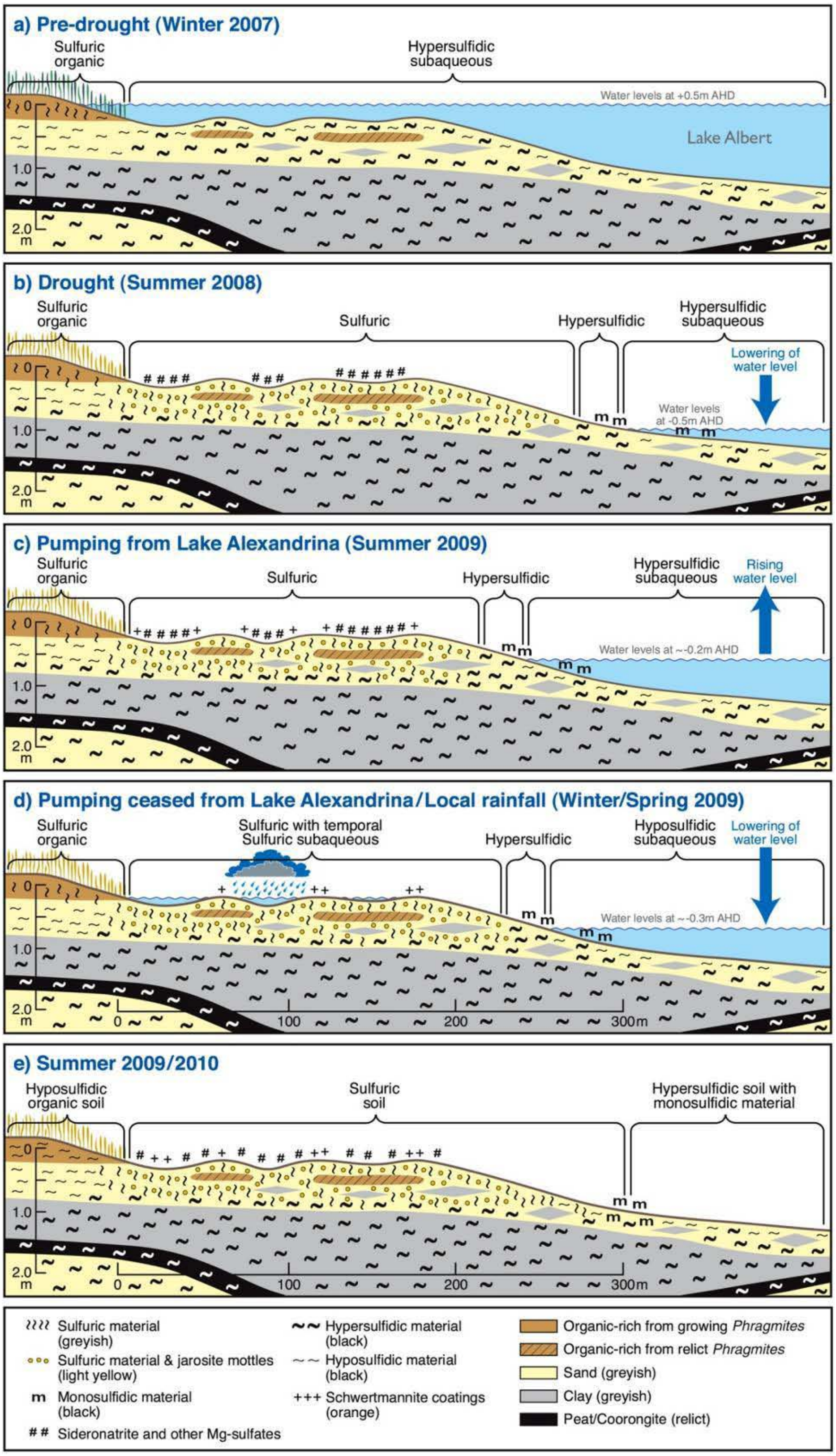


Figure 13-7. Predictive soil-regolith model for an area near Point Campbell (Area C5 in Figure 5-2) that shows changes in the lateral and vertical distribution of ASS material with time due to substantial fluctuating water levels. Sulfuric Soils that formed on the edge of Lake Albert when water levels dropped in 2008 transformed to Hypersulfidic Soils because of rising water levels (profile inundation) after pumping water from Lake Alexandrina during Summer/Autumn 2009**.**

14. Estuaries and River Mouth (Area A in Figure 5-2)

14.1. Background and Environmental Setting

The Coorong is a large body of water that stretches from the Murray Mouth down the south east coast of South Australia for around 110 km. It is up to five kilometres wide and is no deeper than two to three metres (Figure 5-2). The region is an important habitat for a large suite of water birds, some of which come from the Northern hemisphere each summer to rest and forage before flying back to breed. The Coorong once sustained such a wide variety of birdlife that in 1975 Australia became the first signatory of the Ramsar Convention, an international nature conservation treaty. Australia nominated the Coorong as a Wetland of International Importance - not just because of the migratory waders but also because it is an important drought refuge for a large range of Australian waterbirds, including the grey teal duck, black swan, stilts, terns and egrets. One of the conditions of the international agreement is that Australia will endeavour to maintain the integrity of the ecosystem and thereby maintain a quality wetland habitat for those birds. However, the ecosystem and the bird community have changed dramatically in the past few years. Due to lack of freshwater inputs, the Coorong lagoons, particularly the South lagoon have become hypersaline. Several of the key food species for birds have been lost to such a degree that the populations of many migratory and wetland bird species have plummeted compared to levels seen 25 years ago.

The Coorong is also an archaeological site of national importance with shell middens and burial sites throughout the park giving evidence of Aboriginal occupation for more than 5,000 years.

In the past, water that flowed down the Murray River made its way into the Lower Lakes (Alexandrina and Albert) Coorong's. When the lakes were full, the water would flow out through the Murray mouth to sea. Due to a lack of freshwater flows to keep the Murray Mouth open, an emergency dredging operation has been in place during the last two to three years to prevent the closure of the river mouth. This acts as a conservation lifeline for the Coorong Lagoons.

14.2. Acid Sulfate Soil Processes and Hazards

Acid sulfate soils are also present in the River Murray Mouth and Coorong (Area A in Fig. 5), a saline to hypersaline reverse estuary and lagoon system between the Lower Lakes and the Southern Ocean (Fitzpatrick *et al.* 2008h). The sulfidic, hypersulfidic and monosulfidic materials in these ASS have formed in the shallow permanently waterlogged subaqueous soils in the Coorong due to the interaction of seawater with abundant organic material. Although sulfidic materials are formed in the Coorong, the high carbonate mineral content of this sub-coastal environment means that there is excess acid neutralising capacity (ANC) available to counter-act potential acid formation. Notwithstanding this, it is possible that under some conditions localised acidification may occur where there is either not enough ANC, or the carbonate (shells) are coarse grained and therefore not acting to neutralise the acidity effectively.

Malodours that develop on exposure of monosulfidic materials to air have been observed in the Coorong region for a long period of time and are regarded as a natural occurrence. These foul smelling gases are formed when monosulfidic material is present and is a recognised risk factor in ASS environments (Hicks & Fitzpatrick 2008). The presence of thick accumulations of subaqueous monosulfidic material can be readily dispersed through wind and wave action, and may result in rapid de-oxygenation of the water column. It is likely that these soils also contain contaminants e.g. arsenic which may represent a potential hazard if disturbed.

14.3. Management options

Provided the mouth of the River Murray remains open to sea water entry, the Coorong would not be expected to deteriorate significantly as ASS conditions with sulfuric material are unlikely to develop in any significant way. Hence, the management option at this stage is essentially a “No further action or minimum intervention option”. However, it is critical to instigate an Acid Sulfate Soil monitoring program because of the widespread presence of hypersulfidic and monosulfidic materials in these subaqueous Acid Sulfate Soils.

15. Main River Channel and adjacent wetlands for the River Murray section below Blanchetown (Lock 1) (Area E in Figure 5-2)

15.1. Background and Environmental Setting

The biggest impact of the recent extended drought on drying wetlands has been in the stretch of the River Murray below Lock 1 (Area E in Figure 5-2), where most wetlands dried completely during 2007-08 (Fitzpatrick *et al.* 2008f). Two case studies are presented; for Swanport wetland (unmanaged wetland) and Paiwalla wetland (a representative managed wetland because of the installation of a permanent regulator to control water flow in and out of the wetland).

Swanport wetland (Site E1 in Figure 5-2)

Swanport is a wetland located on the south eastern outskirts of the township of Murray Bridge (see Area E in Figure 5-2). The wetland is situated on the east side of the River Murray, 107 river kilometres from the sea. The wetland occurs on crown reserve within the Rural City of Murray Bridge and is a popular place for outdoor education and recreational activities. Swanport has a wetland area of 13.6 ha (3.5 ha of open water) in an overall management unit of 19.4 ha. The wetland consists of one lagoon bisected by an old causeway and is bordered by the River Murray to the west and south and by a large sand hill to the east. The wetland is approximately 0.5 m deep for the majority of its surface area.

The wetland is connected to the River Murray at pool level, however flow and circulation of water through the wetland is impeded by a levee bank that separates it from the River Murray. There are three connections, two upstream of the old causeway (e.g. see photograph in Figure 15-1) and one downstream that facilitate flushing during high river flows.

Paiwalla wetland (Site E4 in Figure 5-2)

Paiwalla wetland is located approximately 14 km northeast of the township of Murray Bridge and 13 km south of the township of Mannum. The wetland is situated on the eastern side of the River Murray, 125 km river kilometres from the sea. The wetland complex comprises two permanent wetland areas separated by a retired dairy irrigation pasture. The wetland complex would naturally have been one continuous wetland however a large levee bank was constructed in 1967, isolating the central irrigation area. From that time until 1998 this area only received water for irrigation purposes as part of a dairy farm enterprise. More recently the central irrigation area has been reclaimed as a wetland and is managed by a group of stakeholders known as the Wetland Habitats Association.

15.2. Acid Sulfate Soil Processes and Hazards

The impacts of ASS in both these wetlands have been very variable depending on the amount of sulfide minerals present and the buffering capacity of the previously sub-aqueous soils (Fitzpatrick *et al.* 2008f).

Swanport wetland explanatory soil-regolith models

A number of distinctive bright yellow oxyhydroxysulfate minerals have been identified in these wetlands as a consequence of sulfide oxidation. In these wetlands, the presence of such key “indicator minerals” has proved particularly useful in the field identification of sulfuric materials (Figure 15-1). In fact, it was these prominent features, which originally led CSIRO to first discover the presence of sulfuric materials in the Swanport wetland near Murray Bridge in June 2007 (Fitzpatrick *et al.* 2008f).

The salt efflorescences sampled from sulfuric materials at Swanport (and also Ukee) wetlands proved to be an assemblage of sulfate-containing minerals (Fitzpatrick *et al.* 2008f). Movement and accumulation of such soluble salts is typical of drained soils under extremely acidic conditions ($pH < 3.5$). In surface soil samples at the Swanport and Ukee wetlands, these salt efflorescences comprised salts with a yellowish (natrojarosite) or golden mineral determined to be the rare mineral metavoltine ($Na_6K_2FeFe_6(SO_4)_{12}O_2.18H_2O$), which formed botryoidal encrustations on the edges of cracks (Figure 15-1) as an alteration product of weathered pyrite. This discovery documents the first occurrence of metavoltine in Australia and possibly the first ever occurrence associated with acid sulfate soils. White crystals of alunogen ($Al_2(SO_4)_3$ $17H_2O$) were also identified, having formed as a result of acidic ($pH < 2.5$), sulfate-bearing solutions that reacted with layer silicates in the soils. These localised solutions were rich in ferrous and ferric iron and also contained dissolved potassium and sodium. Metavoltine and alunogen are presumed to be the last minerals to form in areas of intense evaporation. The sulfuric material, which also contained hexahydrite and gypsum, developed after drainage of the soils as watertable levels dropped below 40 cm in June 2007 to below 90 cm in November 2007 (Figure 15-1).

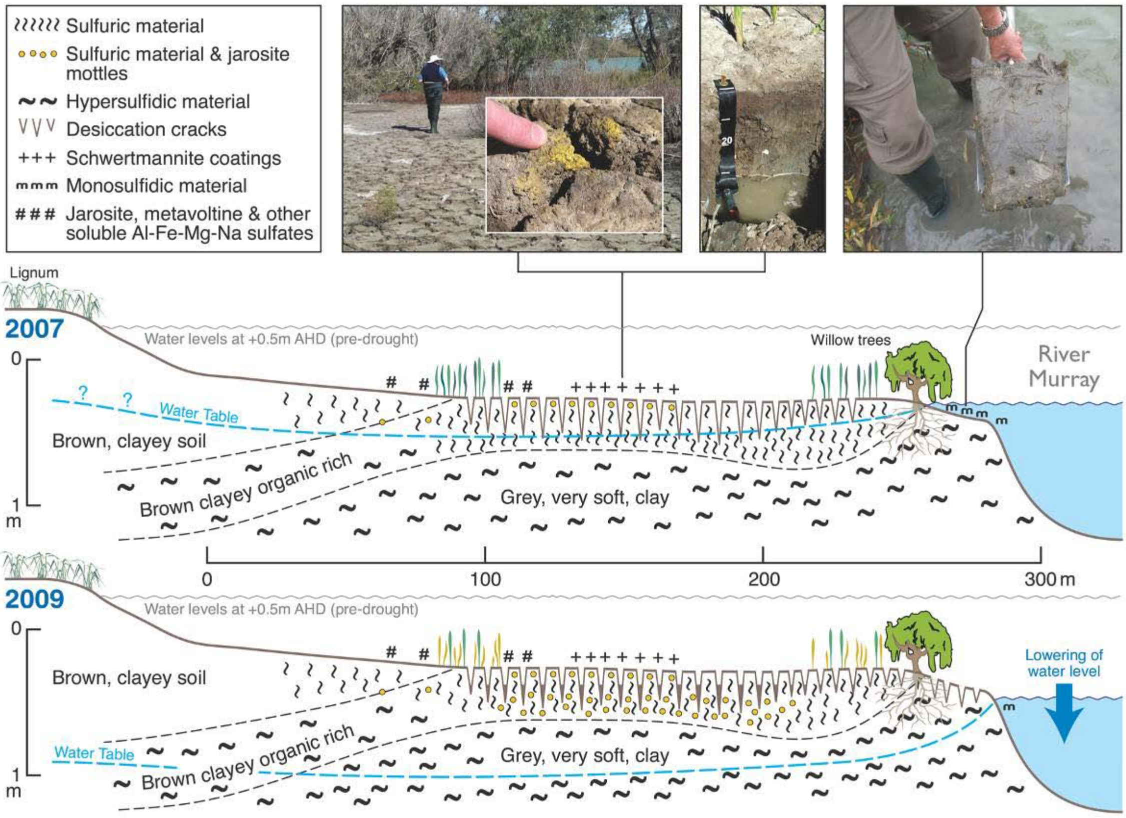


Figure 15-1. Swanport wetland: descriptive soil-regolith models for this wetland (site E1 in Figure 5-2) showing the distribution of Acid Sulfate Soil with sulfuric material in drained wetlands adjacent to the River Murray (left), which shows extensive cracking and accumulation of jarosite mottles (amounts increase in depth with lowering of water levels e.g.in 2009), scale-like, bright golden yellow crystals of metavoltine ($K_2Na_6Fe^{2+}Fe^{3+}{}_6\,(SO_4)_{12}O_2\ 18H_2O$) and white crystals of alunogen (modified from Fitzpatrick *et al.* 2008f).

Paiwalla wetland explanatory soil-regolith models

The central irrigation area is approximately 60 ha area and due to significant earth works has formed a diversity of both shallow and deep environments including islands and a causeway, which separate the reclaimed wetland into two distinct areas (Figure 15-2). There are two remnant water control structures that were used for irrigation but are now used to facilitate management of the wetland.

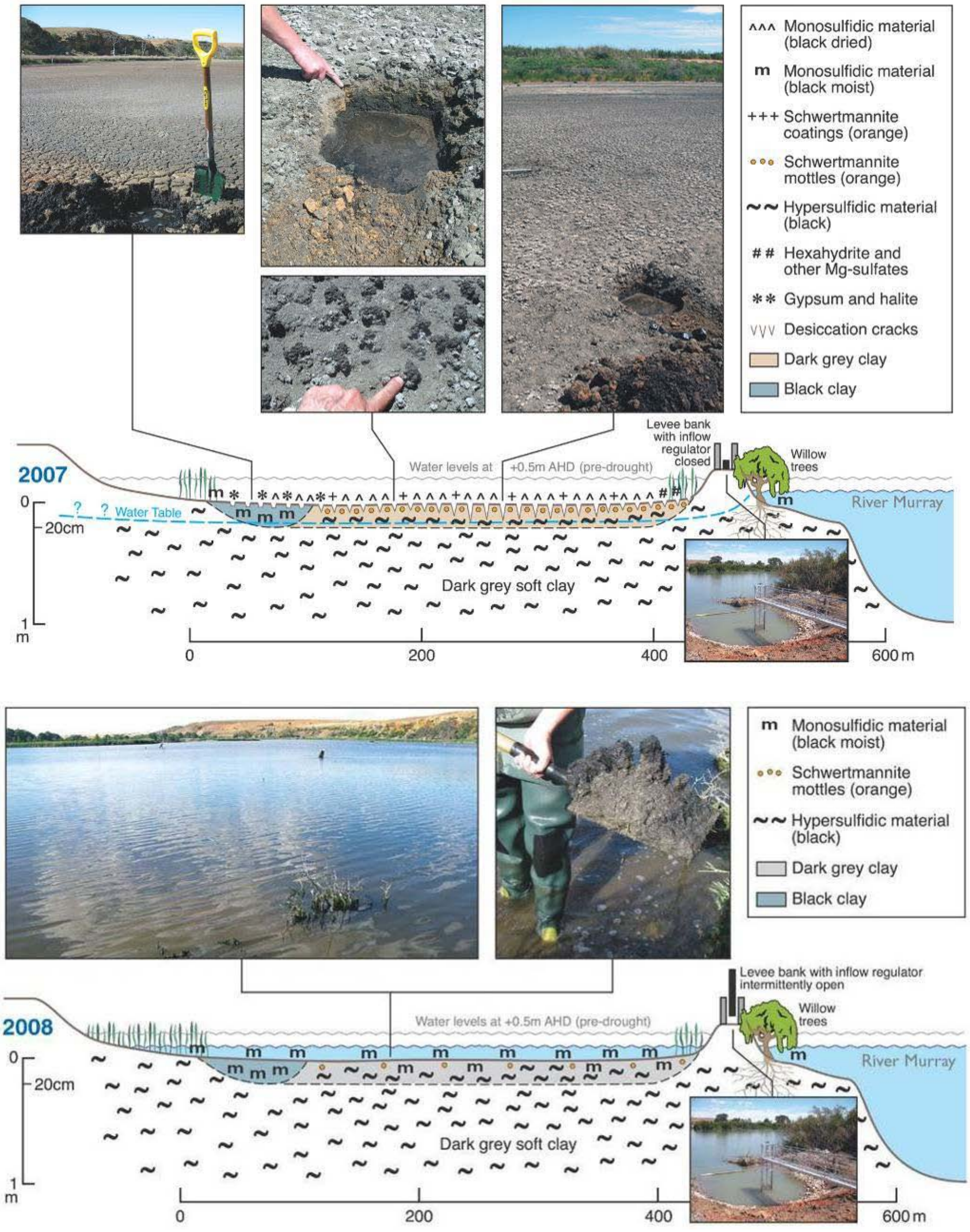


Figure 15-2. Paiwalla wetland: soil-regolith toposequence models for the managed Paiwalla wetland (Site E4 in Figure 5-2) showing: (i) dried wetland (top diagram) following disconnection from the River Murray by closing the inflow regulator in **2007** to aid water savings from reduced evaporation in the extreme drought conditions, and (ii) after reflooding (bottom diagram) by opening the inflow regulator in **2008**. With the receding water levels in 2007 due to the extreme drought conditions the previously hypersulfidic subaqueous soils became exposed, dried and reacted with oxygen to form partly acidic soils (~pH 5) that have cracks and columnar structure with prominent brownish-orange coatings of the iron oxyhydroxysulfate mineral schwertmannite (good mineral indicator of the presence of localised areas with sulfuric material pH < *4*, which has formed during the drying phase). In 2008, the wetland was reflooded and within three months schwertmannite transformed to black monosulfide and sulfide minerals (see black material on shovel).

