Understanding and Managing Irrigated Acid Sulfate and Salt-affected Soils

A handbook for the Lower Murray Reclaimed Irrigation Area

Rob W Fitzpatrick • Luke M Mosley • Freeman J Cook

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The services provided by soils to improve water quality and the resilience and profitability of farming systems are irreplaceable and invaluable! Importantly, if agriculture technologies are directed at improving soil and water quality, a more holistic perspective must be adopted to ensure that agricultural intervention will be both sustainable for whole landscapes and adopted by farmers and communities. Hence now, more than ever before, we need to manage soil and water resources wisely.

The aim of this handbook is to provide the 'basic rationale and describe a set of practical office, field observation and simple chemical test surrogate methods' in order to assist farmers, land managers, agencies and service providers to identify, sample, characterise, classify and map soils and waters so as to better manage degraded landscapes in the LMRIA.

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Using soil-water landscape maps for farm management planning

Soil/water features and materials	Code	Definitions
Subaqueous condition/soils	W	Surface water levels, 2.5 m below the surface water level
Hydric condition/soils	Hyd	Surface water levels, 0.50 m above the surface water level
Unsaturated condition/soils	Uns	Drained soils with water level below 0.50 m
Salt efflorescences	Ef	Fluffy salt accumulations (e.g. gypsum and halite)
Gypsum/Halite crusts	Gyp	See Glossary (Appendix 9)
Calcareous materials	Ct	See Glossary (Appendix 9)
Shells	Sh	Hard, protective outer layer created by an animal that lives in the sea or inland environments
Organic-rich material/soil	Or	See Glossary (Appendix 9)
Clays	Cy	See Table A1-2*
Sands	Sa	See Table A1-2*
Loams	Lo	See Table A1-2*
Sulfuric material/soil	Su	See Appendix 3*
Hypersulfidic material/soil	He	See Appendix 3*
Hyposulfidic material/soil	Ho	See Appendix 3*
Monosulfidic material **wet**	Mow	See Appendix 3, Table A3-1* with n-Value greater than 1
Monosulfidic material **dry**	Mod	See Appendix 3, Table A3-1* with n-Value between 1 and 0.7
Reddish Fe-rich precipitates/gels	Rp	Reddish-yellow Fe-rich precipitates/gels (schwertmannite-rich)
Saline soils	Sal	See Appendix 2, Table A2-1*
Sodic soils	Sod	See Appendix 2, Table A2-1*

* For more details see Fitzpatrick et al. 2017.

Table 1. Example of soil map units and associated map unit codes and soil hazard rating classes

Profile No	Acid Sulfate Soil Subtypes, Saline or Sodic Soil groups + Conditions and features	MAP UNIT CODE	Soil hazard rating classes	Index rating (Map unit)
A-A': a1	Sulfuric subaqueous clay soil with red precipitates	Su, W, Cy, Rp	High	8-10
A-A': a2	Sulfuric cracking clay soil + hydric salt efflorescences	Su, Cy, Hyd, Ef		
D-D': d1	Hypersulfidic subaqueous organic soil	He, W, Or	Moderate	6-7
D-D': d2	Hypersulfidic subaqueous clay soil	He, W, Cy		
	Other soils (non-acid sulfate soil subtypes)			
E-E': e1	Hydric yellow loamy soil with gypsum crusts	Hyd, Lo, Gyp	Low	2-5
E-E': e2	Unsaturated red sandy sodic soils	Uns, Sa, Sod		

Figure 2. Soil subtypes with associated soil hazard rating classes along transects A-A' and B-B' and boundaries entered on the aerial photograph for drain and paddock at Long Flat.

Based on the soil-water landscape map units and associated soil hazard rating classes displayed in Table 1 and on the map overlay shown in Figure 2, management options can be made as part of a farm property management plan for each map unit as displayed in the soil sequence in the centre section of this field sheet.

A field sheet to identify and manage acid sulfate, salt-affected and waterlogged soils in the Lower Murray Reclaimed Irrigation Area, South Australia

Rob W Fitzpatrick • Luke M Mosley • Freeman J Cook

1. From field assessment of your soils and landscape features, match them with the soil sequence displayed in the centre section of this field sheet.
2. Not all soil subtypes will occur, so also check by obtaining soil samples using a soil auger (a gouge auger is ideal) followed by identifying the soil subtype using visual field indicators (e.g. surface cracks, colour) and laboratory indicators (e.g. pH) as outlined in the Handbook (see Fitzpatrick et al. 2017) for the most likely soil subtype in your paddock.
3. Identify and implement appropriate management options in the centre section of this field sheet.