15.3. Management options

Various management scenarios for the Swanport wetland are incorporated into the predictive soil-regolith models

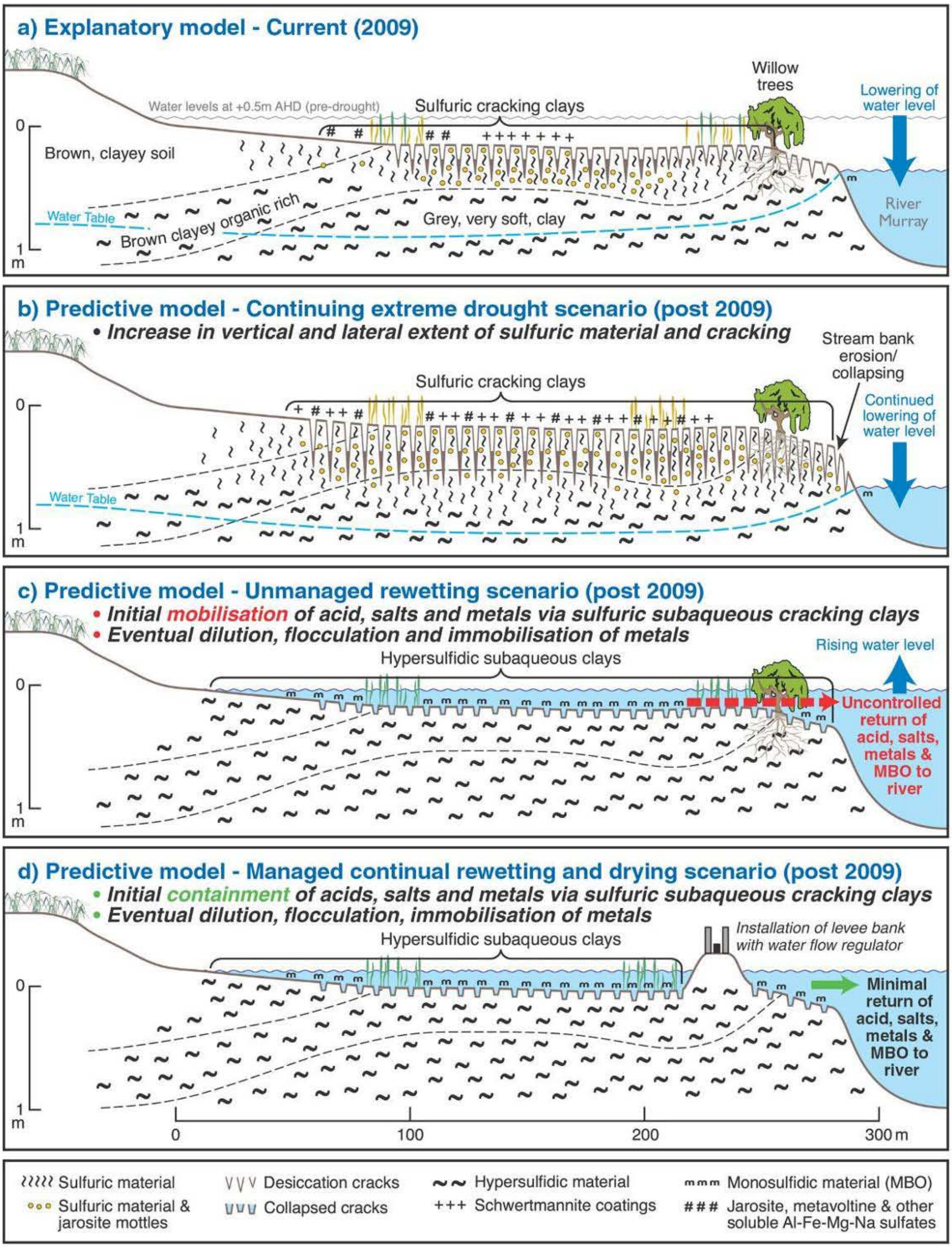


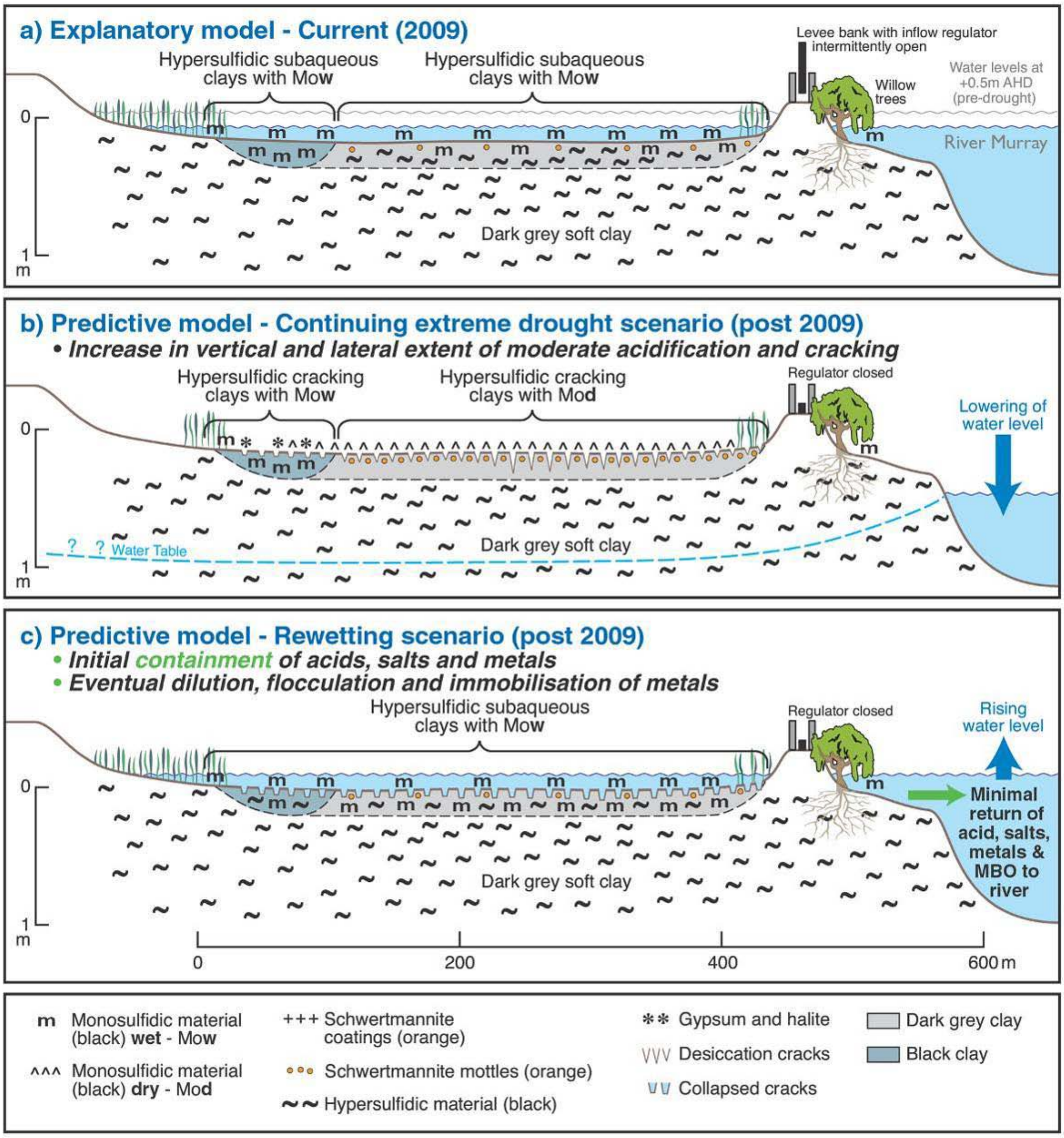
Figure 15-3. Swanport wetland: Descriptive (for 2009) and 3 predictive soil-regolith models for the wetland with no current levee bank structure (i.e. in 2009; Area E1 in Figure 5-2) – illustrating 3 possible management scenarios.

The management scenarios presented here are based on the following comparisons: Panels (a) to (d) in Figure 15-3, which shows the 2009 status and 3 predictive management scenarios. (a) Explanatory soil-regolith model of the 2009 status (also Figure 15-1), (b) No further action or minimum intervention scenario illustrating a predictive model for continuing extreme drought (post 2009) – showing an increase in vertical and lateral extent of sulfuric material and cracking, (c) Predictive model illustrating an “Unmanaged rewetting scenario (post 2009)” – showing uncontrolled mobilisation of acids, salts, metals and monosulfidic material to the river; and (d) Predictive model for a “Managed or controlled continual rewetting and drying scenario (post 2009) – showing minimal mobilisation of acids, salts, metals and monosulfidic material to the river.

To summarise, in order to address the fate of identified sulfuric material in the Swanport wetland, the management option shown in the lower panel (d) in Figure 15-3 involved the construction of a water flow regulator at the river inflow of the Swanport wetland (to control in- and out-flows of water). Under this management scenario, sulfuric materials and metal salts have been contained in the wetland, thus allowing targeted and controlled management to occur to reinstate and maintain wetland quality. This management option enables the sulfate-rich salt efflorescences to dissolve and become diluted and once appropriate wetland and redox conditions resume, sulfidic materials will reform, while metals bioaccumulate, or accumulate in the subaqueous soils. This management option also reduces the risk of saline, nutrient-laden and acidic-metal-rich water draining back into the river as river levels change. In contrast, under an unmanaged wetland or river bank scenario (panel (b) in Figure 15-3) there is little control over the mobilisation of sulfuric materials and eventual fate of sulfate, monosulfidic materials and salts. The fates of these are controlled by natural – but moderated – river water flows and floods, although the volume of water in the river channel would provide considerable dilution to such materials.

Paiwalla wetland predictive soil-regolith models, incorporating management options (i.e. with proven containment of ASS problem achieved by retaining acidity and monosulfidic material within the wetland)

In contrast to the “unmanaged” Swanport wetland, the successful management of sulfuric material in the Paiwalla wetland has involved careful maintenance of water levels by controlling in- and out-flows - see management scenarios (b) and (c) in Figure 15-4. Under this management scenario, sulfuric materials and metal salts have been contained in the Paiwalla wetland, thus allowing controlled management to occur to maintain wetland quality. This management option has enabled the sulfate-rich salt efflorescences to dissolve and become diluted, and once appropriate wetland/redox conditions have formed hypersulfidic materials have been able to reform and enable metals to bioaccumulate, or accumulate in the hypersulfidic subaqueous soils. This strategy has also reduced the risk of saline, nutrient-laden and acidic-metal-rich water draining back into the river as river levels have dropped.


a) Explanatory model - Current (2009)

b) Predictive model - Continuing extreme drought scenario (post 2009)

- *Increase in vertical and lateral extent of moderate acidification and cracking*

c) Predictive model - Rewetting scenario (post 2009)

- *Initial containment of acids, salts and metals*
- *Eventual dilution, flocculation and immobilisation of metals*

Figure 15-4. Paiwalla wetland: (a) current (2009) descriptive or explanatory soil-regolith model and (b) to (c) predictive soil-regolith models illustrating 2 possible management scenarios for the managed Paiwalla wetland with a current levee bank and permanent water flow regulator structure (i.e. in 2009; Area E4 in Figure 5-2).

In summary, the installation of the water flow regulator in the Paiwalla wetland has enabled the mostly hypersulfidic soil with hypersulfidic (locally acidic mottles) and monosulfidic materials soils to be managed satisfactorily (Figure 15-2). Controlled ponding in the wetland during the rewetting of re-flooding of these materials by the permanent flow regulator has minimised potential mobilisation and the return of acids, salts, metals and monosulfidic material to the river [see Figure 15-2 showing predictive soil-regolith models that illustrate the current 2009 status and 2 post 2009 predictive scenarios, which includes: (i) continuation of drought conditions and (ii) rewetting or re-flooding scenario].

16. Main River Channel and adjacent wetlands for River Murray section above Blanchetown (Area F in Figure 5-2)

A wide range of representative case studies were selected from the River Murray channel system above Blanchetown. However, only The Banrock Station wetland (Site F1 in Figure 5-2) and Nelwart Lagoon, near Renmark will be shown in detail, whilst the following three studies have been included for completeness: (i) Loveday Disposal Evaporation Basin (Site F2 in Figure 5-2), (ii) The Noora Disposal Basin, east of Loxton, Murray (Site F3 in Figure 5-2) and (iii) the Ground water salt interception scheme near Bookpurnong (Site F6 in Figure 5-2).

16.1. Background and Environmental Settings

Banrock Station (Site F1 in Figure 5-2)

Banrock Station wetland is located in the lower Murray River system, about 15 kilometres west of Barmera in South Australia (Site F1 in Figure 5-2). This Ramsar-listed wetland effectively by-passes Lock 3 (Figure 3-2) and consists of a single, elongate lagoon covering some 120 hectares at pool level (+8.6 m AHD). A second, eastern lagoon (130 ha) is connected to the main Banrock lagoon but is usually dry at pool level (Figure 16-1; Thomas *et al.* 2011) becoming flooded when water levels are above 9.2 m AHD. The wetland is connected to the River by one meandering inlet creek, and one outlet creek (with flow control structures on each creek installed in 1993) and is situated in a river red gum floodplain that covers an area of about 520 ha.

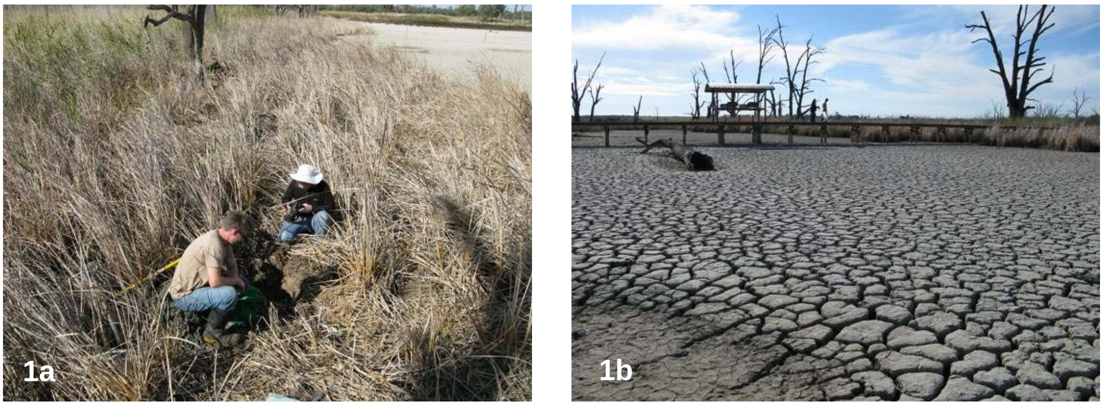


Figure 16-1. Photographs of areas in the Banrock Ramsar wetland (Site F1 in Figure 5-2) near the inlet creek in May 2008 showing: (1a) Sampling a sandy, sulfuric soil profile (RBA1) at the medium to high water mark in *Typha* and *Phragmites* reeds and (1b) Dry, cracked, sulfidic clays in the near surface soils in the bed of Banrock wetland. (From Thomas *et al.* 2011).

Nelwart Lagoon (Site F4 in Figure 5-2)

Nelwart Lagoon is situated close to Renmark in the South Australian Riverland. The 21 hectare wetland dried out following disconnection from the River Murray, after installing a control structure, in October 2007 as an aid to water savings from reduced evaporation. CSIRO completed an acid sulfate soil assessment and monitoring survey of eight wetlands above Lock 1 from November 2007 to November 2008 (Shand *et al.* 2009, 2010), which included Nelwart Lagoon (Figure 16-2 to Figure 16-4), for the South Australian Murray Darling Basin Natural Resources Management Board. Soil and water data were used to identify a number of potential hazards, including soil and water acidification (Figure 16-2 to Figure 16-4) and metal mobilisation.

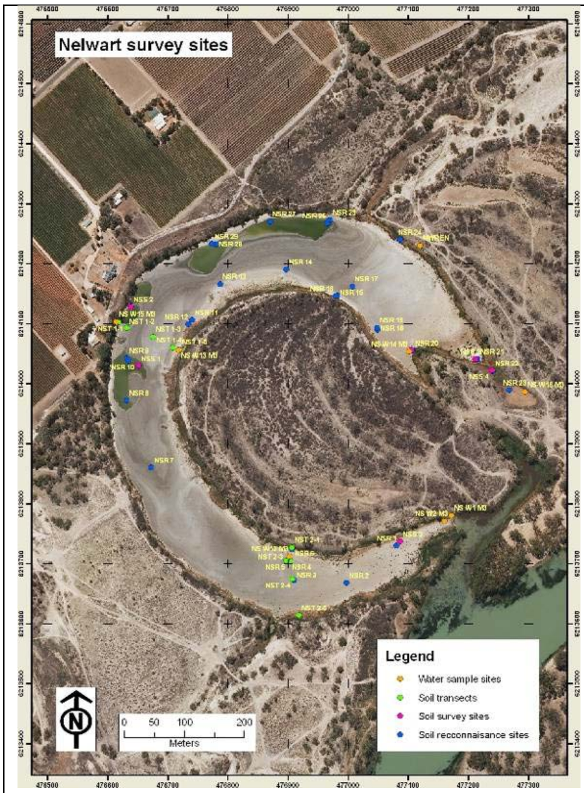


Figure 16-2. Nelwart Lagoon showing (i) soil and water sampling sites and (ii) areas with dried strongly acidic (pH < 4) Acid Sulfate soils and remnant pools with circumneutral pH's and (source CSIRO).

Figure 16-3. Nelwart Lagoon in November 2008 showing remnant pool with dead carp. T (30.2 ^{o}C), DO (15 mg l^{-1}) and SEC (25433 µS cm^{-1}) were high at this time, and pH was circumneutral (7.58).

Figure 16-4. June 2009 when waters were acidic (pH <4).

The wetland was refilled in March 2009 and natural remediation and impacts were assessed by monitoring soils and water intensively during the refill period followed by monthly sampling.

16.2. Acid Sulfate Soil Processes and Hazards

Banrock wetland predictive soil-regolith model (Site F1 in Figure 5-2)

The main Banrock lagoon was permanently flooded from 1925, when Lock 3 was constructed (Figure 5-2 and Figure 3-2), to 1993 when partial drying phases were introduced as a wetland management tool. From 1993 to June 2006 the wetland has been partially dried each winter (to introduce semi-natural wetting-drying cycles). The wetland almost completely dried from 2007 to June 2008 (18 months; Figure 16-1). The wetland was re-flooded in June 2008 and a drying cycle introduced in October 2008. To illustrate these sequential changes as well as the historical/geological changes, we have constructed the following series of predictive soil-regolith models across the Banrock wetland (Fitzpatrick *et al.* 2009b):

(i) Before 1880s (approximately 5,500 BC to 1880s period).
(ii) From the 1880s to the 1930s when the river and wetland systems were first used for navigation and irrigation.
(iii) From the 1925 to 1993 when the river and wetland systems were first managed using locks.

(iv) From 1993 to 2006 when partial drying cycles and substantial rewetting cycles occurred because of the installation of sluice gates.

(v) From January 2007 to June 2008 (18 months) when unprecedented drying took place.

(vi) From June 2007 to October 2008 (5 months) when complete rewetting took place.

(i) Before the 1880s (5,500 BC to 1880s). The Banrock wetland cycled between natural wetting and flushing, and partial drying conditions in response to seasonal and climatic cycles occurring in the upper MDB (Figure 16-5).

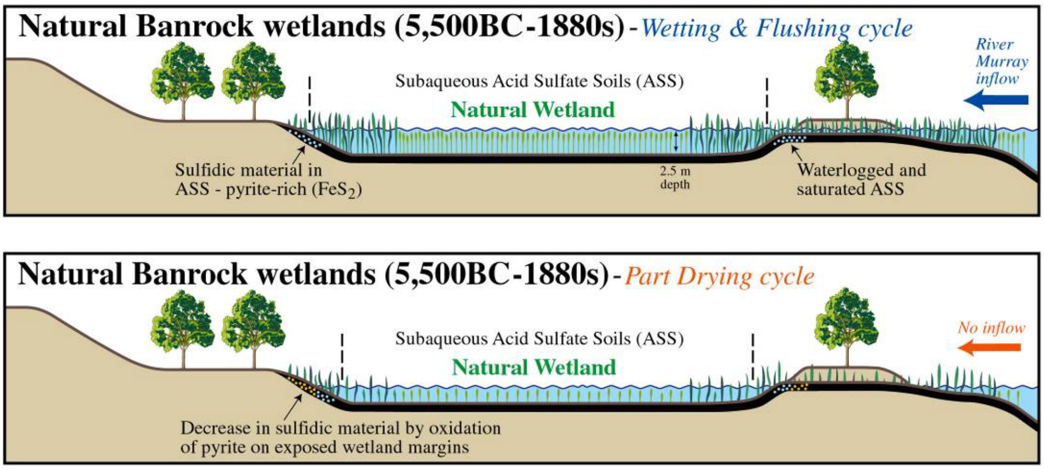


Figure 16-5. Predictive soil-regolith models for Banrock wetland illustrating natural wetting and flushing (upper panel), and partial drying (lower panel) cycle conditions during pre-colonial times (5,000 BC - 1880s) (From Fitzpatrick *et al.* 2009b).

Waters received by the wetlands were transferred via channels, overland flow, and by infiltration. The wetlands accumulated sulfidic materials from sulfate contained in surface flows and groundwaters. However, during dry periods such as droughts (Figure 16-5 - lower panel) when river flows were lower, the wetland dried, causing oxidation of sulfidic materials, especially on the dry margins. Pyrite in the sulfidic material was oxidised with likely formation of sulfuric acid and possibly formation of sulfuric materials. During wetter times and in flood periods, the acidic material was submerged, with dilution and/or neutralisation of acidity and the reformation of sulfidic material. The build-up of sulfidic materials in the Banrock wetland was regularly kept in check by oxidation and removal by scouring floods.

(ii) The 1880s to 1930s period. European settlers moderated the flows of the River Murray by the installation of various irrigation network systems (Figure 16-9). During this period the wetland was "managed for flood irrigation" (citrus and dairy).

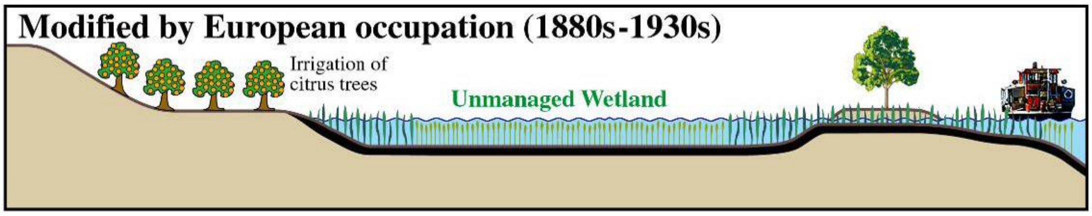


Figure 16-6. Predictive soil-regolith model for the Banrock wetlands; illustrating modification of water flows by European occupation (1880s - 1930s). (From Fitzpatrick *et al.* 2009b).

(iii) The 1925 to 1993 period. The river and wetland systems were managed using locks (see Figure 3-2). The installation of locks enabled considerable build-up of sulfidic and monosulfide material in the wetland (Figure 16-4).

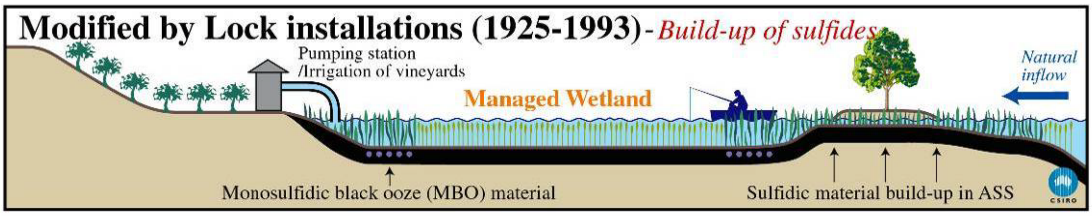


Figure 16-7. Predictive soil-regolith model for the Banrock wetland illustrating modification of water flows by lock installations causing the build up of sulfides under continued subaqueous ASS conditions from 1925-1993. (From Fitzpatrick *et al.* 2009b).

(iv) The 1993 to 2006 period. Partial drying cycles and substantial rewetting cycles occurred following the installation of flow control structures (sluice gates) (Figure 16-8). During dry periods (Figure 16-8- top panel), the wetland partly dried in places, likely causing oxidation of sulfidic materials, especially on the margins of the wetland.

The accumulated pyrite in the thick sulfidic material is likely to have partly oxidised with possibly formation of sulfuric materials, similar to the natural system described in Figure 16-1. During rewetting cycles, the acidic material would have become submerged, with dilution/neutralisation of acidity and reformation of sulfidic material. Hence, the build-up of sulfidic material in the wetland was controlled by regular periods of oxidation. In 2006, the pump used for irrigation purposes was removed because of the Ramsar listing of the wetland (in Figure 16-8 the old irrigation pump has been removed and a new pump installed for pumping river water into the wetland).

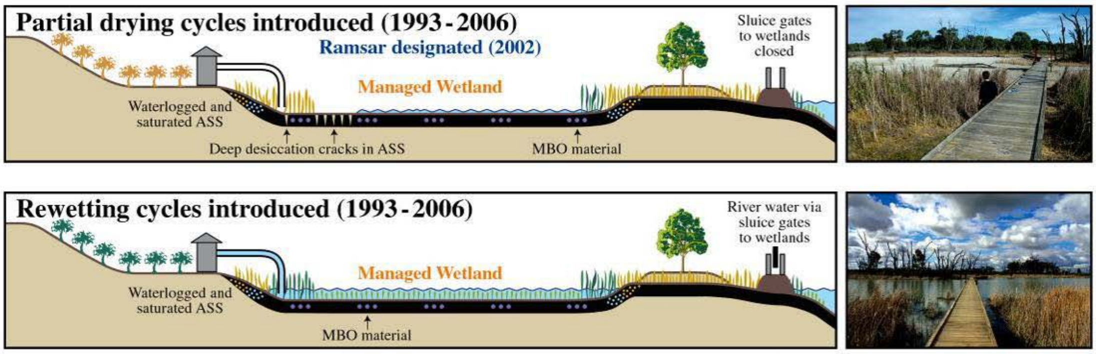


Figure 16-8. Predictive soil-regolith models for the Banrock wetland illustrating the installation of sluice gates to manage the partial drying cycle (upper panel) and the rewetting/ flushing cycle (lower panel) during 1993 to 2006. The Banrock wetland was designated a Ramsar site in 2002.

(v) The 2007 to June 2008 period (18 months). When drying of the upper soil in whole wetland took place (Figure 16-9), the wetland effectively became hydraulically disconnected from the river channel.

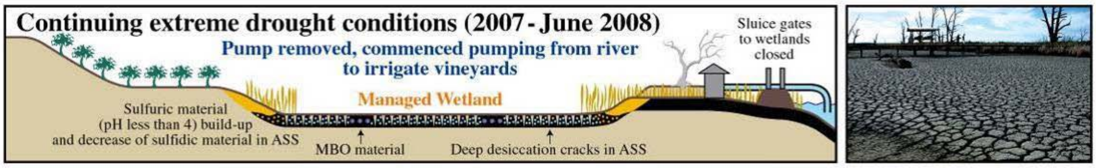


Figure 16-9. Predictive soil-regolith model for the Banrock wetland illustrating the formation of: (i) sulfuric material (pH < *4*) by oxidation of sulfides in sulfidic material on the edges of the wetland, (ii) sulfate-rich salt efflorescences and (iii) deep desiccation cracks; due to continued lowering of water levels under extreme drought conditions during 2007 – 2008.

During this period, subaqueous ASS transformed to waterlogged ASS and eventually to dried ASS. This resulted in the formation of sulfuric material to depths up to 50 cm and deepening of desiccation cracks (> 50 cm), especially in areas that were organic-rich (> 10 % organic carbon) and clayey (> 35 % clay) (Thomas *et al.* 2011). Under such low pH conditions, acid dissolution of the layer silicate soil minerals is likely to have caused the release of Fe, Al, Mg, Si (and other elements) and the formation of sulfate-rich salt efflorescences in and near soil surfaces (Figure 16-9). The continued drying of the wetlands caused further desiccation, and the precipitation of sulfate-rich salt efflorescences in desiccation cracks and on the sandy edges of the wetland. Areas with monosulfides continued to dry out, causing desiccation cracks to develop, especially in the fine textured material.

(vi) From June 2007 to October 2008 period (5 months). When complete rewetting took place by pumping water into the wetland (Figure 16-10), sulfuric, sulfidic and monosulfide materials, including sulfate-rich salt efflorescences became diluted and mobilised. Once appropriate wetland and redox conditions resume, sulfidic materials are likely to reform, while metal salts bioaccumulate, or accumulate in sediments. Under this management scenario, there is control of the distribution and eventual fate of sulfates, monosulfides and salts.

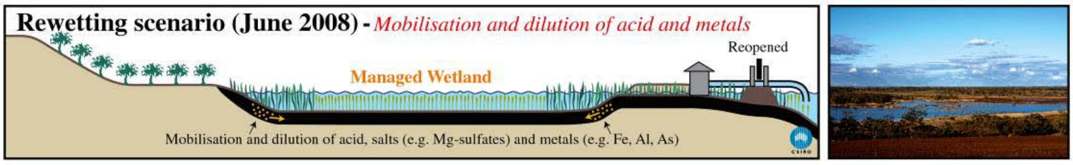


Figure 16-10. Predictive soil-regolith model for the Banrock wetland showing the complete re-wetting of the whole wetland in June 2008 with inundation of sulfuric materials, which occurred on the edges of the wetland. (From Fitzpatrick *et al.* 2009b).

Nelwart Lagoon (Site F4 in Figure 5-2)

The wetland soils initially comprised hypersulfidic clay-rich soils with hypersulfidic subaqueous sandy soils around the margins. A number of groundwater springs were identified at the edges and within the wetland during the drying process. These springs provide sulfur as well as alkalinity to the wetland system, and monosulfidic materials were a typical characteristic at the discharge points.

As the wetland dried, sulfuric materials gradually became dominant over most of the wetland, with a number of sulfate-rich efflorescences forming on surface layers. These included natrojarosite, sideronatrite and tamarugite. A number of Mg and Na sulfate minerals were also noted, particularly where groundwater discharges were present. Where the buffering capacity of the soils was low, the soil pH generally showed a decrease in surface layers as drying progressed (Figure 16-2; Figure 16-11).

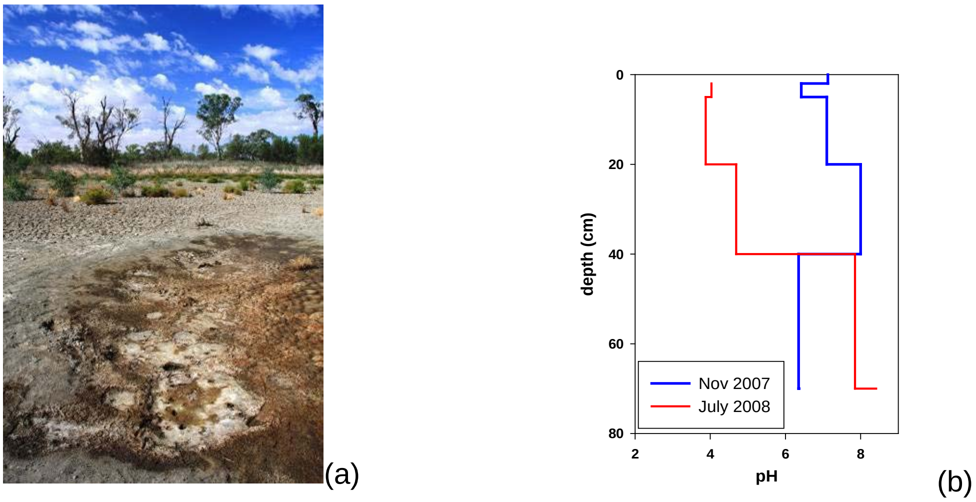


Figure 16-11. Nelwart Lagoon (Site F4 in Figure 5-2): (a) groundwater discharge area showing salt efflorescences; (b) plot showing decrease of pH is surface soil layers during drying of the wetland.

Reflooding of the wetland by the removal of upper sections of the flow control structure in the southern part of the wetland took place in late March 2009 (Figure 16-4). CSIRO (i) completed a baseline map of Acid Sulfate Soils and groundwater springs prior to reflooding, (ii) monitored soil and water quality on reflooding the wetland, (iii) assessed trace metal mobilisation and (iv) determined the timescales over which natural remediation (e.g. production of alkalinity by sulfate reduction) is taking place. The pH of water along the filling front was initially moderately acidic, but infiltration into the soils combined with dilution kept the pH moderately high for a number of weeks (Figure 16-12). Sampling in June 2009 showed that significant transport of acidity and a number of trace elements (e.g. Co, Ni) had occurred. The pH of the surface water remained low and was moderately stable up to December 2009 when it was topped up (Figure 16-12).

Natural wetland soil processes, such as sulfate reduction, were found to be important processes in Nelwart Lagoon, leading to increased soil water pH and neutralisation of stored acidity. The increase in soil pH in December 2009 was considered important as it is thought that this allowed bacteria to thrive and generate alkalinity by reduction reactions.

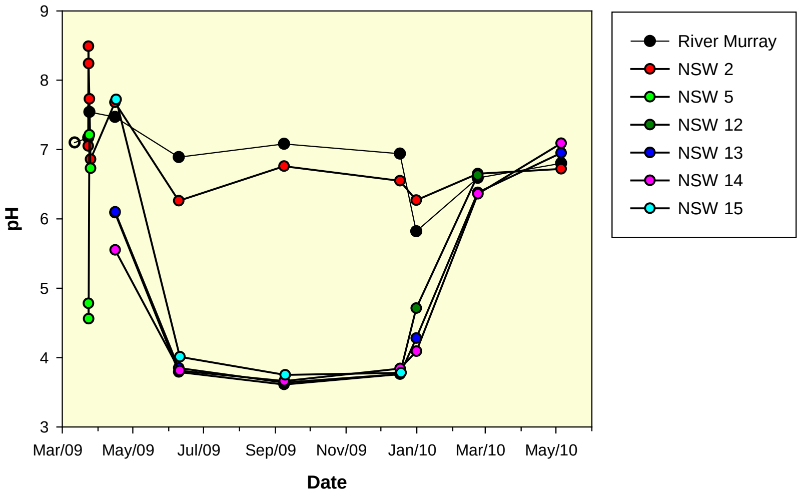


Figure 16-12. pH variations in surface waters at monitored sites in Nelwart Lagoon (modified from Shand *et al.* 2010).

Loveday Disposal Evaporation Basin (Site F2 in Figure 5-2)

The presence of sulfidic soils in a number of wetlands historically used as evaporation basins was studied by Lamontagne *et al.* (2004 & 2006), who concluded that a large number had sufficient alkalinity to neutralise acid generated by the oxidation of pyrite (Figure 16-13). Many of these saline disposal basins contained monosulfidic materials, and although acid generation from sulfuric materials may not be a major issue, other problems such as deoxygenation of surface waters, metal mobilisation and foul smelling odours remain an issue (Hicks & Fitzpatrick 2008).

Figure 16-13. Loveday saline disposal basin, adjacent to the River Murray (Site F2 in Figure 5-2), showing large irreversible trans-horizon polygonal cracks with very coarse columnar ped structures; the result of desiccation and dewatering of clayey subaqueous soils during wetting and drying cycles. It was originally a natural wetland prior being used as a salt disposal basin. Surfaces of peds are coated with thin salt encrustations and efflorescences dominated by gypsum, halite, Mg-calcite & Sr-rich aragonite. There are pyrite framboids within peds despite being exposed to the atmosphere for several months.

Detailed studies by Wallace *et al.* (2008a) of the Loveday Disposal Basin have shown that sulfidic soils are mainly developed in the top 40 cm, principally associated with organic-rich sulfidic wetland clays (Figure 16-13). Wallace *et al.* (2008b) showed that wetting and drying cycles may lead to areas where the acid generation potential is greater than stored alkalinity due to the transport of alkalinity in the soils during evaporation and concentration of carbonate at the soil surface. Although alkalinity was generally sufficient to mitigate acidification risks at the scale of the wetland, local areas were found where net acidity was generated and jarosite was present.

Noora Disposal Basin (Site F3 in Figure 5-2)

The Noora Disposal Basin, east of Loxton, is used as a disposal site for saline waters from salt interception schemes designed to minimise salinity impacts on the River Murray (Site F3 in Figure 5-2). Monosulfides containing up 0.6 % S_{CR} were present in some parts of the basin (Figure 16-14) and were inundated with saline water (similar EC to seawater). However, the acid neutralising capacity (ANC) in the monosulfides was very high (up to 50% ANC as $CaCO_3$), more than sufficient to neutralise potential stored acidity (Shand *et al.* 2008c).

Figure 16-14. Noora disposal basin showing black monosulfidic material beneath a very thin algae-rich oxidised layer. (From Shand *et al.* 2008c).

Ground water salt interception scheme (Site F6 in Figure 5-2)

The clogging of bore pumps and screens by an amorphous Al-hydroxysulfate in a salt interception scheme near Bookpurnong was attributed to the oxidation of pyrite present in the Lower Loxton Sands aquifer of Pliocene age (Shand *et al.* 2006, 2008a). The Loxton Sands comprise a sequence of lower and upper shoreface, beach, estuarine, dune and back-barrier lagoonal sediments. The clogging occurred some time after pumping and the groundwater pH values were slightly acidic to neutral, where Al solubility is theoretically very low.

The presence of large amounts of pyrite was confirmed using SEM. Figure 16-15 illustrates that both framboidal and octahedral pyrite were present. The textures of the sediment and pyrite morphology are very similar to present day coastal ASS, and Shand *et al.* (2006, 2008a) postulated that the pyrite, which was present in fine-grained facies may have formed as part of an ancient coastal ASS.

In addition to pyrite, secondary sulfate minerals of natrojarosite-natroalunite were abundant (Figure 16-16), indicating acidic conditions. The sediments were recovered from cores which had been stored and the hydroxysulfate minerals are likely to have formed by pyrite oxidation and dissolution of aluminosilicate minerals (clays and feldspar) during slow drying of the core material. Their presence indicates that there was insufficient buffering to neutralise the acidity generated during pyrite oxidation.

A conceptual groundwater model (Figure 16-16) was developed whereby cavitation and lowering of the water table towards the redox boundary led to the introduction of oxygen and induced acid production and Al mobilisation close to the redox boundary. The mixing of this locally-derived acidic groundwater with groundwater of circumneutral pH from above and below induced rapid Al precipitation on borehole screens, and in particular at the pump inlet. This model explains the delay in clogging as well as the conflicting hydrogeochemistry (high Al concentrations at circumneutral pH).

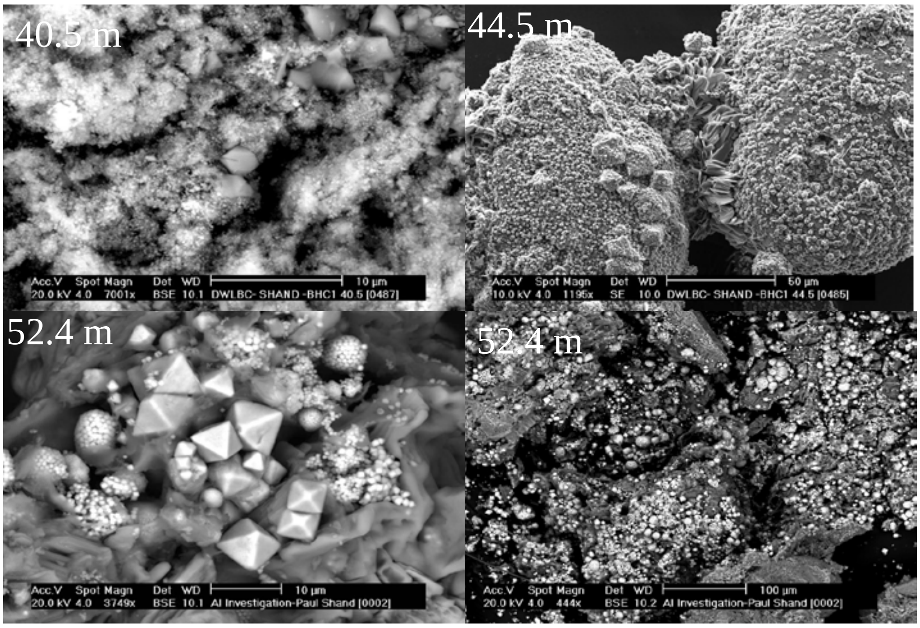


Figure 16-15. SEM images of samples from Loxton Sands (samples depths shown in metres). 40.5 m: Fe oxyhydroxide coating of sand grain with euhedral to subhedral crystals of alunite-jarosite; 44.5 m: two sand grains coated with abundant euhedral (cuboid and octahedra) pyrite and bridging laths of hydroxysulfate mineral (natrojarosite); 52.4 m (left image) framboidal and octahedral pyrite on a base of natrojarosite-natroalunite; (right image) abundant coatings of framboidal pyrite (bright areas). (From Shand *et al.* 2006, 2008a)

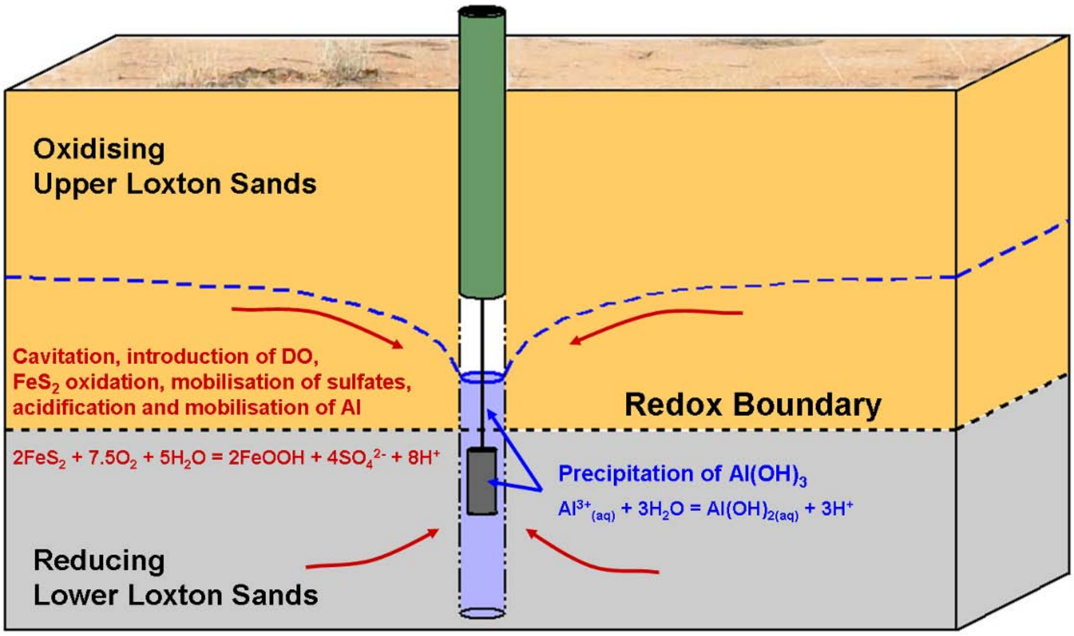


Figure 16-16. Conceptual soil-regolith model showing the development of a cone of depression in water level during extended pumping. Oxygenated water is introduced below the redox boundary allowing pyrite oxidation, the production of acidity and dissolution of aluminosilicate minerals (e.g. clays). Mixing of this water in the high pH environment of the bore column causes rapid precipitation of Al-oxyhydroxide on screens and in the pump. (From Shand *et al.* 2006, 2008a).

16.3. Management options

Banrock wetland

Continued management of the Banrock “managed Ramsar wetland” will involve the careful maintenance of water levels by controlling in-flows and out-flows. Under this management scenario, sulfuric materials and metal salts will be contained in the wetland and flushed at appropriate times, thus allowing targeted and controlled management to occur to re-instigate and maintain wetland quality.

Nelwart Lagoon

Following reflooding of the wetland, initial decreases in pH occurred, but increased rapidly due to further alkalinity inputs and dilution with river water. Once the wetland had saturated, a decrease in pH and a concomitant increase in many trace metals occurred due to mineral dissolution, mixing and an upward diffusive flux from the underlying acidic soils. The wetland was monitored for a number of months (Shand *et al.* 2010) during which time the surface water acidity remained stable at pH < 4, despite some recovery of the underlying soils.

Soil pH increased significantly between March and September (Figure 16-12) showing that acid neutralisation in the soil column was taking place. A good indicator of such processes is the development of monosuolfidic material or black sulfidic oozes (Figure 16-17), which were particularly well developed close to the wetland inlet and in association with previously mapped groundwater discharges. Although the signs were positive that natural remediation was taking place, the duration of the recovery of wetlands containing identified acid sulfate soil hazards appear to be of the order of several months to years. Specific recovery periods, however, will be related to the amount of released acidity (related to time of drying) and refilling scenarios.

The following two management options are currently being investigated and favoured, as indicated in **Table 6-7**.

- Prevent oxidation of hypersulfidic material and/or reverse oxidation of sulfuric material.
- Contain and treat acid drainage to minimise risk of significant offsite impacts.

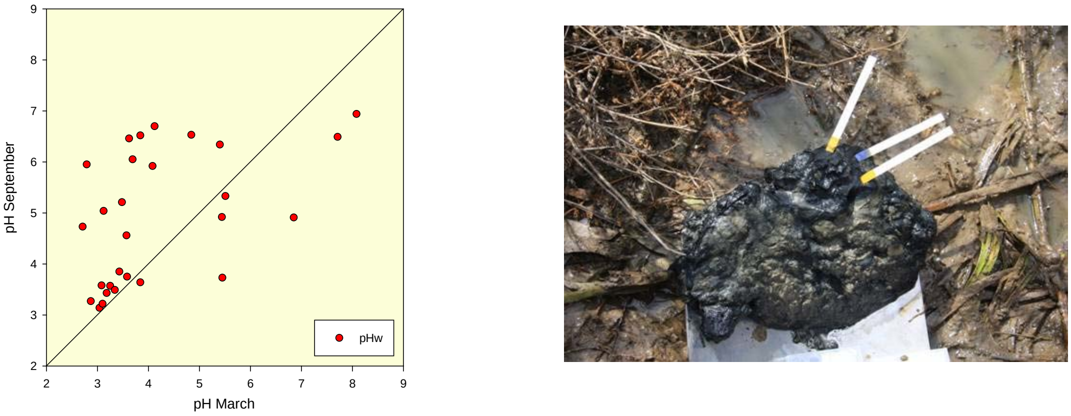


Figure 16-17. Left: Changes in pH between soils sampled prior to (March), and post refilling (September). Samples plotting above the 1:1 line show that pH has increased, which for some soils was more than 2 pH units; Right: Monosulfidic material (Black sulfidic ooze) with neutral pH, indicating recovery of soils due to natural soil processes.

The wetland was topped up using river water in December 2009 to introduce water lost by evaporation and assess the impact of further alkalinity addition. Although the alkalinity was largely consumed by reaction with the wetland acidic waters, the pH after some weeks increased to values approaching pH 7 (Figure 16-12). This was interpreted as being due to alkalinity generation caused by sulfate reduction, which was kick started by an increase in pH in the surface soils of the wetland.

Loveday Disposal Evaporation Basin

The following management option is recommended as indicated in Table 6-7.

- Minimise oxidation rate and isolate higher risk materials from exposure.

Noora Disposal Basin

The following management option is recommended as indicated in Table 6-7.

- No further action or minimum intervention option.

Ground water salt interception scheme

The following management option is recommended as indicated in Table 6-7.

- No further action or minimum intervention option.

17. Seepages overlying mineralized zones in the Mt Lofty Ranges (Area G in Figure 5-2)

These case studies focus on the Eastern Mt Lofty Ranges, near Mt Torrens (Area G in Figure 5-2). The area has been the subject of a long program of research by scientists in CSIRO (e.g. Fitzpatrick *et al.* 1996) and CRC LEME, associated with mineral exploration research in the region (see references in Skwarnecki and Fitzpatrick 2003a,b). The landscape of the region is described as undulating low hills, with typical altitudes of 400 to 500 m. Inland ASS can occur at all altitudes and slope aspects. The Eastern Mt Lofty Ranges has a Mediterranean climate with hot dry summers and wet winters. Average rainfall varies within the region from ~500-800 mm/yr, and is controlled by the topography.