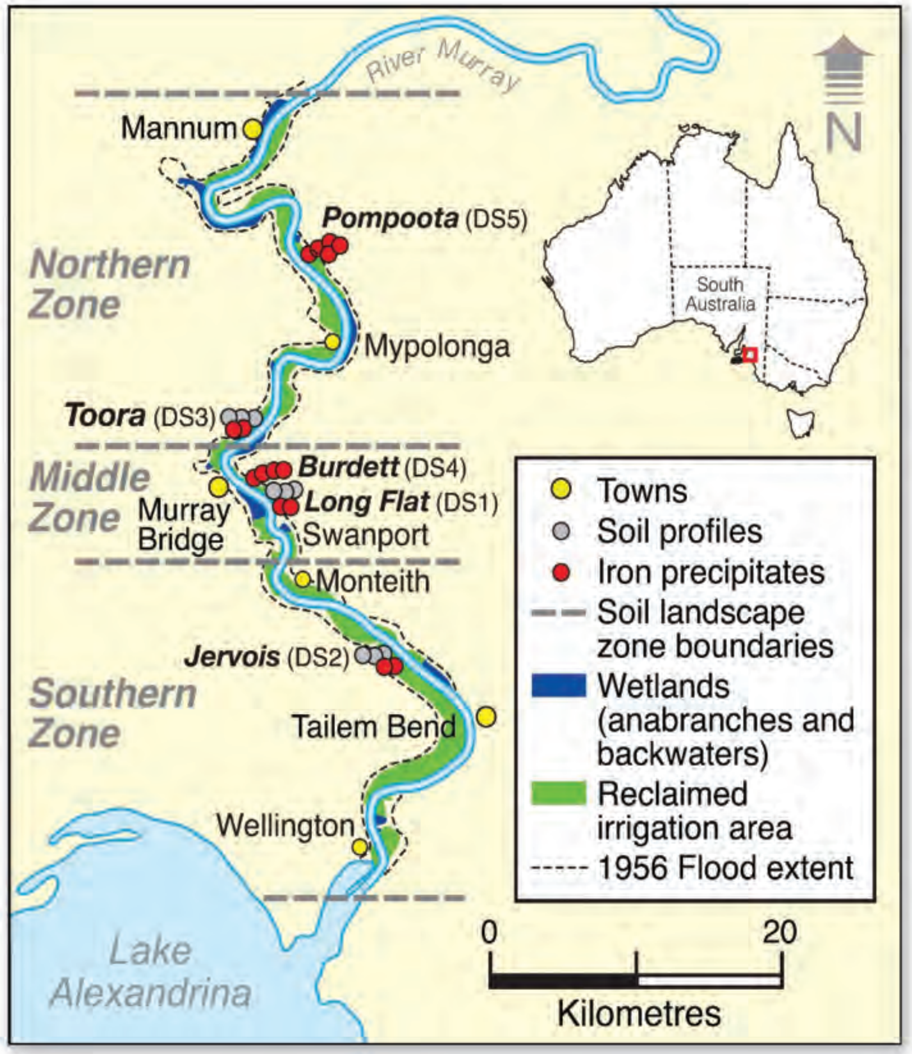

Figure 1. Map of the Lower Murray Reclaimed Irrigation Area (LMRIA) showing the distribution of the three soil landscape zones, adjacent natural wetlands (anabranches and backwaters) and the 1956 flood extent.