The underlying geology of the region is Cambrian metasediments of the Kanmantoo Group, which consist of interbedded, vertically dipping micaceous sandstones and schists (Fitzpatrick *et al.,* 1996). There are numerous sulfide-rich lenses or bands, some of which have been mined just south of the main study area.

The hydrology has been described by several workers (e.g. Fitzpatrick *et al.,* 1996; Cox *et al.* 1996; Salama *et al.* 1999). There are two water tables in landscape positions upslope of the seepage and marsh areas. The perched, usually fresh water table fluctuates within the upper soil layers, and is very responsive to rainfall events. The deeper aquifer water table fluctuates more slowly, and contains saline-sulfidic water due to contact with the deep sulfidic mineral lenses. The explanatory soil-regolith models in Figure 17-1 and Figure 17-2 illustrate groundwater and surface water movement, which is connected to the seepage and marsh areas, where the Inland ASS are found.

17.1. Acid Sulfate Soil Processes and Hazards

The Acid Sulfate Soils overlying mineralised zones in the Mount Lofty Ranges (Area G in Figure 5-2) differs from the ASS in the River Murray flood plains system (Areas B to F in Figure 5-2) because the source of sulfur is from sulfate-rich ground waters derived from sulfide mineralization (ore bodies) of the Kanmantoo rocks of the eastern Mt Lofty Ranges.

Herrmanns catchment explanatory soil-regolith model

Fitzpatrick *et al.* (1996) constructed explanatory soil-regolith process models to describe: (i) water flow paths in saline seepages (Cox *et al.* 1996; Salama *et al.* 1999), (ii) development of sulfidic and sulfuric materials in ASS and (iii) contemporary geochemical dispersion and erosion processes present in the lower parts of a toposequence in the Herrmann catchment in the Mount Lofty Ranges (Figure 17-1 and Figure 17-2). Sulfidic material containing pyrite framboids was formed in these seepages by a combination of: (i) saline groundwaters with high sulfate concentrations (with other elements sourced from mineralised zones e.g. Pb and Zn) seeping up through soils, (ii) anaerobic conditions and (iii) organic carbon in saturated soils, contributed to formation of sulfidic material containing pyrite framboids formed by anaerobic bacterial reduction of sulfate. When these sulfidic materials are exposed to air, pyrite is oxidised producing sulfuric acid, which dissolves soil minerals and leads to precipitation of a number of secondary mineral combinations such as: (i) sideronatrite, tamarugite, copiapite, halite and gypsum in sandy sulfuric materials with pH < 2.5, (ii) natrojarosite, jarosite and plumbojarosite in clay-rich sulfuric materials with pH 3.5-4 and (iii) schwertmannite (pH 4), ferrihydrite (pH > 6), akaganéite and white, poorly-crystalline Al oxyhydroxide precipitates.

The exposure of sulfidic material in eroded stream banks results in the rapid weathering of pyrite present in previously buried swamp deposits as shown in Figure

17-2, Figure 4-3 and Figure 4-4). The chemical and microbial reactions that form sulfuric acid can dissolve a variety of layer silicate minerals, mobilising aluminium and trace metals. In addition to pyrite, the underlying rocks in this region contain sphalerite and traces of galena and other minerals that contain zinc, lead and arsenic. These elements are often concentrated in white and reddish seeps and pools at the base of the eroded streamline and greatly exceed criteria for the protection of fresh-water aquatic organisms. In addition, the seeps and soil leachate contain elevated concentrations of dissolved iron, aluminium, and sulfate. Soluble sulfate minerals (sideronatrite and tamarugite) were found to crystallise on the bank face, immobilizing metals when these waters evaporate. However, during rainfall events, these minerals readily dissolve and release the stored acidity and metals to runoff and infiltrating stream water. The cycle of salt formation and dissolution contributes to acid-drainage from the site as long as moist sulfidic material remains exposed to air.

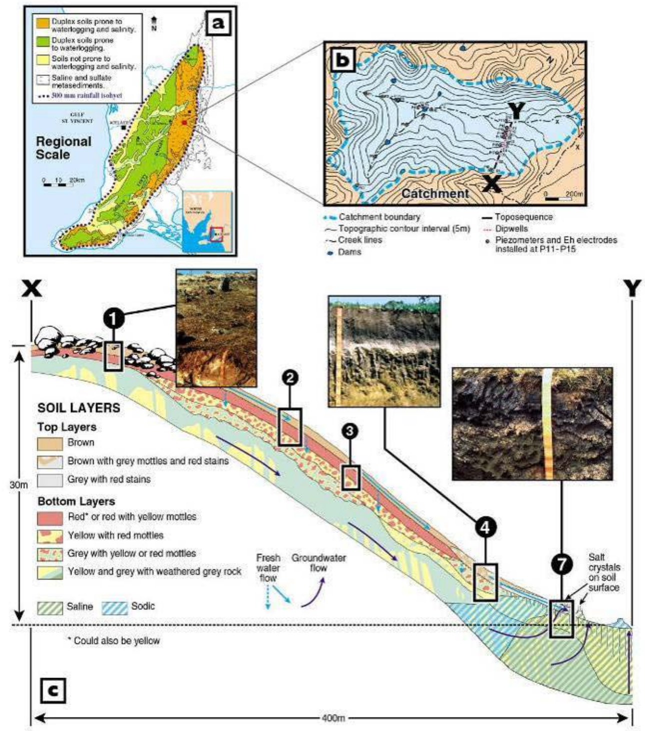


Figure 17-1. Descriptive soil-regolith model showing toposequence with three selected profiles, soil features (e.g. relict purple mottles and current very poorly drained saline soils with grey and red stains), direction of perched fresh water flow and groundwater flow (after Fritsch and Fitzpatrick 1994; Fitzpatrick *et al.* 1996). Site G1 in Figure 5-2.

These descriptive process models have been used to help characterise catchment-scale variability of relict (past geomorphological processes in development of deep weathering and erosion) and current (saline, sodic and acid sulfate soils) soil forming processes to develop practical solutions for ameliorating soils at farm scale (Fitzpatrick *et al.* 2003a,b), and for use in mineral exploration (Skwarnecki & Fitzpatrick 2003, 2008; Skwarnecki *et al.* 2002; Fitzpatrick & Skwarnecki 2005).

Mount Lofty Ranges predictive soil-regolith model

Fitzpatrick *et al.* (2000a) used the information contained in Figure 17-1 and Figure 17-2 to construct a generalised soil-regolith model showing the sequential hydrogeochemical processes that transform sulfidic material in a perched wetland to sulfuric material (Figure 17-3).

Stage 1*:* Saline groundwater enriched in sulfate (SO_4) seeps up through the soil, along with other solutes such as Na, Ca, Mg, As, I and Cl, and concentrates by evaporation to form various mineral precipitates within and on top of the soil surface (Figure 17-3a). The combination of: (i) rising sulfate-containing groundwater, (ii) anaerobic conditions associated with saturated soils, (iii) agricultural activity and (iv) fractured rocks relatively enriched in Fe, S, Pb, Zn, etc. led to the formation of sulfidic material and precipitation of high concentrations of Pb and Zn. If the soil is wet and contains sufficient organic carbon, anaerobic bacteria use the oxygen associated with the sulfate (SO_4) during the assimilation of carbon from organic matter. This process produces pyrite and forms sulfidic materials (Figure 17-3a) (Fitzpatrick and Skwarnecki 2003).

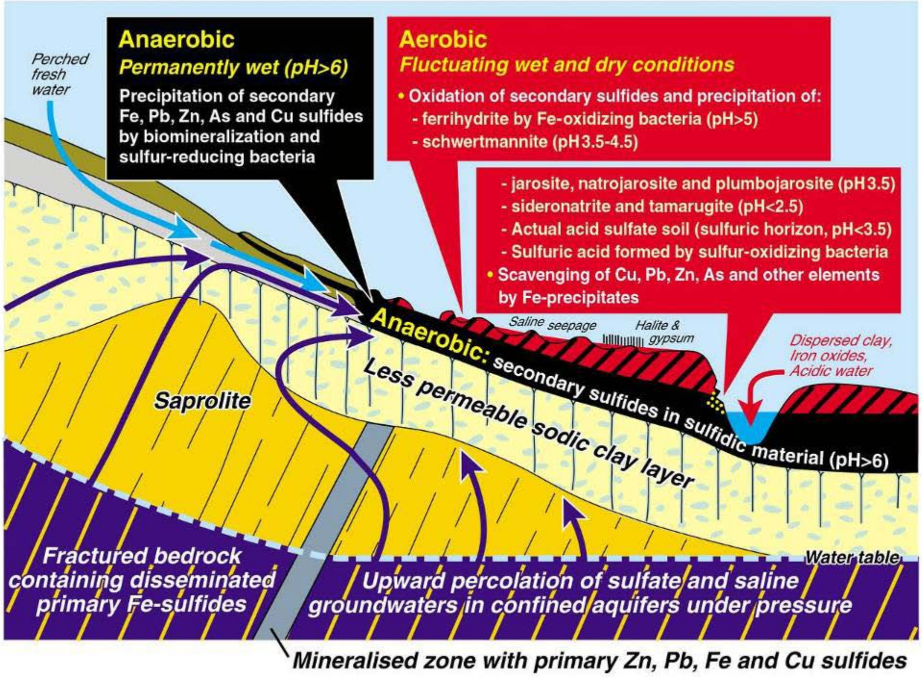


Figure 17-2. Descriptive soil-regolith toposequence model showing geochemical dispersion and erosion processes in saline seepages and formation of secondary sulfides in sulfidic material in a perched wetland and sulfuric materials along eroded drainage lines (after Fitzpatrick *et al.* 1996).

Stage 2: Sulfuric materials result when pugging from animals, drainage works or other disturbances expose pyrite in previously saturated soils to oxygen in the air. Thus, pyrite is oxidised to sulfuric acid and various Fe sulfate-rich minerals (Figure 17-3b). When sulfuric acid forms, the soil pH can drop to below pH 4; locally, pH may decrease to as low as pH 2.5. The sulfuric acid dissolves clay particles in soil, causing base cations and associated anions (e.g. Na, Mg, Ca, Cl, SO_4, SiO_4), trace elements, and metals such as Fe and Al to be released into the soil and transported to stream waters. As the regolith structure degrades due to the accompanying sodicity, soils become clogged with dispersed clay and Fe precipitates and they lose their permeability and groundcover. This prevents groundwater below from discharging and forces it to move transversely through the soil (Figure 17-3b). Soil around the clogged area eventually erodes, causing movement of acid, dissolved metals and salts into waterways and dams. If cattle or other activities continue to disturb the soil around the newly created sulfidic material, the area affected continues to expand (Figure 17-3b) (Fitzpatrick & Skwarnecki 2005).

Stage 3: If these processes become expressed on the surface of the soil, bare eroded saline scalds surrounding a core of lower permeability, highly saline, eroded sulfuric material may result (Figure 17-3c). These saline landscapes are characterised by slimy red or white ooze and scalds with impermeable Fe-rich crusts. As shown in Figure 17-3, when the sulfidic materials undergo change, different salt and Fe minerals form because of differences in pH, increases in salinity and differences is relative concentrations of salts. In the final stage of formation, a hard soil layer remains, with only few salts (Figure 17-3c). Schwertmannite was first sampled and identified in inland

ASS in the Mount Lofty Ranges, South Australia in 1990 (Fitzpatrick *et al.* 1992; 1993; 1996; Fitzpatrick & Self 1997).

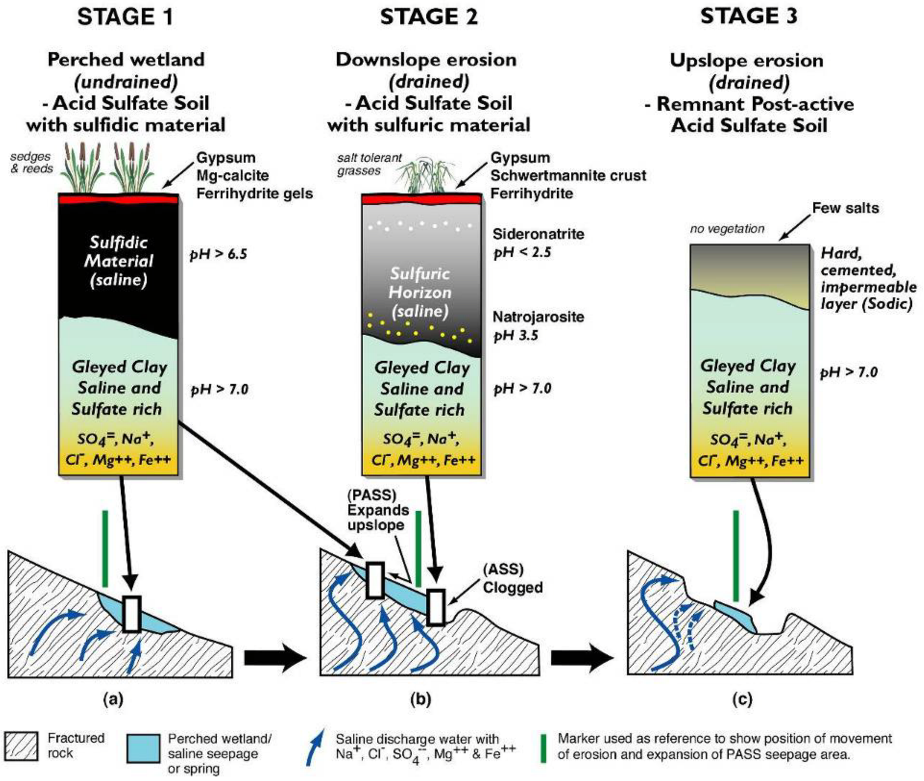


Figure 17-3. Predictive soil-regolith model showing the hydrogeochemical processes, which transform sulfidic material in a perched wetland to highly saline sulfuric material (after Fitzpatrick *et al.* 2003b).

Degraded agricultural areas in this region are conspicuous by the presence of ephemeral to semi-permanent saline seepages with surface accumulations of Fe oxyhydroxides and salts that overlie strongly reduced subsoil horizons containing pyrite formed by bacterial sulfate reduction. During wet winters, surface reddish-brown precipitates of ferrihydrite, containing high levels of scavenged cations (e.g. As and Si) are the dominant Fe oxyhydroxide formed. In summer, the seasonal changes in soil redox conditions strongly modify the geochemistry of the soil solution causing ferrihydrite to transform to goethite and schwertmannite in the presence of excess sulfate and chloride, usually in the form of cemented crusts (Figure 17-3c). Schwertmannite is indicative of a weathering environment with soil solutions having a pH in the range 3 to 4 and sulfate concentrations between 1000 and 3000 mg/L (Fitzpatrick *et al.* 1996; Schwertmann & Fitzpatrick 1992).

17.2. Management options

Approaches for managing ASS in the upland saline seepages in the Mt Lofty Ranges (Area G in Figure 5-2) are briefly covered in this section. The sequence of steps used to develop an easy-to-follow pictorial manual for identifying soil indicators, land use options and best management practices for this area is shown in Figure 17-4 (Fitzpatrick *et al.* 2003a). Steps 1-5 describe soil layers and construct them in toposequences (explanatory or predictive models shown in Figure 17-5), which are also used to help the mapping of soil types in areas with variable geochemistry (Fitzpatrick *et al.* 2003a,b).

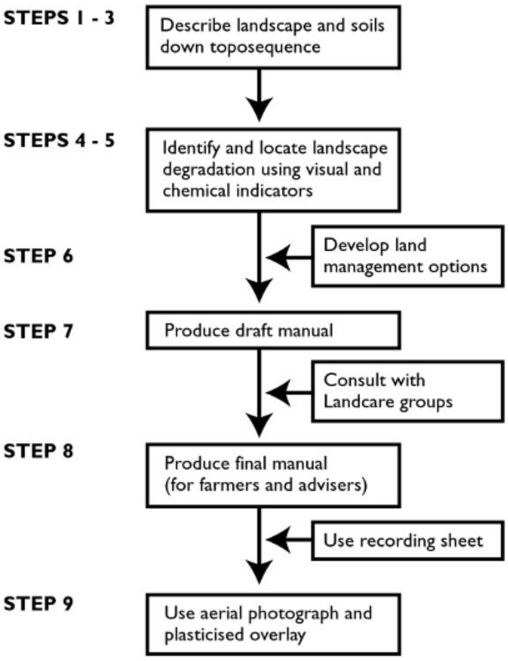
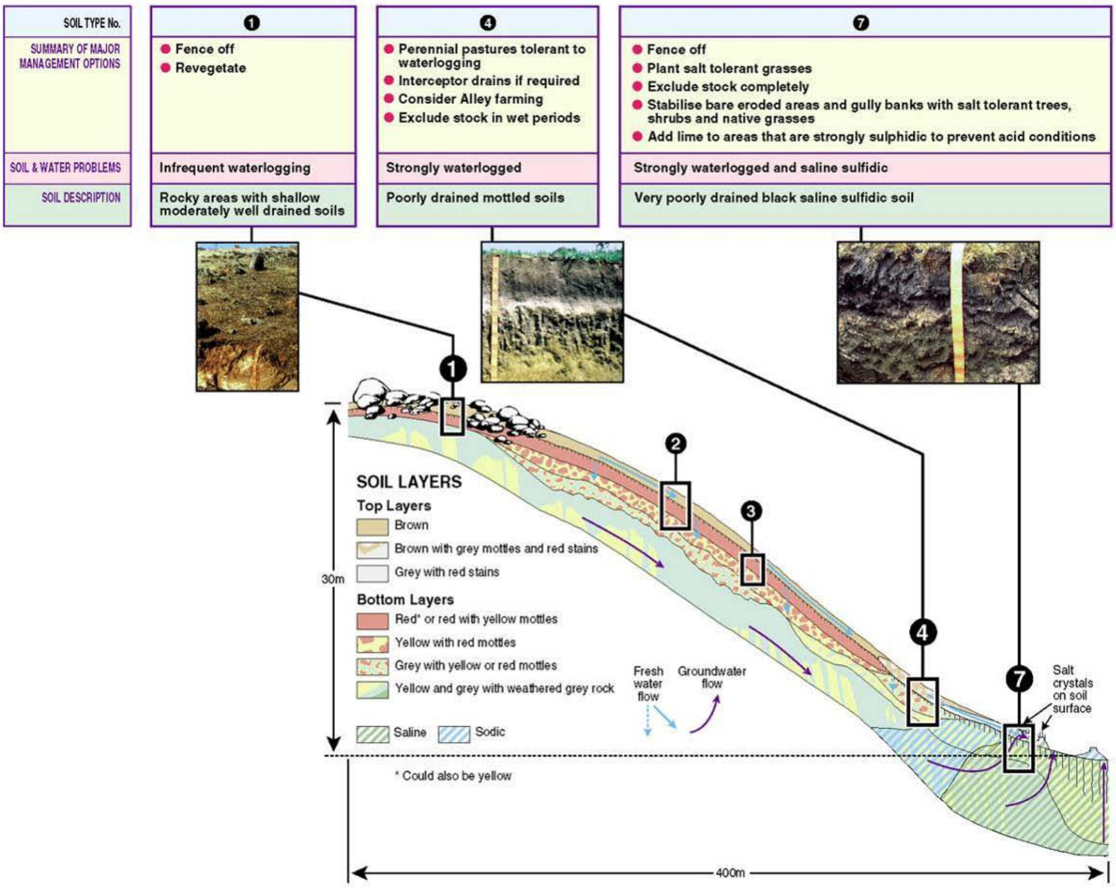


Figure 17-4. Flow diagram showing steps involved in developing manuals for land management (from Fitzpatrick *et al.* 2003a,b).



SOIL TYPE No.	❶	❹	❼
SUMMARY OF MAJOR MANAGEMENT OPTIONS	● Fence off ● Revegetate	● Perennial pastures tolerant to waterlogging ● Interceptor drains if required ● Consider Alley farming ● Exclude stock in wet periods	● Fence off ● Plant salt tolerant grasses ● Exclude stock completely ● Stabilise bare eroded areas and gully banks with salt tolerant trees, shrubs and native grasses ● Add lime to areas that are strongly sulphidic to prevent acid conditions
SOIL & WATER PROBLEMS	Infrequent waterlogging	Strongly waterlogged	Strongly waterlogged and saline sulfidic
SOIL DESCRIPTION	Rocky areas with shallow moderately well drained soils	Poorly drained mottled soils	Very poorly drained black saline sulfidic soil

Figure 17-5. Descriptive soil-regolith toposequence model showing sequence of soils down a slope (two of the seven soils are illustrated) linked to a 3D mechanistic model of soil and water processes with summaries of management options associated with each soil type (Table 17-1) (from Fitzpatrick *et al.* (2003a).

Steps 6-9 involve local communities in developing the manual through a process where knowledge of the hydrological and soil-regolith processes models (bottom half of Figure 17-5) and production systems are bought together in recommendations for appropriate best management practices (top half of Figure 17-5; Table 17-1). For example, in the Mount Lofty Ranges (Fitzpatrick *et al.* 1997; 2003a,b) and Woorndoo region in Victoria (Figure 22-1; Fitzpatrick *et al.* 1997; 2003a,b), fencing and protecting saline-sulfidic wetlands from physical disturbance (i.e. cattle) has:

- Facilitated the reestablishment of more reducing soil conditions in the A horizon
- Decreased the amount of pyrite oxidation
- Allowed rapid recovery of wetland vegetation
- Prevented physical erosion of the A horizon
- Allowed a return to neutral pH (pH = 6.5 to 7)

Table 17-1. Management Options for ASS in the Mt Lofty Ranges (Fitzpatrick *et al.* 1997).

Soil Type No	**Soil Description**	**Soil and Water Problems**	**Management Option**
1	Rocky areas with shallow moderately well drained soil	Infrequent waterlogging	• Fence off • Revegetate
2	Deep well drained red and yellow soils	Infrequent waterlogging	• Perennial pasture
3	Moderately well drained mottled soils	Periodic waterlogging	• Perennial pastures tolerant to waterlogging • Consider Alley farming
4	Poorly drained mottled soils	Strongly waterlogged	• Perennial pastures tolerant to waterlogging • Interceptor drains if required • Consider Alley farming • Exclude stock in wet periods
5	Poorly drained grey sodic soil	Strongly waterlogged and sodic	• Perennial pastures tolerant to waterlogging • Agroforestry • Alley farming • Exclude stock throughout winter
6	Very poorly drained grey saline soil	Strongly waterlogged and saline	Normally occur as a mosaic and managed together: • Fence off • Plant salt tolerant grasses • Exclude stock completely • Stabilise bare eroded areas and gully banks with salt tolerant trees, shrubs and native grasses • Add lime to areas that are strongly sulfidic to prevent acid conditions.
7	Very poorly drained black saline sulfidic soil	Strongly waterlogged and saline sulfidic	
8	Very poorly drained saline eroded gully	Strongly waterlogged saline and eroded	

18. Abandoned Mines (Area H in Figure 5-2)

A wide range of mine spoil Acid Sulfate Soils have been identified and characterised in waste rock stockpiles, tailing impoundments and mine retention ponds at several mine spoil environments in the Mount Lofty Ranges (Area H in Figure 5-2). These soils are essentially the same as those in seepages overlying mineralized zones (Section 15), except that the pyritic rocks have been deposited on the landscape surface, often filling-up whole valleys. A wide variety of ASS soils that developed from rocks in various stages of physical and chemical breakdown have been described and sampled along hydrotoposequences (i.e. from the drier upper to wetter lower surfaces) of mine spoils at the Brukunga pyrite mine (Site H1 in Figure 5-2). Fitzpatrick & Self (1997) identified schwertmannite, jarosite, goethite and gypsum in orange and yellow precipitates in acid drainage water seeping through the rehabilitated pyrite-rich tailings dam and waste-rock dumps at the abandoned Brukunga pyrite mine.