This fieldsheet is part of the handbook; Fitzpatrick, RW, Mosley, LM and Cook, FJ. (2017). *Understanding and managing irrigated acid sulfate and salt-affected soils: A handbook for the Lower Murray Reclaimed Irrigation Area.* Acid Sulfate Soils Centre Report_086. University of Adelaide Press. DOI: https://doi.org/10.20851/murray-soils

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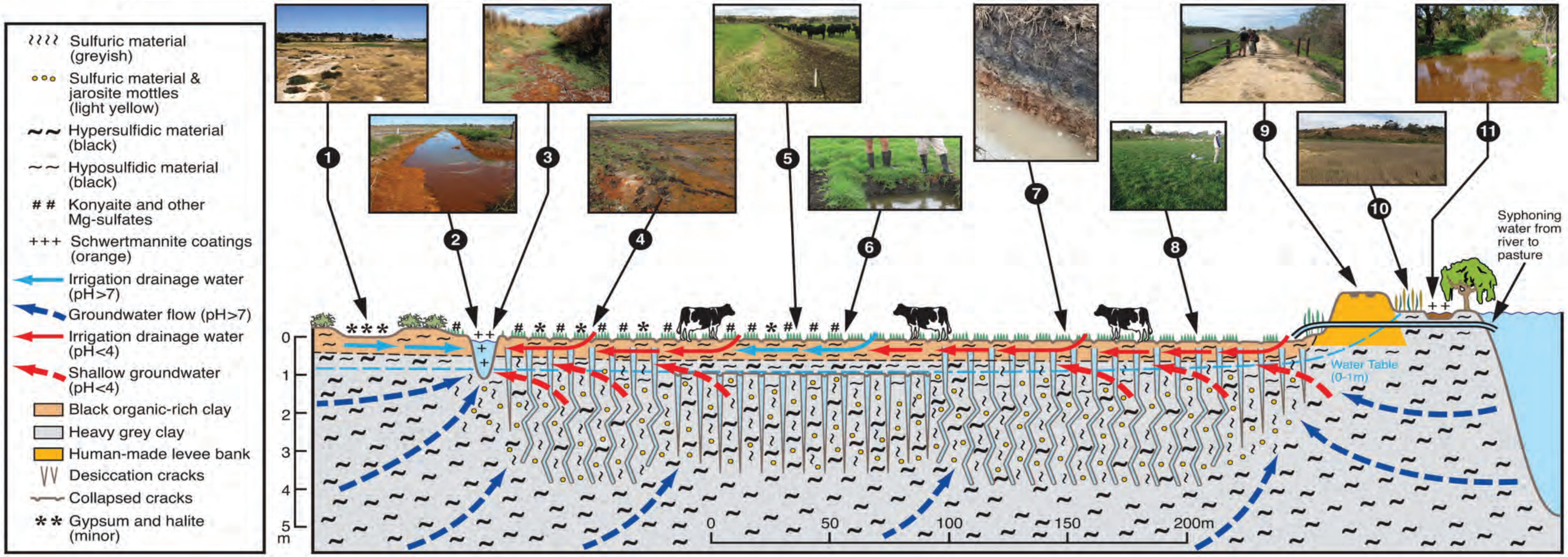
Generalised schematic cross-section diagram displaying the sequence of soil-water features, soil types, water flow paths and management options