Large applications of fine limestone are being continually applied to diverted stream water via a hopper system to neutralize the flowing acidic waters from the pyrite-rich tailings dam and waste-rock dumps.

19. Seepages overlying mineralized zones in Eastern Dundas Tablelands, Victoria (Area I in Figure 5-2)

19.1. Background and Environmental Setting

The Eastern Dundas Tablelands (EDT) is a slightly domed tableland with two siliceous volcanic lava domes, which creates a generally radial drainage pattern. Dissection of the plateau by rivers and streams has created shallow U-shaped valleys rarely deeper than 20 m. The climate is Mediterranean. The district annual average rainfall is 628 mm (±114 mm), although the annual totals during the last 20 years have been predominantly below this average.

Land degradation in the form of salinisation, acidic waters and associated soil erosion affects 5300 hectares, or seven per cent, of the EDT (Area I in Figure 5-2, Munroe 1998). Located within degraded zones are permanently flowing springs with associated iron precipitates and salt efflorescences. Within the discharge zones, conditions exist for formation of sulfidic material in ASS. Sulfidic material identified is only located in discharge zones connected to the regional groundwater flow system that have been shown to be "primary discharge zones" (Fawcett *et al.* 2008) known to have discharged prior to land clearing by Europeans. This case study outlines the hydrogeological and soil-landscape toposequence processes associated with springs that contain the ASS and illustrate the impact that inland ASS have on soil degradation and water quality in this region.

19.2. Acid Sulfate Soil Processes and Hazards

Field measurements were conducted at the Merrifields research site located south of Balmoral, on the north side of Glenndinning Creek and east of Rocklands Reservoir (Area I in Figure 5-2). Irregular shaped scalds occur on the drainage flats at the breaks-of-slope and along valley walls, but never directly within the creek. These scalds are dominant on the northern side of the creek. Downslope of barren scalds are areas of poor grass growth (soil salting class 1 and 2) occupied mainly by salt tolerant species (Fawcett *et al.* 2008). The toposequence models (Figure 19-1) interpret various soil characteristics: soil macromorphological features (top), soil EC and sodicity (middle); and soil pH (bottom) along transect 1 shown in Fawcett *et al.* (2008).

Acid sulfate soils with predominantly sulfidic material and minor sulfuric material occur within spring zones of the EDT but are not as obvious as those identified in coastal or large scale wetland settings. The conditions for their formation exist only within discharge zones associated with the regional groundwater system, which may be only several meters in size (Figure 19-1; Figure 19-2). Field observations and the following laboratory analyses based on the classification of Isbell (1996) were used to identify the presence of sulfidic material and sulfuric material at the Merrifields research site: (i) pH before and after incubation of moist samples for 8 weeks (pH<4) and treatment with hydrogen peroxide (pH<2.5), (ii) mineralogical identification of iron sulfide and iron oxyhydroxide minerals (mainly schwertmannite) and (iii) detailed measurements of

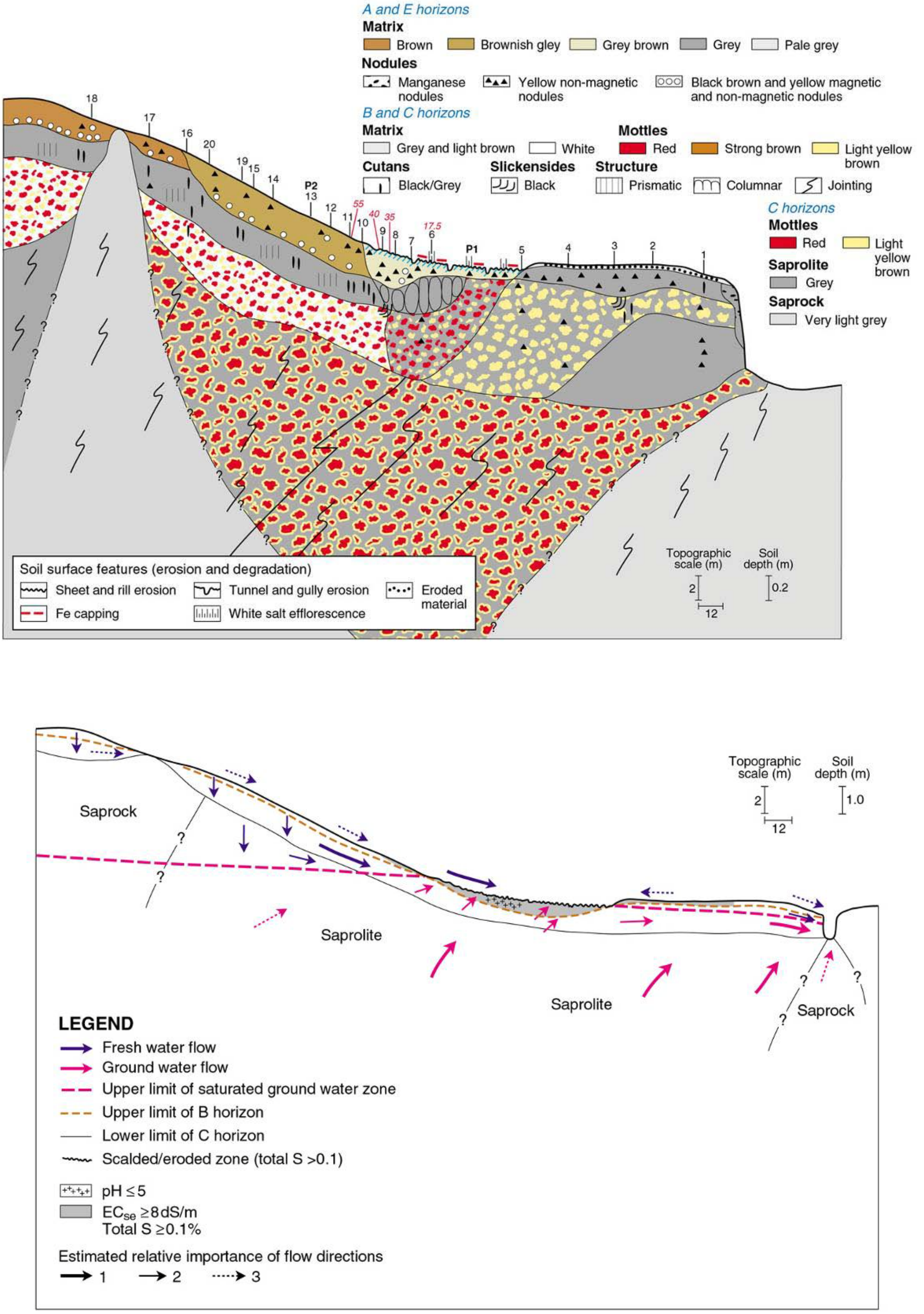


Figure 19-1. Descriptive (top) and explanatory (bottom) soil-regolith toposequence models for transect across western side of the bank at the Merrifields research site: morphology (top) and waterflow systems with salinity and pH across toposequence (bottom) (modified from Fawcett *et al.* 2008)

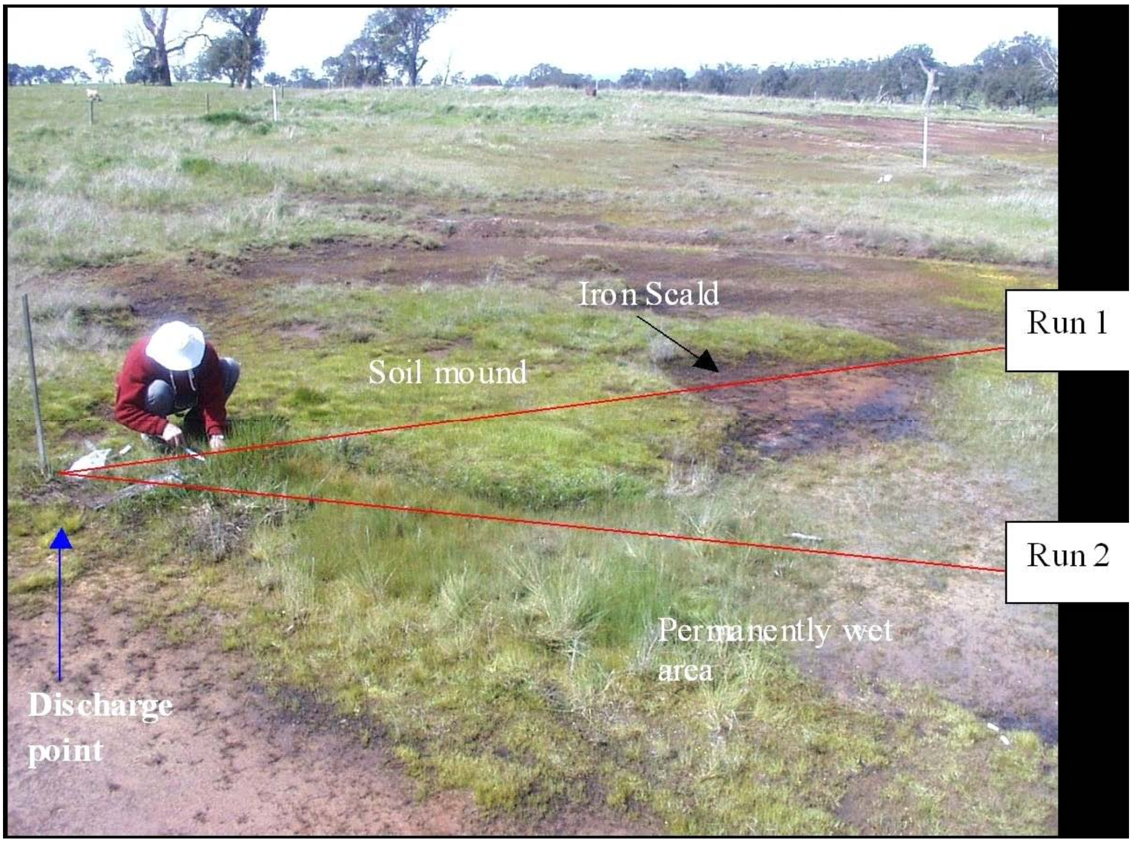


Figure 19-2. Location of sampling point runs from artificially created discharge point for redox, EC and pH. (From Fawcett *et al.* 2008)

discharge water chemistry. Water chemistry of surface water within scalded regions was sampled via a series of surface drains, with groundwater chemistry sampled via a series of shallow piezometers and drain inserted into a 6 m deep trench within and around degraded springs. Detailed redox, pH and EC measurements of spring discharge water were taken along two transects through a disturbed discharge zone (Figure 19-2). Run 1 was made across an area where discharge water evaporated and iron scalding was present, and Run 2 was in an area where the discharge rate was sufficient to enable water to freely drain away from the scalded zone.

The evidence presented by Fawcett *et al.* (2008) shows that suitable conditions exist for the formation of inland ASS within discharge zones on the EDT. It was also shown that degradation is in part caused by the altered surface environment within these primary groundwater discharge zones that cause sulfidic materials to transform to sulfuric material. It is also apparent that the process of acidity and iron precipitation is halted if the discharge area is permanently saturated, which prevents the oxidation of iron sulfides. Therefore, remediation is in part achieved by promoting a stable permanently saturated wet-land environment.

The direct implication of the identification of sulfidic and sulfuric materials within these degraded discharge zones is that land management options aimed at lowering water tables are impacting on part of the hydrogeological cycle that is not a driver of the degradation processes observed on the EDT.

This research has enabled the construction of conceptual soil-regolith models (Figure 19-3), which explain how land clearing causes severe degradation of primary groundwater discharge zones on the EDT that contain ASS with both sulfidic and sulfuric materials. The major process and assumption used in the model are:

- Groundwater discharge is a primary process, and occurred prior to land clearing

- Groundwater discharge occurred into wet-land like environments where hydrogen sulfide was able to dissipate into the atmosphere
- Land clearing following European settlement caused discharge zones to be exposed and adversely impacted by agriculture
- Land clearing caused an increase in the magnitude of the local nested flow system

Table 19-1 Summary of field observations on Acid Sulfate Soils at the Merrifields site on the Eastern Dundas Tablelands.

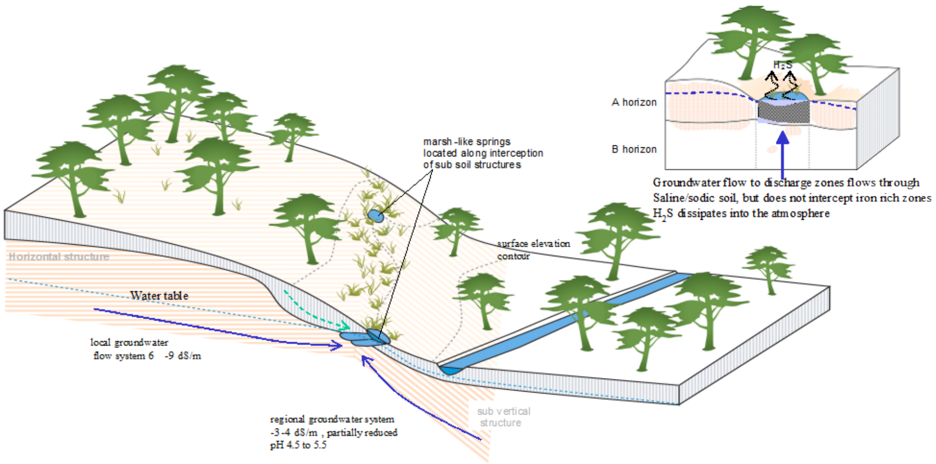
	Permanent diffuse discharge zones	**Seasonal discharge zones**	**Permanent point discharge zones**
Wet periods	Sealing and clogging of soil pores by illuviated material and iron precipitants, erosion of highly sodic soils along exposed sections	Erosion of highly sodic soils, waterlogging of low-lying areas and sealing and clogging of soil pores by illuviated layer silicates and iron oxide-rich materials	Little evidence of active degradation during wet periods
Dry periods	Accumulation and concentration of salts, salt efflorescence on soil surfaces driven by evaporation. Periodic sealing and clogging of soil pores by illuviated layer silicates and iron oxide-rich materials. Erosion of the sodic top soil during storm events	Accumulation and concentration of salts combined with salt efflorescence, loosening of surface soil by the expansion of thenardite and wind and water erosion of highly sodic soils during storm events	Accumulation and concentration of salts combined with minor salt efflorescences. The periphery of the discharge zone may erode during storm events.

In the model presented in Figure 19-3 and Figure 19-1, a stable discharge environment exists. As the area is cleared and impacted by agriculture, the discharge environment is altered. Salts accumulate within the discharge zone and exposed sodic soils are eroded by increased activity of the local groundwater flow systems. The interaction of hydrogen sulfide in the groundwater and the iron in the soils causes the formation of inland acid sulfate soils with both sulfidic and sulfuric materials. Land degradation occurs without any measurable change to the regional groundwater system. Groundwater discharge and shallow water tables existed prior to and after European settlement. The driving cause of the degradation is the exposure of the discharge zone.

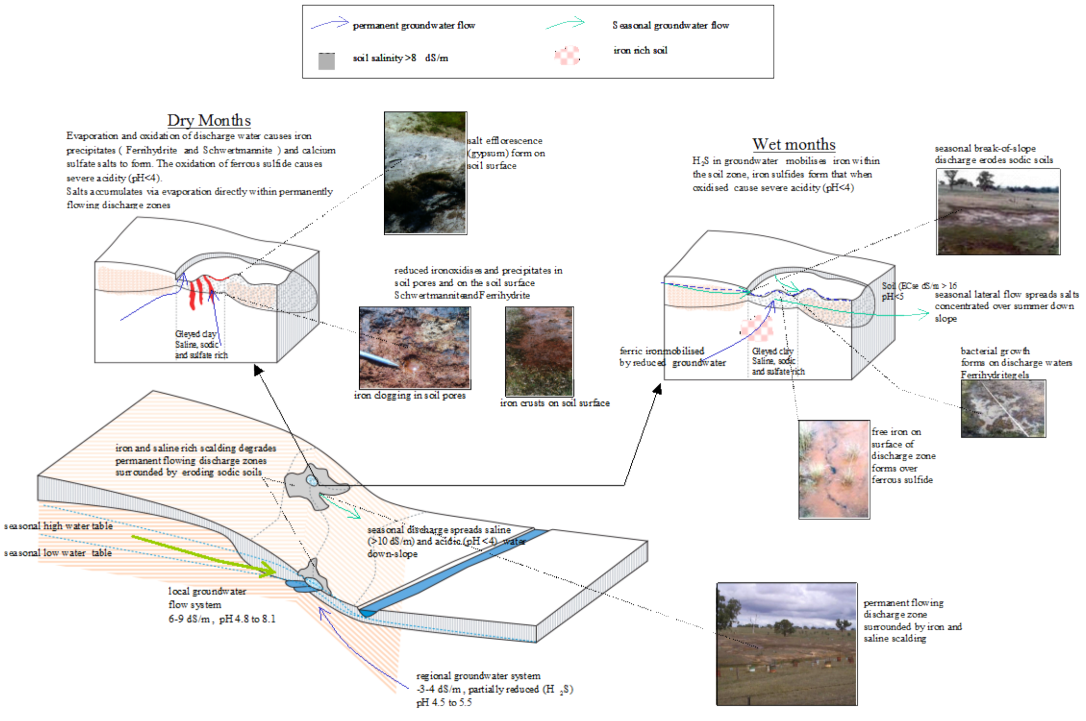
19.3. Management options

The recommendations for appropriate best management practices for the range of Inland ASS subtypes occurring in seepages in the Dundas Tableland were fencing, protecting the saline-sulfidic wetlands from physical disturbance (i.e. cattle) and mulching, has:

- Facilitated reestablishment of reducing soil conditions in degraded soils.
- Decreased the amount of pyrite oxidation in degraded soils.
- Allowed rapid recovery of wetland vegetation in degraded soils.
- Prevented water erosion.
- Allowed a return to neutral pH (pH = 6.5 to 7).



Conceptual landscape model illustrating key hydrogeological and soil and water chemical process pre-cleared groundwater discharge zone



Conceptual landscape model illustrating key hydrogeological and soil and water chemical process post-cleared groundwater discharge zone

Figure 19-3. Predictive soil-regolith model for Dundas Tableland illustrating key hydrological and soil-water biogeochemical processes for pre-cleared and post-cleared discharge zones (from Fawcett *et al.* 2008)

20. Main river channel and adjacent wetlands in the lower Loddon River, Victoria (Area K in Figure 5-2)

20.1. Background and Environmental Setting

Wetland observations originally made by staff of Waterwatch and Goulburn-Murray Water as part of the rapid assessment phase of the Murray-Darling Basin Acid Sulfate Soils Risk Assessment Project led to a request being made by the Murray-Darling Basin Authority (MDBA) for CSIRO to conduct a detailed assessment (MDBA 2010) of two sites along the Loddon River and Burnt Creek waterways. ASS were identified at these target areas following observations made during rapid field assessments conducted using chip tray samples, soil and water analyses and visual evidence to identify the presence of ASS.

CSIRO undertook Phase 1 (MDBA 2010) of the detailed ASS assessment to determine whether or not ASS materials are present at 2 locations in the Loddon River catchment in north central Victoria (Figure 5-2; Thomas *et al.* 2009). The assessment was undertaken during December 2008, along a 6 km section of the Loddon River (MDBA Wetland ID 40850) at Majors Line Crossing. In this study, 69 soil layer and mineral samples were analysed from 35 geographically well-distributed and locally representative soil profiles from the Loddon River (27 sites) to assess current and potential environmental hazard due to acid sulfate soils. Eleven water samples were collected and analysed from several stretches of waterways (seven from the Loddon River) to assess water chemistry. A number of additional sites and stretches of the waterways were visually assessed, but not sampled.

Typically three soil profiles were sampled from toposequence transects across the river or creek channel as shown in Figure 20-1.

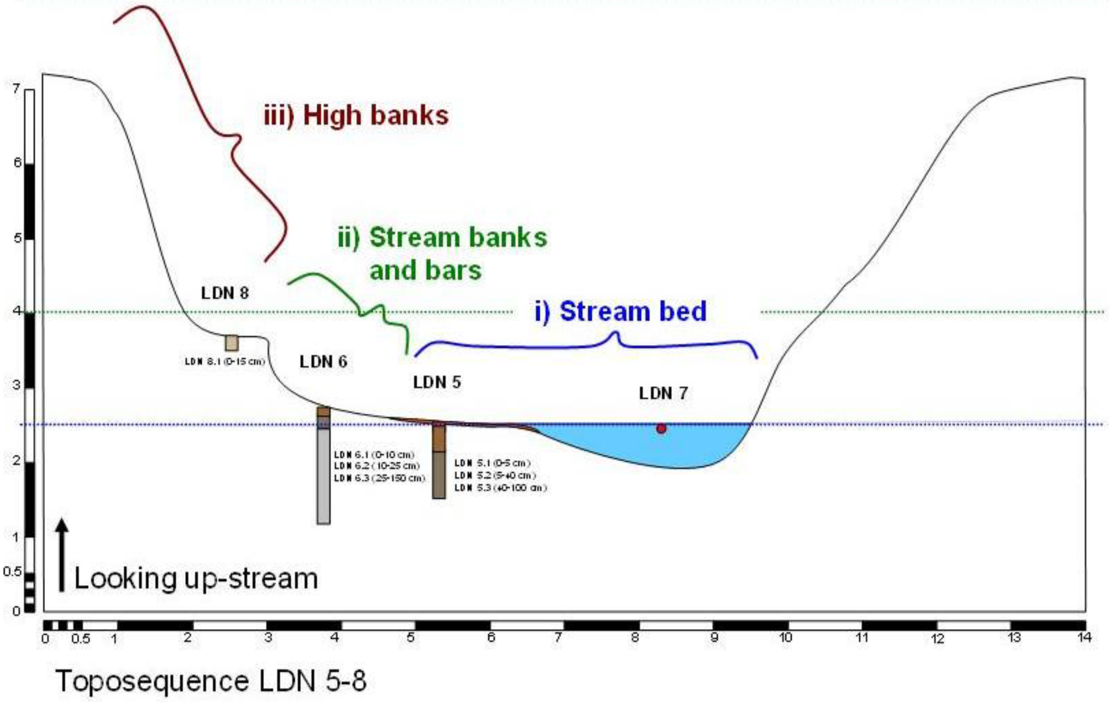


Figure 20-1. Descriptive soil-regolith toposequence model showing the relative positions of the 3 soil-landscape categories referred to in this section. Scale bars are metres. (from Thomas *et al.* 2008)

The Loddon River and Burnt Creek tributaries share similar geomorphic characteristics and were sampled according to the following three soil-landscape categories: (i) stream bed – lowest point in the landscape (low to zero flow level); (ii) mid elevation on stream bank and bars (level of moderate flow level); and (iii) high embankment (top of high flow or flood level) (Figure 20-1; Thomas *et al.* 2009).

20.2. Acid Sulfate Soil Processes and Hazards

The pH data for the Loddon River soils show that the soils were slightly to moderately acidic. Some soils, where saline groundwater seeps were observed, contain excess neutralising capacity.

Peroxide testing, incubation and Acid Base Accounting (ABA) are consistent in showing that some further acidification is possible. The ABA and incubation data indicate that with complete drying, soil acidification is likely to be moderate with soil pH decreasing generally to around pH 4 to 5.

Most soils also contain existing acidity (as TAA). This may allow mobilisation of Al and other trace elements at pH < 5.5, but soil pH (and stream water pH) is likely to increase during re-flooding, causing re-precipitation of metals.

The waters influenced by groundwater, and proximal to monosulfide-containing sediments were circum-neutral (about neutral) with moderate to high EC and alkalinity. Surface water (rainwater runoff) that pooled in the stream channel was acidic to very acidic within the Loddon River stream bed where it had been in contact with sulfuric soil materials.

Water from the Loddon weir pool was very slightly acidic with reasonably low alkalinity, and therefore provides a limited capacity to neutralise the acidity of sulfuric sediments downstream of the weir.

Re-wetting, within the area assessed, may initially cause stream waters to become acidic as existing acidity in sulfuric soils and orange salt efflorescences are mobilised, however pH is likely to gradually rise due to dilution effects. Dissolution of white, alkaline salts that were observed to occur along some embankments will help raise the pH of stream water. Re-wetting will also (eventually, after some weeks) initiate sulfate reduction in the stream bed sediments. This process produces alkalinity, but is also likely to form black monosulfidic materials in the stream bed sediments.

The significance of the minerals found in these salt efflorescences is that they may appear each summer, or in dry periods, and are environmental indicators of acidity. A change in the minerals present may also indicate a change in the nature of the salts entering the system from surface or ground waters. Hence, additional monitoring work should be undertaken to confirm seasonal changes, and changes between wet and dry periods in mineralogical composition in these environments.

During winter rainfall, the soluble sulfate-containing minerals identified (e.g. Fe-sulfate and Mg-sulfate salts) play important roles in the transient storage of components (Fe, Al, Na, Ca, Mg, and SO_4), which may dissolve to form the saline monosulfidic materials in the wetlands.

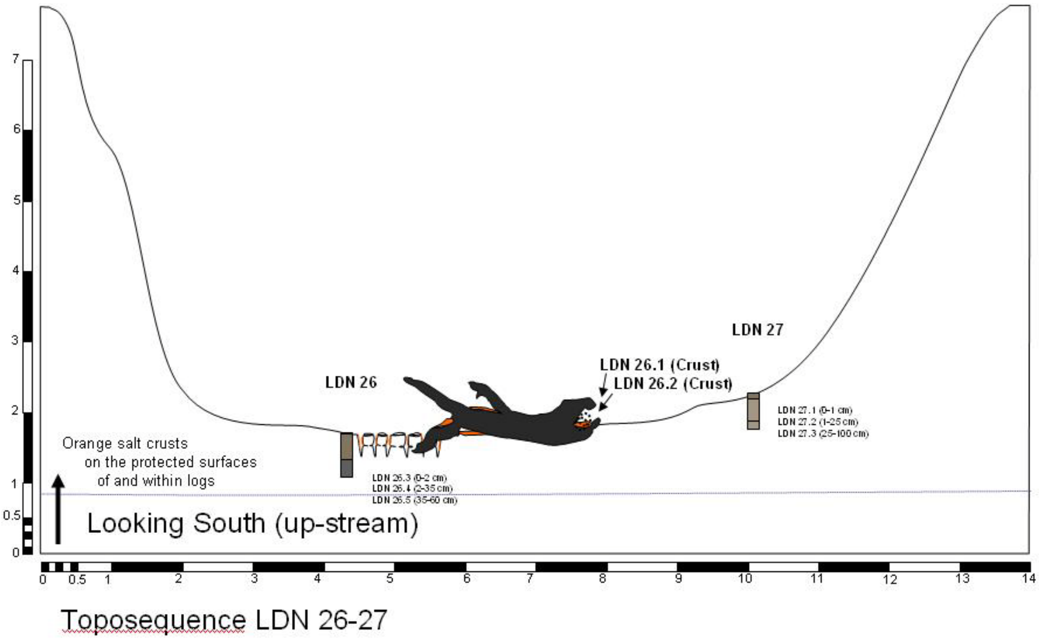


Figure 20-2. Descriptive soil-regolith toposequence model showing Loddon River samples at sites in toposequence LDN 26-27 (scale increments of one metre).

Figure 20-3. Dry river bed at site LDN 26-27 in the Loddon River showing the orange mineral schwertmannite which forms thin coatings or layers on logs and on clays and tree litter.

The bright orange mineral schwertmannite [$Fe^{3+}_{16}O_{16}(OH)_{12}(SO_4)_2$], which in turn may form as an alteration product of sideronatrite, were identified in very thin coatings on logs, clays and leaves and twigs of the recently exposed river beds (Figure 20-2 and Figure 20-3).

These salts are likely to continue to form if water levels decrease, and have the potential to become a problem during re-wetting if not managed properly.

In addition to dissolution following either rain or re-wetting, salt efflorescences also have potential for aerial transport by wind. Some of the non-acidic salts e.g. Mg-sulfates (similar to Epsom salts) may lead to lead to scouring in sheep and cattle.

Magnesium salts can become toxic to livestock. As such, there is a need to prevent stock from ingesting these salts.

Five independent, standard methodologies were applied to classify the various subtypes of ASS (e.g. sulfidic subaqueous soils or sulfuric soils) and non-ASS (e.g. hydrosols) to assess ASS hazard caused by the current drought conditions. The present study suggests potential impacts of environmental and management changes, including from seasonal (and event) re-flooding of waterways.

For the area of the lower Loddon River region that was assessed, the soil acidification hazard and subsequent metal mobilisation hazard is considered to be high in stream bed sediments, stream banks and mid stream bars, particularly where sulfuric soils already exist. Monosulfidic materials exist in ponds and moist stream beds, and pose a deoxygenation and metal mobilisation hazard if disturbed. The potential for monosulfides to form upon re-wetting (under stagnant and low flow conditions) is likely to be high.

Finally, it is recommended that further detailed examination (i.e. Phase 2, MDBA, 2010) be undertaken to determine the type, extent and severity of environmental risks posed by the ASS materials found at the Lower Loddon River sites. It is recommended that representative soil materials be considered for the following Phase 2 work:

- Fifteen sites for detailed analysis of the suite of sulfur compounds, rapid metal release, metalloid dynamics, major and trace elements by XRF and mineralogy by XRD (High priority), and
- Eleven sites (surface materials) for monosulfide formation potential (High priority)

20.3. Management options

Frequent monitoring of the waters and soils should be conducted following re-wetting to determine any adverse impacts on water quality. ASS parameters to be monitored should include pH, SEC, DO and if possible, alkalinity, major and trace elements, and nutrients.

Disturbance of stream beds should be minimised by controlling and slowing stream flow rates, where possible.

Permanent or semi-permanent re-wetting will allow expansion and sealing of cracked clays and a return to reducing conditions, which should increase soil and water pH to near neutral pH over time (possibly weeks to a few months).

Finally, low flows result in the accumulation of soil and organic materials in ponded areas and this can be exacerbated by the establishment of plants in the stream beds to form new mid stream bars, especially in the lower Loddon and banks. A return to wetter conditions is likely to help flush stream blockages and subsequently sulfur-containing minerals further downstream to more alkaline areas and prevent local accumulations of ASS materials.

21. Tributaries in Burnt Creek, Victoria (Area J in Figure 5-2)

21.1. Background and Environmental Setting

Wetland observations originally made by staff of Waterwatch and Goulburn-Murray Water as part of the rapid assessment phase of the Murray-Darling Basin Acid Sulfate Soils Risk Assessment Project led to a request being made by the MDBA for CSIRO to conduct a detailed assessment of selected sites along the Burnt Creek waterway. ASS were identified at these target areas following observations made during rapid field assessments conducted using chip tray samples, soil and water analyses and visual evidence to identify the presence of ASS (Creeper *et al.* 2010; MDBA 2010).

CSIRO undertook Phase 1 of the detailed MDBA ASS assessment (MDBA 2010) to determine whether or not ASS materials were present at three locations in Burnt Creek in the vicinity of Dunolly (MDBA Wetland ID 40854; Figure 5-2; Thomas *et al.* 2009). The assessment was undertaken during December 2008 along Burnt Creek (8 sites) to assess current and potential environmental hazards due to ASS. Four water samples were also collected and analysed to assess water chemistry. A number of additional sites and stretches of waterways were visually assessed.

21.2. Acid Sulfate Soil Processes and Hazards

Prominent pale yellow mottles in the subsoil of profile BCR 3 (Figure 12-1 and Figure 21-2) comprised natrojarosite. Surface salt efflorescence minerals and sub-surface mottles were observed at all four sites. Bright yellowish green surface efflorescences were observed at BCR 1 (sample numbers 1.1 to 1.4: in Figure 21-3 and comprised the mineral sideronatrite [$Na_2Fe(SO_4)_2.OH.3H_2O$], which is an alteration product of weathered pyrite. In addition, the minerals, hexahydrite [$MgSO_4$•$6H_2O$], epsomite [$MgSO_4$•$7H_2O$], gypsum and halite were also present). These minerals form seasonally during summer months under high evaporative conditions, but may also form during winter cyclic wetting and drying events. This is likely to be an important mechanism for acidity to get transferred from ASS to the river water.

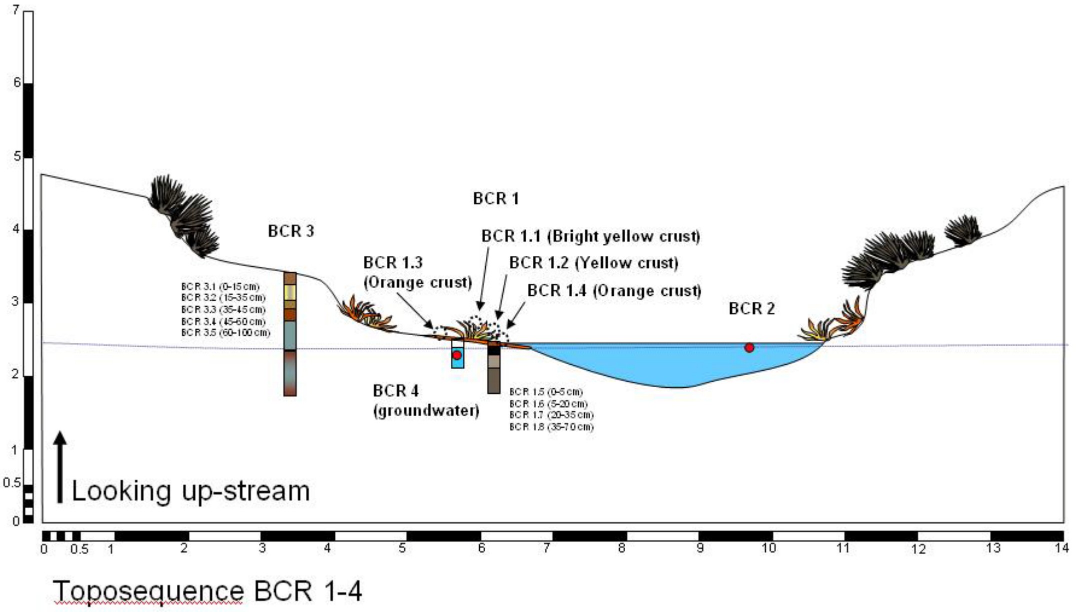


Figure 21-1. Descriptive soil-regolith toposequence model showing sampling locations BCR 1-4 at Burnt Creek. (Scale bar increments are one metre.) (from Thomas *et al.* 2008)

Figure 21-2. Burnt creek site BCR 3 showing a soil pit with distinct light yellow or straw coloured mottles comprising mainly natrojarosite (sulfuric material with a pH ranging between 3.0 to 3.6) at a depth of 15 to 38 cm, which overlies sulfidic material between a depth of 38 to 50 cm. A gleyed greyish clay occurs at depth (> 70cm).

Figure 21-3. Burnt creek site BCR 1 showing the bright yellowish (gold) salt efflorescences comprising dominantly sideronatrite. Salt efflorescences contained the bright yellow mineral sideronatrite [$Na_2Fe(SO_4)_2.OH.3H_2O$], which is an alteration product of weathered pyrite. In addition, the minerals, hexahydrite [$MgSO_4{\cdot}6H_2O$], epsomite [$MgSO_4{\cdot}7H_2O$], gypsum and halite were also present (from Thomas *et al.* 2009).

Five independent, standard methodologies were applied to classify the various subtypes of ASS (e.g. sulfidic subaqueous soils or sulfuric soils) and non-ASS (e.g.

hydrosols) to assess ASS hazard caused by the drought conditions, which existed during 2006 to 2010. The formation of increasing areas of sulfuric soils is a consequence of the severe drought conditions impacting the MDB, causing river, lake margins and wetlands to dry. The present study suggests the potential impacts of changes in environmental conditions and management, including re-flooding of waterways due to seasonal conditions or particular weather events.

For the area assessed in the Burnt Creek locality, the soil acidification hazard and subsequent metal mobilisation hazard is considered to be high in stream bed sediments, stream banks and mid stream bars, particularly where sulfuric soils already exist. Monosulfidic material exists in ponds and in moist stream beds, and poses a deoxygenation and metal mobilisation hazard if disturbed. The potential for monosulfides to form upon re-wetting (under stagnant and low flow conditions) is likely to be high.

Recommendations for this work included further detailed examination (i.e. Phase 2; MDBA 2010) of the extent, type and severity of environmental risks posed by the ASS materials found at the Burnt Creek sites and more detailed work on trace contaminants in the soils.

21.3. Management options

Frequent monitoring of the waters and soils was recommended following re-wetting to determine any impacts on water quality. ASS parameters to be monitored typically include pH, SEC, DO and if possible, alkalinity, major and trace elements, and nutrients.

Disturbance of stream beds should be minimised by controlling and slowing stream flow rates, where possible. Permanent or semi-permanent re-wetting should allow expansion and sealing of cracked clays and a return to reducing conditions which should increase soil and water pH to near neutral pH over time (possibly weeks to a few months).

Finally, the question arises as to the source of sulfur in the Burnt Creek region. The likely source is likely to be groundwater and possibly bedrock weathering (though this would need confirmation) with mobilisation into groundwater and concentration locally in streams by evapotranspiration. It is possible that past mining operations may be leading to increased mobilisation of sulfur, particularly in the Burnt Creek area. For these reasons, the potential for acid generation is likely to be long-term.

Another significant contributor to the accumulation of sulfidic materials is the lack of strong, regular, environmental flows in Burnt Creek. The current situation may be the result of the extended drought conditions experienced in the area. Low flows result in the accumulation of soil and organic materials in ponded areas and this can be exacerbated by the establishment of plants in the stream beds to form new mid stream bars and banks. A return to wetter conditions is likely to help flush stream blockages and subsequently sulfur-containing minerals downstream to more alkaline areas and prevent local accumulations of ASS materials.

The significance of the minerals found in prominent salt efflorescences is that they may appear each summer, or in dry periods, and are environmental indicators of acidity. A change in the minerals present may also indicate a change in the nature of the salts entering the system from surface or ground waters. Hence, additional monitoring work must be undertaken to confirm changes occurring in mineralogical composition through the seasons or between wet and dry periods in these environments.

These salts are likely to form if water levels decrease and they have the potential to become a problem during re-wetting. Salt efflorescences also have potential for aerial transport, such as via wind and also to be dissolved in water. There is a need to prevent stock from ingesting these salts (similar to Epsom salts) because this can lead to scouring in sheep and cattle. Magnesium salts may be toxic to livestock.

22. Lakes and adjacent wetlands in Lake Bolac-salt creek, Victoria (Area L in Figure 5-2)

22.1. Background and Environmental Setting

The main outcome of this case study was the development of a soil diagnostic field key (Cox *et al.* 1999) to help farmers manage saline, poorly drained duplex soils and Acid Sulfate Soils in the Glenelg Region of Victoria (Area L1 in Figure 5-2). Management options such as drainage works and/or improved agronomy can then be matched to easily identifiable soil characteristics indicative of the causes of salinity and waterlogging. This project was targeted at modifying the soil diagnostic key that had been developed to manage saline and waterlogged catchments in the Mt. Lofty Ranges, South Australia (Fitzpatrick *et al.* 1997), so that it could be adapted for managing saline, waterlogged and acid sulfate soils found in the Woorndoo Land Protection Group area (Cox *et al.* 1999).

Clearance of native tree vegetation and its replacement by shallow rooted annual pastures, which use less water, has resulted in salt-affected and waterlogged soils, often with ASS properties on farms. These problems are common to many catchments in southern Australia.

22.2. Acid Sulfate Soil Processes and Hazards

This project determined the major causes of waterlogging associated with salinity. These results are outlined in a Catchment manual (Cox *et al.* 1999). Most soils in the Woorndoo district have an abrupt textural boundary between the top soil layers and relatively impermeable sodic subsoil layers (duplex soil; see Figure 22-1).

- A representative descriptive morphological soil key was produced, which included salinity management options specific to the Woorndoo district
- A well developed "conceptual" view was developed, showing where water is moving through the soils, where water is being impeded causing waterlogging and where saline and sulfatic groundwaters are causing soils to degrade
- Two distinct water flow systems were found in the catchments:
    - A seasonal fresh perched water table develops between May and October on relatively impermeable subsoil layers
    - A rising saline sulfatic permanent localised groundwater table or aquifer occurs in the underlying geology sediments

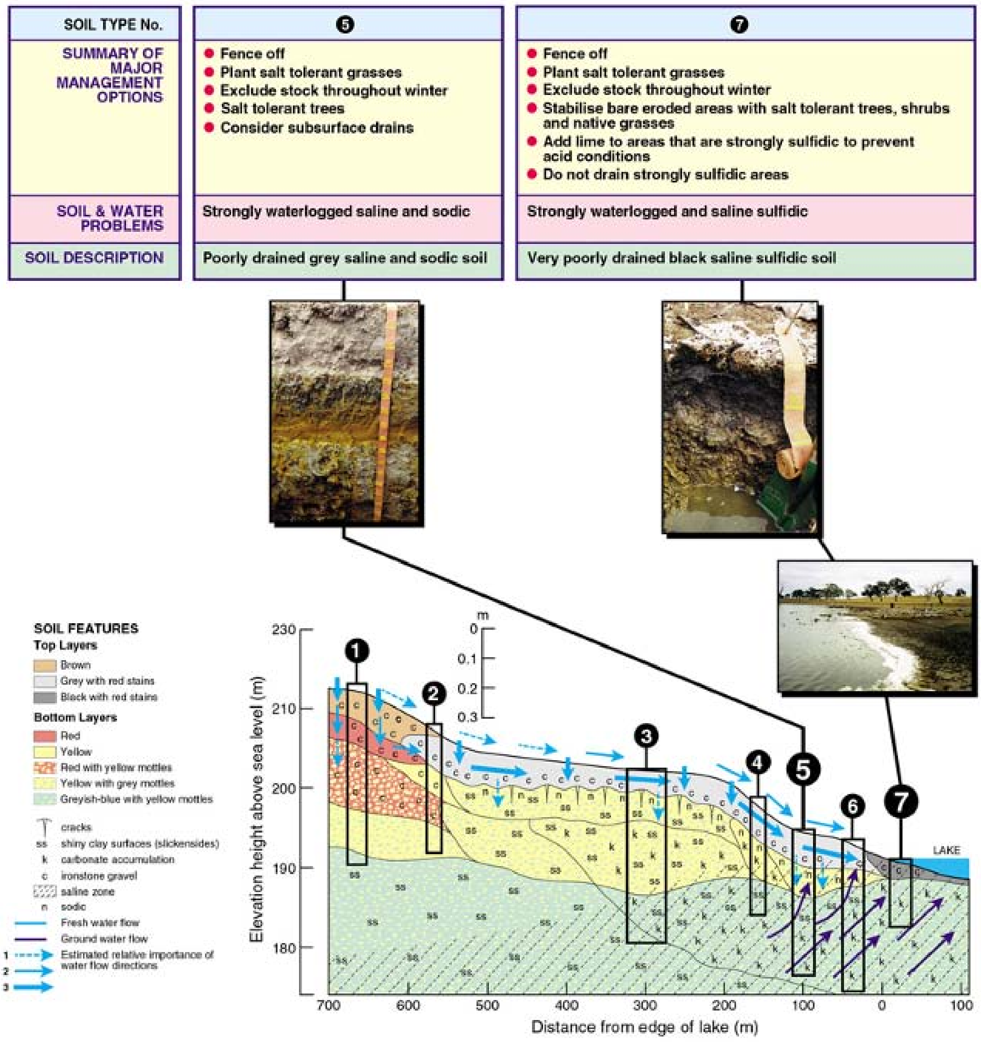
22.3. Management options

A soils diagnostic key was developed and landholders were provided with field training in its use for improved property management planning (Fitzpatrick *et al.* 2003a). A catchment manual (Cox *et al.* 1999) was produced, which not only gave landholders important information about their soils but also matched appropriate land management options to different soil types. Seminars and field days were conducted to provide landholders with the opportunity to make comment on the manual and to learn how they can apply it to their own farming situations.

The manual was developed to enable farmers to compile a map of key soil features on their properties. In the descriptions in the manual, key features are accompanied by cross-sections of conceptual soil-regolith models with colour photographs of soils to enable farmers to easily compare these with their own soil-landscape. With each colour soil profile is a checklist of suggested management practices, which enables farmers to maintain or rehabilitate the soils (see Figure 22-1). Using an aerial photograph or topographic map, a farmer is able to systematically delineate soil features and areas where salinity, waterlogging and Inland ASS are a major issue.

With this information, specific soil samples can be taken for analysis, and better management decisions can be made (e.g. fencing, tree planting and drainage). The manual assists in increasing pasture productivity and biodiversity, as well as reducing rising water tables and associated waterlogging. Use of the manual has proved especially important when implementing property management plans to attain sustainable land management practices and a healthier catchment.