Soil-water landscape feature No	1 Back-swamp area	2 Salt Drain (ponded water) WINTER	3 Salt Drain (dry) SUMMER	4 (North/Mid zone) Bottom end of paddocks	5 (North/Mid zone) Floodplain soils (0-1 m depth)	6 (North/Mid zone) Floodplain soils (1-3-5 m depth)	7 (North/Mid zone) Floodplain soils (>3.5 m depth)	8 (South zone) Floodplain soils (>3.5 m depth)	9 Levee Bank	10 Riparian zone (near river)	11 River Murray
Summary of major management options	Keep drainage infrastructure operating effectively. Irrigate if possible Fence to exclude stock. Plant salt tolerant grasses. Add lime to areas that that are strongly hypersulfidic	Keep the main drain water level around 0.5 to 0.75 m below paddock surface. Maintain banks and infrastructure Keep drains clear of vegetation Limestone dosing (if acidic)	Limestone dosing Keep the main drain water level > around 0.75 m below paddock surface. Maintain banks and infrastructure	Plant perennial pasture tolerant to salinity and waterlogging. Plant moderately salt tolerant Agroforestry. Remove stock in wet periods. Apply gypsum or limestone (if required)	Maintain height of water in the river at +0.5m AHD or greater to enable flood irrigation. Maintain irrigation efficiency	Soil cracking & land subsidence management	Soil cracking & land subsidence management. Flushing of acidity	Soil cracking & land subsidence management	Maintain river levels to prevent bank cracking & subsidence. Repair and maintain banks. Maintain irrigation infrastructure	Maintain wetland vegetation. Minimise drainage volumes and water quality impacts	Maintain suitable river levels (>0.5 m AHD) and salinity (<1,000 EC)
Soil & water problems	Waterlogging, salinity, sodicity	Acidification, water pollution, infrastructure damage	Acidification, salt efflorescences wind pollution	Salinity, sodicity, waterlogging acidification	Cracking, heaving, slumping, low fertility, salinization, water logging infrastructure damage	Compaction during drought	Deep cracking, oxidation and acidification (during drought)	Deep organic-rich clayey soil; oxidation and acidification (during drought)	Cracking, slumping and leaking	Waterlogging, encroachment by vegetation	Low River Level (<0.5 m AHD) High salinity
General soil-water description	Strongly waterlogged, saline and/or eroded	Main & side drains leading to drainage pump, level controlled by irrigation and pumping operation. Ponded after Millennium drought followed by reflooding or winter rains (saline, acidic, nutrient-rich)	Main & side drain systems: Drained / dry after Millennium drought &/or summer (salt efflorescences saline, acidic, nutrient-rich and monosulfidic material)	Cracking clays (Vertosols), hypersulfidic material with salt efflorescences and brownish precipitates	Cracking clays (Vertosols), hyposulfidic material (contain insufficient pyrite to acidity) with salt efflorescences and/or brownish precipitates	Cracking clays (Vertosols) hypersulfidic material (contain pyrite and would acidify to pH<4 if exposed to oxygen)	Cracking clays (Vertosols), sulfuric material (pH<4 after millennium drought)	Organic-rich clayey soils with sulfuric materials (pH<4 after millennium drought)	Excavated an compacted clay material (human-made soil)	Organic-rich clayey soils with hypersulfidic material (contain pyrite and would acidify to pH<4 if exposed to oxygen)	River Murray – water level controlled by upstream flows and barrages in Lower Lakes. Ponds in the mixing zone of drain discharge into the River Murray.
Soil-subtype (soil key)	Strongly waterlogged saline and sodic cracking clay soil	Sulfuric subaqueous clay soil with brownish precipitates	Sulfuric clay soil with brownish precipitates/salt efflorescences and monosulfidic material	Hypersulfidic cracking clay soil with salt efflorescences/ brownish precipitates	Hyposulfidic cracking clay soil	Hypersulfidic cracking clay soil	Sulfuric cracking clay soil	Sulfuric organic soils (clayey and hydric)	Anthropogenic clay soil	Hypersulfidic organic soils (clayey and hydric)	Hypersulfidic subaqueous clay soil with brownish precipitates



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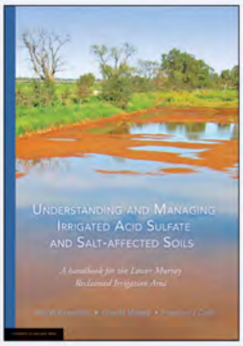

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Acid Sulfate Soils Centre (ASSC), The University of Adelaide

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Executive summary

Extreme drought conditions from 2007 to 2010 (the 'Millennium Drought'), resulted in the lowest River Murray levels (1.75 m decline from average) in over 90 years of records below Lock 1 in South Australia. This placed increased pressures on existing water resource, land use and soil management practices in the Lower Murray Reclaimed Irrigation Area (LMRIA), making sustainable soil management much more difficult. The crisis of declining soil/water quality and productivity in the LMRIA is also the result of dysfunctional land and water management systems in many irrigation areas, which was exacerbated by the drought and restructuring of the region in the 2000s. Over the past decade or so there has been a marked 'demand pull' for soil and water quality information in the LMRIA at a high level of policy- and decision-making in South Australian and Commonwealth Government agencies, especially for acid sulfate soils (ASS) and salt-affected soils.

The services provided by soils to improve water quality and the resilience and profitability of farming systems are irreplaceable and invaluable! Importantly, if agriculture technologies are directed at improving soil and water quality, a more holistic perspective must be adopted to ensure that agricultural intervention will be both sustainable for whole landscapes and adopted by farmers and communities. Hence now, more than ever before, we need to manage soil and water resources wisely.