In summary, several key soil and vegetation features are the most critical indicators to look for in the manual to easily recognise and delineate salt-affected and Inland ASS wetland areas (see Figure 22-1). Visual soil indicators were used as a tool to devise options for amelioration and property planning.



SOIL TYPE No.	❺	❼
SUMMARY OF MAJOR MANAGEMENT OPTIONS	● Fence off ● Plant salt tolerant grasses ● Exclude stock throughout winter ● Salt tolerant trees ● Consider subsurface drains	● Fence off ● Plant salt tolerant grasses ● Exclude stock throughout winter ● Stabilise bare eroded areas with salt tolerant trees, shrubs and native grasses ● Add lime to areas that are strongly sulfidic to prevent acid conditions ● Do not drain strongly sulfidic areas
SOIL & WATER PROBLEMS	Strongly waterlogged saline and sodic	Strongly waterlogged and saline sulfidic
SOIL DESCRIPTION	Poorly drained grey saline and sodic soil	Very poorly drained black saline sulfidic soil

Figure 22-1. Descriptive soil-regolith toposequence model showing sequence of soils down a slope (two of the seven soils are illustrated) linked to a 3D mechanistic model of soil and water processes with summaries of management options associated with each soil type (from Fitzpatrick *et al.* 2003a; modified from Cox *et al.* 1999).

23. Lakes, adjacent wetlands and drains in Western Australian Wheat belt region (Area M in Figure 5-2)

23.1. Background and Environmental Setting

Shallow, acidic (pH< *4*) saline groundwaters are widespread in low-lying landscapes of the eastern WA Wheatbelt (Shand and Degens 2008, Degens and Shand 2010). In many parts of the WA Wheatbelt, watertables are continuing to rise (George *et al.* 2008) and increase the discharge of these groundwaters, with associated salinity and acidity, to broad valley floors. Deep open drains are increasingly being used by landholders to manage the rising water-tables and recover or protect land from salinisation in these areas (Dogramaci and Degens 2003; Kingwell and Cook 2007). Such drains are frequently acidic as a result of intercepting shallow acidic saline groundwater. Furthermore, drains commonly discharge to sacrificial lakes or floodways, where flows eventually collect in lakes further down-stream (Dogramaci and Degens 2003; see also several chapters in Shand and Degens 2008, Degens and Shand 2010). A number of drains and lakes (including reference lakes not receiving surface drainage water) were studied in detail to determine hazards from acid sulfate soils in the region (Shand and Degens 2008, Degens and Shand 2010) as well as guidelines proposed for treating acidic drain water (Degens 2009).

23.2. Acid Sulfate Soil Processes and Hazards

Drain water salinity and acidity

Most drains are typically very saline with specific electrical conductance (SEC) in the range 60-100 dS/m (approximating TDS of 38 to 64 ppt). Low pH is widespread, with more than half of the drains sampled in October 2004 being less than pH 3 (Fitzpatrick *et al.* 2008a). Drain pH also decreases during summer, due to oxidation of ferrous iron in groundwaters, iron minerals in sediments and/or evaporation. Data show that in most eastern drains with a low pH (less than 4.5), iron, aluminium, cobalt, copper, zinc, lead, uranium and a range of other trace elements and rare earth elements all elevated (Shand et al. 2008d).

Drain mineral environments

Several materials were generally evident within the drains and used to indicate different geochemical process zones (Fitzpatrick *et al.* 2008a). These materials broadly consisted of (from the original excavated base of the drain): unconsolidated saturated sediments including sulfidic materials, monosulfidic black oozes, sulfuric materials, saturated gels and precipitates, salt crusts overlying saturated sediments and salt crusts in the capillary zone above the drain waters. Not all materials were present within all drains. For example, in recent constructed drains (< 3 years age) or drains with little sediment, there was little sedimentation and therefore minimal sediment profile development, gels and precipitates. The main materials and key processes that these indicate are discussed in the following sections.

Sulfidic material

Sulfidic material occurred in almost all the drain sediments (e.g. Figure 23-1 and Figure 23-2) as a thin horizon/layer (5 to 10 cm thick) representing a pool of stored acidity, that could contribute to drain water acidity seasonally or in aged drains. The sulfidic material mostly consists of accumulations of iron sulfide minerals. Sulfate reduction is a natural process that occurs in virtually all the drains. However, the quantities or thickness of sulfidic material that accumulate in the drains is a function of many factors. The key requirements for high rates of sulfate reduction and sulfide accumulation are: (i) a high concentration of sulfate in surface or groundwater, (ii) saturated iron-rich soils and sediments for periods long enough to favour anaerobic conditions, and (iii) the availability of labile carbon to fuel microbial activity. Saline groundwaters in the Wheatbelt generally contain quite large concentrations of sulfate and ferrous iron. Thus, drains that intercept saline groundwater should be expected to accumulate some sulfides in their sediment over time, especially if they are permanently flowing or waterlogged. However, in some drains the ubiquitous presence of carbonates of calcium, magnesium and sodium in drain sediments and banks may neutralise drainage acidity. The extent to which this occurs, however, it dependent on whether the carbonates remain in contact with the acidic waters and are not armoured with precipitates or buried.

Monosulfidic material

Monosulfidic material or Monosulfidic Black Ooze (MBO) is readily observed in the surface sediments of most drains (Figure 23-1) and in receiving lakes (Figure 23-2). The high nutrient environment, especially at the edges of drains and the activity of algae and micro-organisms cause reducing conditions to develop and the formation of black, smelly iron monosulfides and other sulfides. Erosion of organic rich topsoils and influx of saline ground-water, with low redox potential (reducing), into the drains are also likely to contribute to MBO formation. MBO is very reactive if exposed to oxygen, but provided that the materials remain anoxic and undisturbed they are relatively non-reactive.

Sulfuric material – including gels and precipitates

Subaqueous soil horizons and sediments in some drains and receiving environments are highly acidic (pH < 3.5) and by definition classify as “sulfuric materials’ according to Isbell (2002). Acidity can form through several mechanisms:

(i) primarily by iron hydrolysis reactions or ferrolysis when anoxic ground water containing dissolved ferrous ions is exposed to air and ferrous ions are oxidised to the ferric ions, which reacts with water to form orange -brown precipitates, gels or crusts of ferric oxyhydroxides, releasing hydrogen ions in the process
(ii) When sulfidic materials are drained and exposed to air, they oxidise and produce sulfuric acid (e.g. Dent & Pons 1995)

In the WA Wheatbelt drains, the dominant source of acidity appears to be the acidic, oxidising, iron-rich shallow ground-water discharging to the drains (where the water is acidic prior to drainage), though formation of secondary minerals in the drain sediments provides additional pathways of acid storage and release.

Mineral precipitates and gels present in the drains were indicative of specific geochemical conditions occurring (or having occurred). The occurrence of bright yellow natrojarosite mottles in some of the clay-rich sulfuric horizons are indicative of acid conditions in the pH range 3.5-4. Similarly, the occurrence of orange coloured mottles, gels and crusts (Figure 23-1) are indicative of schwertmannite and akaganéite, which forms from the oxidation of ferrous iron in acid conditions in the range pH 4-5. Many of these minerals occurred in drains above the ground-water level, indicating that there is a store of acidity in soil profiles that could contribute to future, if not current drainage acidity. The minerals also present a reactive surface that can alter the solubility of trace metals in the drainage waters (see below). Saline and subaqueous soils with sulfuric material may occur in receiving lakes.

Salt crusts-sulfate-containing salt efflorescences and oxyhydroxysulfate minerals

Soluble sulfate/chloride-containing minerals in efflorescences are produced by evaporation of groundwater and capillary waters. These evaporite minerals reflect the geochemical reactions resulting from the combination of groundwater, drainage water and drained soils in regions. For example, zones under:

- alkaline conditions (e.g. surface soil horizons in the drain batters) where Na/Ca ratio > 4, eugsterite, gypsum and thenardite (i.e. Na-Ca-sulfate salts) form
- acid conditions (e.g. interface of groundwater and drain batter in the base of drains) where Na/Ca ratio < *4*; bloedite and pentahydrite (i.e. Na-Mg-sulfate salts) form

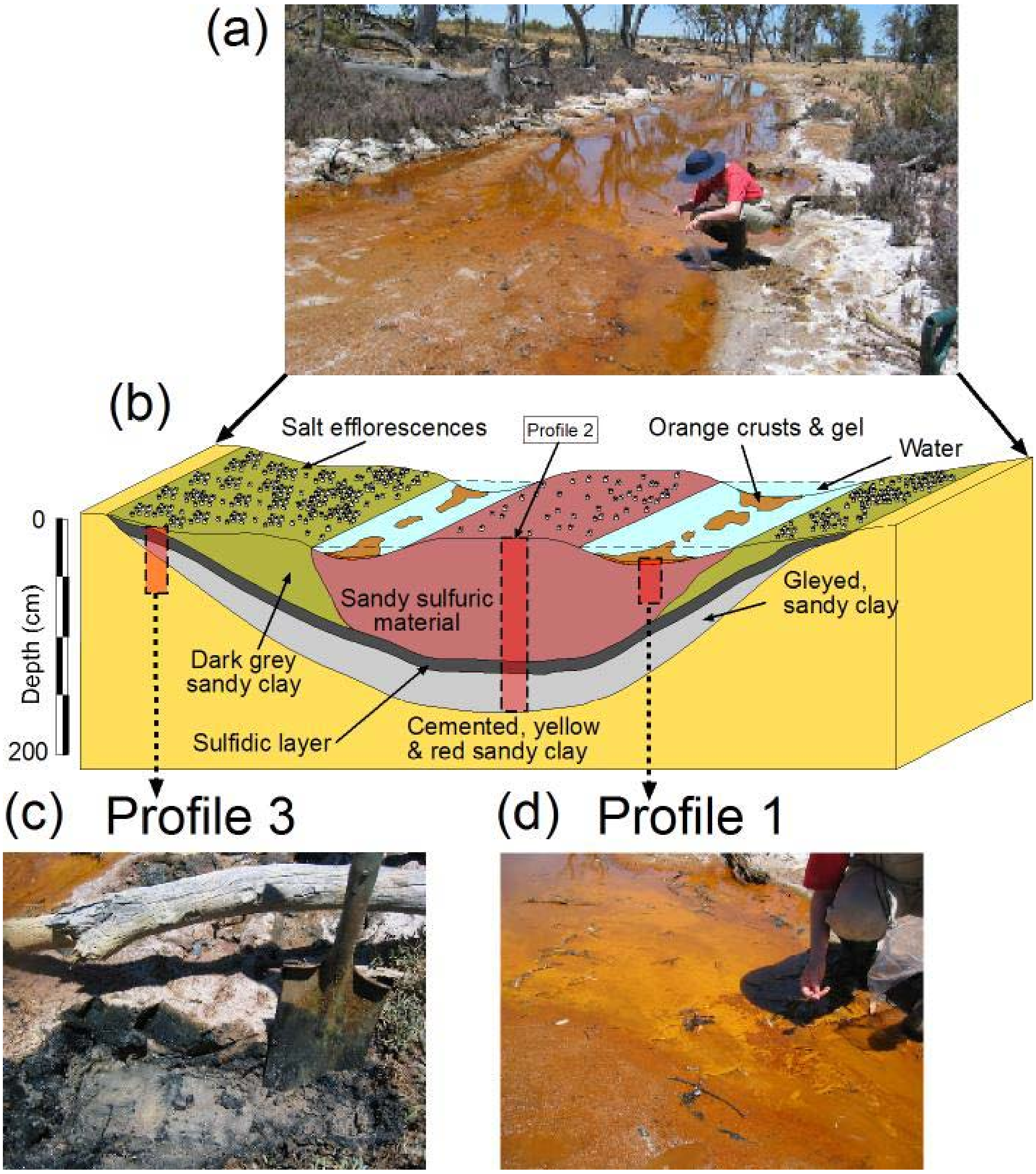


Figure 23-1. Descriptive soil-regolith toposequence model showing: (b) drain showing acid sulfate soils with orange crusts and gels (a and d) comprising mostly Fe-oxyhydroxides (akaganéite: β-FeOOH; see Profile 1) and Fe-oxyhydroxysulfates (schwertmannite: $Fe_8O_8(OH)_6SO_4$) in surface waters overlying soil horizons consisting of: (i) reddish sulfuric material (pH < 3.5), soft and sandy in Profiles 1 and 2, (ii) black sulfidic material (pH > 4) friable and sandy clay in profiles 1, 2 and 3, (iii) greyish gleyed sandy clay and (iv) yellow matrix with red mottles, hard, sandy clay. (c) White salt efflorescences occur on the sides of the drain in profile 3 overlying a mixture of uniform black, sulfidic material and monosulfidic black ooze, which in turn overlies mottles of black, sulfidic material in a yellowish-greenish-grey to olive mottled clay. (From Fitzpatrick *et al.* 2010a).

Acidic drainage waters have the capacity to acidify some lake bed sediments (e.g. Degens and Shand 2010; Degens *et al.* 2010; Fitzpatrick *et al.* 2010a). Seepage of acidic drainage waters into alkaline sediments (pH> 7 in 1:5 deionised water) was still evident at one receiving site (Gambles Rd, Cowcowing) where a thin layer of acidic surface sediments (pH< *4*, 0-1cm) overlay more alkaline bed sediments (pH> 6.3, 1-30 cm). There were no free carbonates in the deeper sediments of this lake, though these may have been present at some time in the past, since the bed sediments of an adjoining reference lake (Ski Lake, Cowcowing) contained up to 9% by mass $CaCO_3$ within the surface 15 cm.

The majority of acidity in acidic receiving and reference lakes (e.g. Figure 23-2 and Figure 23-3) is contained in the shallow sediments (< 40cm) rather than overlying waters (Degens *et al.* 2008a,b; 2010). Some sites contained up to several thousand times more existing acidity in sediments than in waters at the time of sampling in spring 2005 (Degens *et al.* 2008a,b). These results indicate that neutralisation of acidic waters in acidic drain receiving lakes must take into account the acidity store within the sediments since these will tend to buffer the pH of the system.

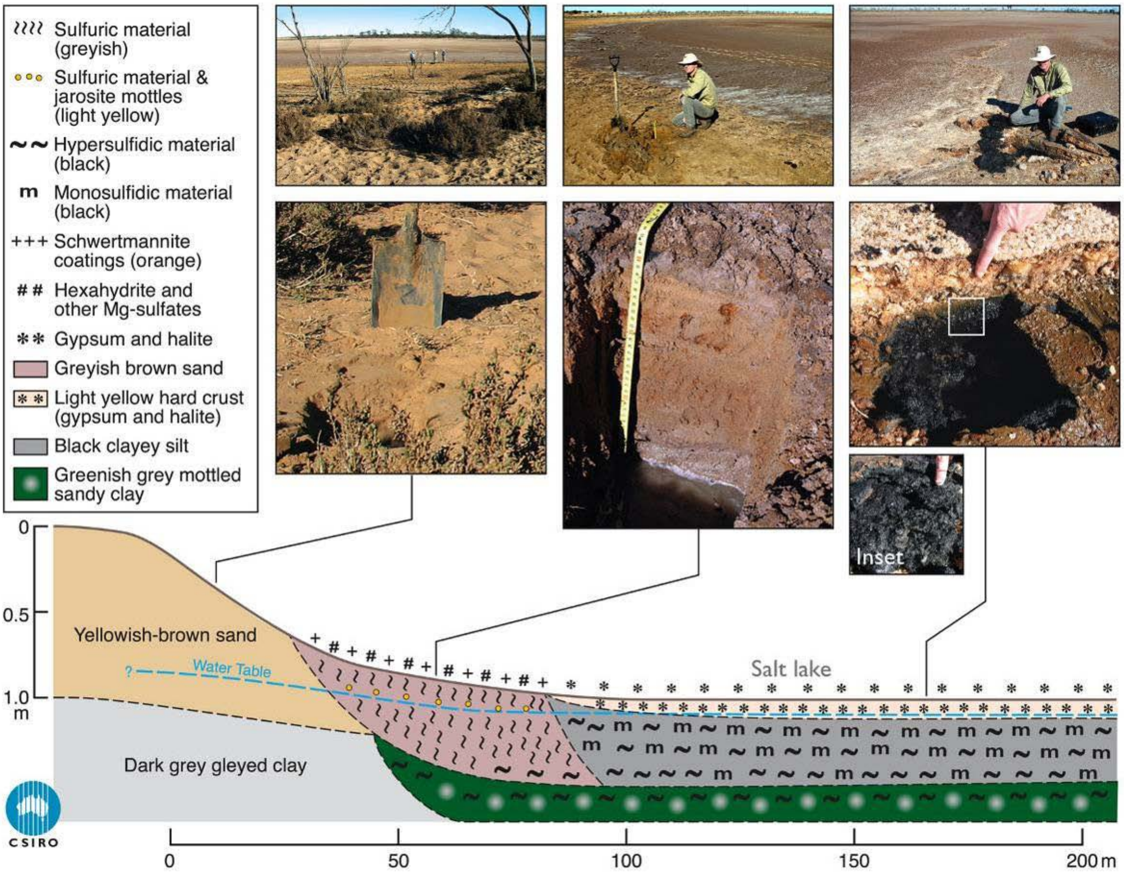


Figure 23-2. Descriptive soil-regolith toposequence model showing the occurrence and spatial distribution of ASS features (salt efflorescences) and materials (sulfuric, hypersulfidic and monosulfidic) along a representative transect across MacPhersons Lake (site M3 in **Figure 5-2**). (From Fitzpatrick *et al.* 2010a).

Significant amounts of reactive soluble and exchangeable acidity can be present in shallow lake sediments requiring up to 9.7 tonnes per hectare of pure limestone (as $CaCO_3$) to neutralise, even in acidic reference lakes. Notably, these estimates only indicate the more readily neutralisable acidity, generally present as exchangeable cations and soluble Al and Fe minerals, and do not include less reactive forms of acidity (Ahern *et al.* 2004) that were present as iron (e.g. jarosite and natrojarosite) and aluminium hydroxysulfate (e.g. alunite) minerals at some sites (Degens *et al.* 2010).

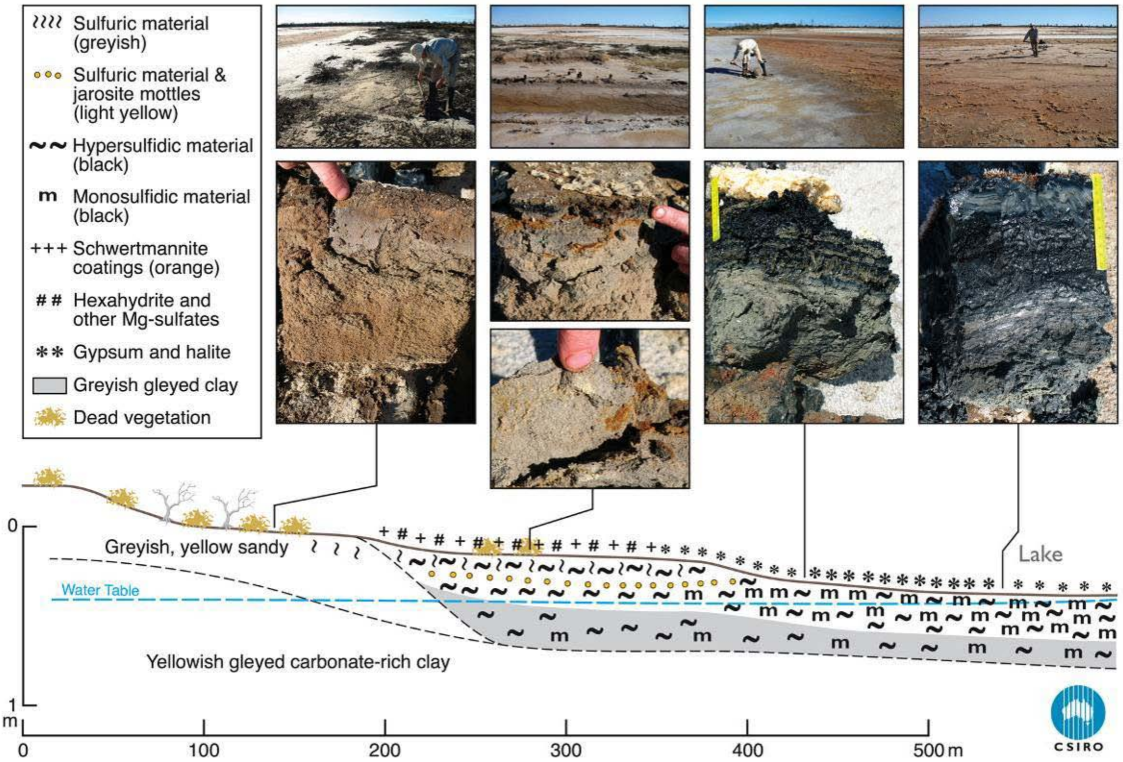


Figure 23-3. Descriptive soil-regolith toposequence model showing the occurrence and spatial distribution of ASS features (salt efflorescences) and materials (sulfuric, hypersulfidic and monosulfidic) along a representative transect across the Wubin-Carter road Lake (see site M2 in Figure 5-2). (From Fitzpatrick *et al.* 2010a).

Acidic drainage discharge to lakes can result in acidification of waters, soils and sediments and formation of inland ASS materials. However, in some cases lake waters and sediments may have been acidic prior to discharge in which case the impacts would depend on the magnitude of drain inputs compared with regional groundwater discharge. Concentrations of Al, Fe and trace metals including Pb, Ni, Co and U appear to have increased in the surface waters of sites receiving acidic drainage, particularly when compared with alkaline lakes. This acidification and associated increased trace metal solubility may result in impacts on aquatic ecosystems, including loss of habitat and reduced ecosystem functioning during lake filling events.

Lakes can be acidic in the absence of discharge from deep drains, most likely due to the discharge of regionally acidic ground-waters. Numerous acidic lakes occurring in the upper reaches of the Lockhart, Mortlock and Yilgarn catchments were found to be acidic with no evidence of deep drainage discharge. These lakes may have always been acidic since before land-clearing began, however, there is sedimentary evidence that some lakes may have become acidic in recent times. Notably, the acidic reference lakes exhibited geochemical conditions similar to those in lakes receiving acidic drainage.

Some existing alkaline lakes may be under on-going acidification pressure if discharge of regionally acidic ground-waters continues to occur (Degens *et al.* 2008a,b). For current acidic lakes, this will result in increasing acidification and accumulation of trace elements (determined by rates of ground-water discharge). For current alkaline lakes this could result in acidification.

Preliminary results from Degens *et al.* (2008a,b) indicate that acidic drain discharge does not necessarily result in readily distinguishable elevated accumulations of trace metals compared with lakes not receiving acidic drainage. Some concentration of trace elements may occur in the shallowest sediments of receiving lakes. However, the sampling density was too sparse for this to be certain. More detailed investigations would be required to predict which drains are likely to result in increased accumulation of trace metals in receiving environments compared with acidic reference lakes. These investigations should involve comparisons of paired lakes (acidic reference and acidic drain receiving lakes) as well as before-after investigations of trace metal accumulation in environments receiving acidic saline drainage.

Initial overflows from acidic lakes (both receiving lakes and non-receiving lakes) following rainfall events are likely to be laden with high concentrations of dissolved aluminium and iron and potentially high concentrations of trace metals. These may form significant concentrations of Al species (e.g. $Al(OH)^{2+}$, $Al(OH)_2^+$) that can be toxic to aquatic to some aquatic biota and iron floc (smothering benthic communities) on mixing with neutral/alkaline floodwaters. The greatest risk of this is likely to occur during the first flush part of flood-flows and for small rainfall events that result in localised lake filling, and therefore concentration of discharge, in the Avon. These will require greatest management emphasis.

23.3. Management options

Treatment comparison

In a comparative evaluation of treatment options it was clear that anaerobic compost treatment systems show most promise in achieving low–cost passive treatment of these waters over long time periods (Table 23-1). In comparison, lime-sand would have limited applications in treating acidic drainage waters containing high iron concentrations without use of fluidised flow systems with regular monitoring and maintenance (Table 23-1). Reasonable and consistent performance of lime-sand as a neutralising agent appears achievable with a pulsed flow lime-sand reactor offering a low-technology, potentially cheap option (based on the low cost of lime-sand) for waters with high acidity and few trace elements. However, full treatment using a lime-sand reactor would require multiple holding ponds and at least 2 treatment units. In contrast, treatment using the more reactive hydrated lime represents a very attractive option for the short term, though is not ideally suited to long-term treatment (over more than 12 months) due to ongoing pumping costs, reagent supply and reagent storage requirements (Table 23-1). An important consideration for all neutralising approaches is the need to trap and store iron and aluminium precipitates (which can adsorb and concentrate trace metals) prior to downstream discharge or re-use of waters (e.g. for desalination, saline aquaculture, solar ponds or salt harvesting). Within composting systems, these are mostly retained within the system design (i.e. not requiring removal).

Land availability may limit where compost wetlands can be used. A 300 m^2 pilot compost wetland treated acidic waters at a conservative, sustainable average of 1.1 kg $CaCO_3$ per day, which suggests that up to 1.2 ha of land would be required to treat average baseflow acidity loads from a drain discharging at 1 L/s (assuming a titratable acidity of 500 mg $CaCO_3$/L). Long-term effectiveness of this treatment depends on attention to design in order to handle expected acidity loads and use of organic materials that would support sustained rates of sulfate reduction. The trials demonstrate that even with a minimal mix of cheap and locally available organic materials (5-6% sheep manure in straw) it is possible to achieve extended treatment of highly acidic waters.

Table 23-1: Summary of effectiveness (acidity and trace metals) and operational maintenance requirements of a range of passive and active saline acidic drainage treatment options trialled in the WA Wheatbelt (Degens *et al.* 2008c).

Treatment Option	**Effectiveness (acidity)**	**Effectiveness (trace elements)**	**Operational maintenance requirements**
Passive lime-sand riffles (in-drain)	Very limited with Fe-rich waters (> 5 mg/L), greater with Al dominated acidity	Very limited adsorption of metals (poor Fe floc development)	• Retention of Al precipitates within drainage channels and regular cleaning (no Fe floc formation occurred) • Annual reapplication of lime to drains • Regular, monthly removal of iron crust will be required to achieve > 20% acidity treatment efficiency
Passive lime-sand lined storage/ evaporation basin	Initially high effectiveness (> 80% acidity) decreasing with time (beyond 1 month). Limited with Fe rich waters	Effective removal of some elements including Al, Fe, Pb and to a lesser extent U, Ce, La, but not Mn, Ni or Se.	• Annual removal and disposal of Al and Fe precipitates (with trace metals) and fine clays washed into basin may be required • Regular reapplications (broadcasting) of lime or removal of iron/gypsum crusts may be required to maintain high acidity treatment effectiveness
Active lime-sand tank reactor (vertical flow, fluidised reactor)	Can be > 100% during first 48 hours, sustained at 50-60% over longer term.	No removal in reactor. Dependent on elements treated & Fe floc formation (removal by adsorption to Fe precipitates/ sediments).	• Retention of Al and Fe precipitates (with trace metals) within settling tanks/ponds • Cleaning and disposal of Al and Fe precipitates (also likely to contain trace metals) • Ongoing addition of lime-sand and regular, monthly removal of non-reactive/armoured lime-sand • Pump maintenance and continuous power supply
Active hydrated lime dosing (dosing unit with pumping, dosing and mixing)	Highly effective for a range of acidity loads to target end-point pH. Aeration can be included to facilitate treatment of Fe-rich waters	Can be highly effective for most elements, except Mn and Ni (in trials).	• Retention of Al and Fe precipitates (with trace metals) within settling tanks/ponds • Cleaning and disposal of Al and Fe precipitates (also likely to contain trace metals) • Ongoing reloading of hydrated lime slurry (requiring specialist transport and on-site storage) • Pump, dosing and mixing unit maintenance • Continuous supply of power/fuel for pump
Passive anaerobic compost wetland	Can achieve > 100% treatment of acidity (pH> 6) for more than 6 months when design and organic mix is optimal.	Highly effective for a range of trace elements (e.g. Al, Cu, Cd, Fe, Ni, Pb, U, Zn) but not Mn.	• Periodic additions of new organic matter may be required (every 2–5 years) • Occasional cleaning of outflow pipes and flow checks
Passive in-drain anaerobic compost system	Can achieve > 100% treatment of acidity (pH> 6) for more than 6 months when design and organic mix is optimal.	Highly effective for a range of trace elements (e.g. Al, Cu, Cd, Fe, Ni, Pb, U, Zn) but not Mn.	• Periodic additions of organic matter may be required (possibly every 2–5 years) • Sediments will require on-site containment and/or treatment on cleaning of drains (every 5–10 years)

The uncertainties regarding performance of individual passive treatment options over months to years can potentially be offset using a combination of sequential treatment options distributed throughout a drainage network (often called a treatment train). This can potentially provide some level of redundancy and capacity to handle changes in acidity loads over future years. Use of multiple options distributed throughout a drainage system also mitigates risks due to under-sizing treatment options. The success of many passive treatment options is dependent on sizing to handle expected acidity loads, which may be difficult to obtain for WA Wheatbelt drains prior to construction.

Management Implications (modified from Degens *et al.* 2008c)

- Marginal gains in acidity treatment and metal removal can be made with cheap, low-technology passive treatments using a range of locally available materials
- Anaerobic compost-based treatment systems can effectively treat acidic drainage waters removing a wide range of trace elements, but construction will require land area, and consistent performance depends on correct sizing and use of suitable mixtures of organic materials during construction
- Passive treatment options are likely to be most applicable in many Wheatbelt drains over the long term since landholders are not likely to have the time to maintain and service active treatment systems. Passive treatment options concentrate effort in the design and construction stages
- It may be possible to integrate passive treatment options of acidic drainage waters within drainage systems to achieve progressive neutralisation of acidity and removal/retention of trace metals at source and during transit along drains. This may also need to be followed by final polishing treatment at the discharge point of drains
- Active treatment can be highly effective in treating acidic drainage waters, but will involve greater on-going maintenance and costs than passive treatment systems
- Acidic lakes due regional ground-water discharge (i.e. not drainage) may require management of geochemical risks including acidity and soluble trace metals to protect alkaline down-stream environments
- Acidic ground-water discharge is best managed by containment and/or treatment in sites with minimal risk of down-stream transport, which may be difficult to achieve for discharge to lakes in the central floodway
- Where drains discharge acidic waters to sites with poor containment, management of geochemical risks to down-stream environments will need to focus on acidic and metal mobilisation occurring during the first flush
- Containment of acidic saline discharge may require treatment with neutralising agents (e.g. limestone or coastal lime-sand) at regular intervals, depending on the risk to down-stream environments. This periodic treatment of accumulated acidity may be more cost effective than continuous treatment of drain discharges, which can be difficult in remote sites
- Soils with carbonates surrounding receiving environments could be mixed into the bed or used to line lakes to provide some capacity to neutralise acidic waters and sediments
- Use of alkaline flood flows to neutralise acidic sediments in acidic lakes may only be likely with significant volumes of water and flooding time.

It is vital for all landholders, community groups, drainage contractors and local governments in the Avon catchment to be aware of the many impacts that result from: occurrence of sulfuric materials and disturbance of sulfidic materials as these have important consequences for environmental, engineering, economic, and quality of life perspectives. Disturbance and oxidation of sulfidic material can destroy wetlands, acidify and deoxygenate waterways and increase the incidence of fish kills and disease, contaminate valuable groundwater resources and public park space, facilitate the mobility and accumulation of heavy metals, corrode, attack and destabilise roads, concrete and steel infrastructure, stimulate blooms of marine blue-green algae, decrease the agricultural productivity of land, increase odour problems and increase mosquito and arbovirus incidence.

24. Wetlands on the Gnangara Mound, Western Australia (Area N in Figure 5-2)

24.1. Background and Environmental Setting

The Swan Coastal Plain is a region covered by sandy, aeolian sediments that abuts the Indian Ocean coastline between about Geraldton and Busselton in Western Australia, and is bounded to the east by the Darling Fault (Figure 24-1). These sediments form a regionally extensive unconfined aquifer, which contains a number of distinct groundwater flow systems. The Gnangara Mound is one such flow system located in the Perth region, which provides about 314 GL per annum of groundwater for Perth.

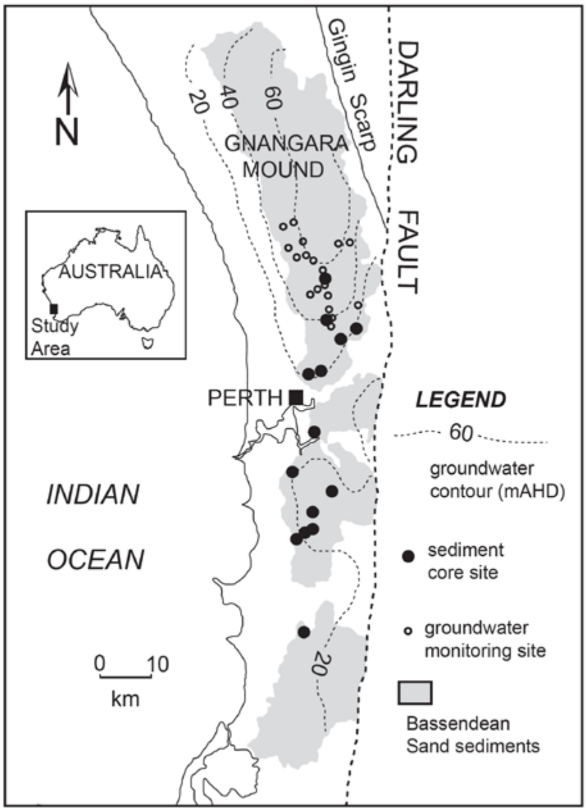


Figure 24-1 Regional map of extended Perth region (modified from Appleyard, *et al.* 2006, 2008)

Groundwater on the Gnangara Mound flows from an area of elevated dunes, which form the crest of the mound, radially towards the coast, rivers and estuaries which are the boundaries of the flow system (Figure 24-1). The dune sediments near the crest of the Gnangara Mound consist of highly leached white to grey-coloured siliceous sands of Pleistocene age (Bassendean Sands), which have been extensively podsolised. Groundwater-dependent wetlands occur in swales between dunes where the water table is shallow.

Annual rainfall on the Gnangara Mound has been typically about 30% below the long-term average of average of about 800 mm since 1975, a trend, which is consistent with predicted rainfall-declines for the region made by global climate change models (IOCI 2002). During this period, the combined effects of low rainfall, high rates of groundwater use, and reduced recharge in areas covered by pine plantations have caused the water table on the Gnangara Mound to decline by up to 5 m, and aquifer storage to decline by about 500 GL (Appleyard & Cook 2008).

As a result of these factors, a number of wetlands are progressively acidifying in areas on the Gnangara Mound, which have a high rate of water table decline (Degens & Wallace-Bell 2009; Sommer & Horwitz 2001; Searle *et al.* 2010), and shallow groundwater in these areas is typically acidic (pH values often less than 4.5, and as low as 3.0) with elevated concentrations of sulfate, and metals including Al, Fe, Zn, Cu, Ni and Pb (Cook *et al.* 2006; Appleyard & Cook 2008). Acidification is particularly rapid in wetlands that have dried sufficiently to allow bushfires to burn peaty lake sediments, which contain pyrite (Horwitz and Sommer 2005; Figure 24-2).

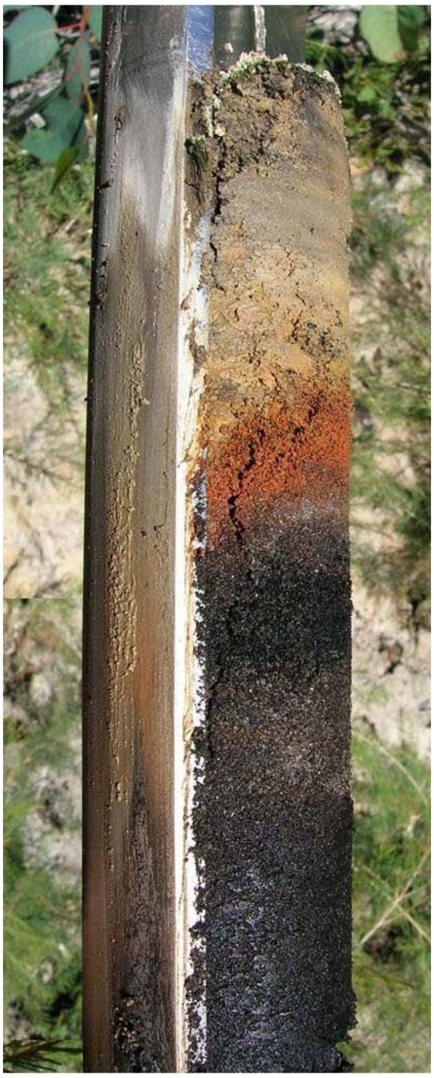


Figure 24-2 Burnt soil profile from the Wilgarup within-wetland core (from Horwitz *et al.* 2007)

24.2. Acid Sulfate Soil Processes and Hazards

Soil and groundwater investigations on the Gnangara Mound (Appleyard & Cook 2008; Degens & Wallace-Bell 2009; Prakongkep *et al.* 2010; Searle *et al.*, 2010; Figure 24-1) have indicated that both sands and peaty lake bed sediments in this region contain pyrite, and release acidity and soluble metals due to oxidation. The sulfur in pyrite in these materials is likely to be derived from the deposition of sulfate aerosols in the region, both of marine origin and from historical air pollution (Hingston and Gailitis 1976; Appleyard and Cook 2008). Groundwater contamination by arsenic has been recorded, resulting from the oxidation of arsenic-containing pyrite (Appleyard *et al*. 2006).

Investigations of the Gnangara Mound suggest that soils in this region have acidified as a result of regional water table decline and air pollution, and consequently an acidification front has penetrated between 4 and 10 metres below the land surface in many areas. Geochemical modelling (Ward *et al.* 2010) suggests that the current acidification phase commenced in the early part of the 20th century with the increased use of fossil fuels in the region. A conceptual soil-regolith model of the problem is depicted Figure 24-3, including the multiple sources and consequences of acidification.

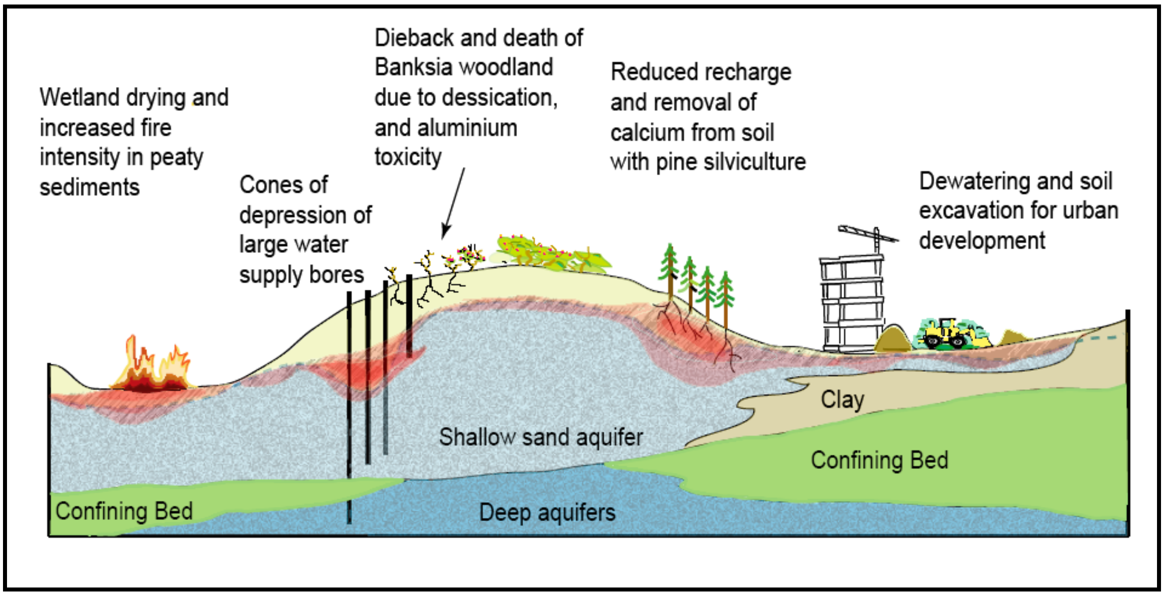


Figure 24-3 Soil-regolith model of acidification sources on the Gnangara Mound (DEC, 2008)

The properties and behaviour of many sandy aquifers in terms of chemistry are unique in that the non-calcareous conditions provide poor buffering mechanisms. These sediments are, therefore, particularly vulnerable to the progressive leaching of calcium and magnesium over time. This can be seen in aquifers where there is an increase in the concentrations of these ions with depth (Kjøller *et al.*, 2004). Acidification affects aquifers that are lacking in carbonates or silicate minerals as these sediments are more susceptible to this process due to their limited buffering capacity. However, acidification in undisturbed soil occurs over long periods of time (tens of thousands of years), and under normal conditions an equilibrium is developed that maintains a stable soil profile (DEC, 2008).

This equilibrium can be disturbed by a number of factors that contribute to gradual acidification of the soil and groundwater. Acidification in these sandy soil profiles is facilitated by a number of factors, both natural and anthropogenic:

- Low rainfall
- Changes to atmospheric quality
- Decomposition of organic matter
- Oxidation of pyritic soils

- Low buffering capacity (lack of primarily carbonate minerals)
- Changes to water table levels
- Prolonged drought
- Urban development
- Dewatering
- Limited recharge capacity

As a consequence of one or a combination of these factors, the soil can be exposed to oxygen, which then acts as the catalyst for the oxidation of sulfides that may be present, resulting in the production of sulfuric acid. The Gnangara mound is underlain with Bassendean Sands of Pleistocene age, sediments which have a limited capacity to neutralise acidification (Appleyard and Cook, 2008). Groundwater in 2008 is present at depths up to 1500 m below the surface in a Permian aquifer and recharge is largely dependent on seepage from Quaternary sediments due to the unconfined nature of the aquifer. The siliceous sediment at the top of the soil profile is largely depleted of base cations by natural causes and the groundwater flow system is dominated by the elevated nature of the mound causing the water to flow in a radial manner towards the coast and tributaries (Appleyard and Cook, 2008). According to Appleyard *et al.*, (2004; www.water.gov.au), the groundwater resources comprised 70% of Perth's total water supply (and a 5 m decline in the water table on the Gnangara mound has been estimated over a 20 year period with the storage depleting at a rate of 25 GL per year (Salama *et al.,* 1999; Yesertneer 2002; Vogwill 2004). In 2004, 320 GL per year was authorised for use in supplementing the population's water supply from the Gnangara mound. Additionally, unlicensed domestic bores may account for 60 GL per year (McCrea, 2004). Annual rainfall recharge in the main wet season is 800 mm (long term average) mainly from May to October. However, it is important to note that the rainfall values at present have been much lower than the recorded long term average in this region of Western Australia, a trend which may be partially attributed to local climate change.

The Gnangara mound also harbours a large area of intermittent wetlands that rely on the groundwater resource in the area. Also of environmental importance are the woodlands that are habitat for Banksia species. According to van Tol *et al.* (1998), modified geochemistry in the soil and shallow groundwater, which is caused by natural and more extensively anthropogenic interference, has the potential to significantly harm these ecosystems. These wetland ecosystems are being heavily impacted, primarily by disturbance causing a declining pH, associated aluminium release and the natural leaching of base cations. Peaty wetlands and lakes occurring in parts of the Gnangara mound are known to experience acidification events at regular intervals due to the presence of pyrite and a decline in the water table caused by low rainfall, low recharge and continued drainage for urban water consumption (DEC 2008).

24.3. Management options

This involves educating the public to the appropriate use of limited resources by making domestic households more sustainable by the installation of water saving devices and limiting water consumption. Also associated with this is increasing awareness among not only the public but also state and local government bodies; industrial and commercial sectors; and other private corporations and stakeholders that share the problem of limited water supply, especially where there is risk of contamination with toxic metals.

Remediation of areas where problems have already become significant is vital and can be achieved due to the reversible nature of acidification and trace metal desorption. Whilst current remediation techniques are quite costly and intensive, if they are to be effective, they can be applied simultaneously to optimise the return to a near natural environment for the aquifer. This may include:

- Artificial water replacement - the initiation of water augmentation for a number of lakes inhabiting the Gnangara mound have proved to be successful based on previous studies and have improved the conditions of the water chemistry following the gradual acidification of these water bodies due to drought, low rainfall and groundwater withdrawal (DEC, 2008). For example, Lake Jandabup has improved in terms of a rise in pH to that which is close to neutral and capable of sustaining biodiversity in this ecosystem. Deterioration of biodiversity had been evident due to acidification, however macro-vertebrates began to return after water levels were artificially supplemented. The limiting factor in this solution is the source of water supply. Drought has rendered the restriction of water resources in Western Australia, however treated wastewater is a viable and effective supplement
- Increasing the buffering capacity of the aquifer profile by increasing the carbonate content in the sediment will effectively reverse acidification over time. A rise in pH will also result in the decline in metal concentrations through adsorption. The most common technique is liming. The problem with this solution is that intensive liming is costly and difficult if the area is large, which is usually the case. Another disadvantage is that the reversal of ion exchange processes occurs over a time-scale equal to that which it took for the problem to occur (Appleyard and Cook, 2008).
- The use of the Gnangara mound as a water resource for the supply of the Perth population requires that intensive monitoring and implementation of a drastic management plan is instigated to ensure that there is no risk to the public. The threat of acidification and elevated trace metals also extends to fragile ecosystems that occupy the Gnangara such as wetland, woodland and lake systems. These hold significant environmental value and are known to suffer from inhibited plant growth and biodiversity loss as a consequence of modified geochemistry due to anthropogenic interference.

List of Figures

List of Tables

Contact Us

Phone: 1300 363 400
+61 3 9545 2176

Email: enquiries@csiro.au

Web: www.csiro.au