There are numerous ways in which agriculture can contribute to improving soil and water quality. For example, this can be achieved by closely coupling agriculture to land management by developing a set of field soil-water indicators (for example, soil-water colour) in the form of a user-friendly soil identification key to classify soil subtypes, which are linked to land use options with the aid of a schematic cross-section diagram with colour photographs of soil-water features.

The aim of this handbook is to provide the 'basic rationale and describe a set of practical office, field observation and simple chemical test surrogate methods' in order to assist farmers, land managers, agencies and service providers to identify, sample, characterise, classify and map soils and waters so as to better manage degraded landscapes in the LMRIA. This handbook comprises 12 sections and involves the following two main phases of activity:

- ***office assessment phase***, using aerial photographs of paddock/farm to demarcate paddocks, drains and wetlands undergoing land degradation (for example, salinity, acidification)
- ***field assessment phase***, by undertaking field visual observations, with the aid of a schematic cross-section diagram with colour photographs of soil-water features, soil profiles and water flow paths, followed by simple chemical measurements of soil properties in the field, in order to
    i. identify soil subtypes with associated soil hazard rating classes
    ii. demarcate soil-water boundaries on aerial photographs to produce a soil map
    iii. assign to each soil map unit a soil-water hazard class to produce a colour-coded soil-water hazard map (red is associated with highest hazard, amber with moderate hazard and green with lowest hazard) with appropriate soil-water management options.

This information is designed to be used by farmers, land managers, agencies and service providers to provide land management options as part of farm property management plans which incorporate options that help prevent the spread of acid sulfate and salt-affected soils. These options are targeted to specific parts of the landscape (for example, irrigated floodplain land, drains, levee banks) and should be incorporated into farm management plans.

1

Purpose

The aim of this handbook is to provide the basic rationale and describe a set of data requirements/soil indicators that provide instruction to conduct soil investigations for the assessment and management of acid sulfate soils, salt-affected soils and all other soils in the Lower Murray Reclaimed Irrigation Area (LMRIA; Figure 1-1). This handbook is overwhelmingly focused on linkages between soils, irrigation, water quality and drought/seasonal conditions in the LMRIA. Climate variability and change are important considerations for the sustainable management of the LMRIA's water resources and hence future food security.

The limited amount of quality soil and water information in the LMRIA at a scale relevant to decision-making at both regional and paddock scale indicated the need for an improved system in the form of a handbook for farmers, land managers, agencies and service providers to provide land management options as part of farm property management plans. This handbook incorporates options that help prevent the spread of acid sulfate and salt-affected soils.

Experience gained from conducting over 70 case study investigations across Australia, together with research by CSIRO and the Acid Sulfate Soils Centre (ASSC), has led to the development of several practical handbooks for assessment and management of soils in badly degraded areas to help farmers and regional advisors (for example, Appendix 5; Fitzpatrick et al. 1997, 2003; Cox et al. 1999). However, this handbook has been expanded to also include a review and historical background information to explain how drought and subsequent reflooding events changed the LMRIA soil-water landscape and led to the development of severe and widespread acidification, especially during and after the Millennium Drought. As a consequence, this handbook substantially expands on earlier soil assessment manuals to incorporate

1. recent field assessment and interpretation information based on numerous case investigations conducted by the ASSC in the LMRIA (for example, Fitzpatrick et al. 2017a,b; Mosley et al. 2017a,b)
2. water quality and irrigation information (for example, Mosley et al. 2014a,b; Mosley and Fleming 2008, 2009, 2010).

There are various approaches, phases, stages and steps for ensuring that objectives are achieved, but there is no 'authoritative one-size-fits-all' field and laboratory methods soil handbook for the LMRIA. The approach and method of each soil investigation in the LMRIA have to be taken on each site's merits according to the characteristics of the particular site, existing conditions and constraints (for example, extreme drought or flood conditions), but the investigation must involve using standard methods to record, describe, analyse, classify and map soils (Fitzpatrick 1999 et al., 2013).

In the LMRIA, there is a distinct danger that traditional soil science, agronomy, pasture science and horticultural resources are being diverted away from food production to solve the declining land and water availability issues (i.e. in favour of alternative engineering solutions). Hence, this handbook will address the following issues:

- the critical role of soil and water management, both in the context of extreme drought conditions and the likelihood that such conditions may become more frequent, widespread and intense
- the need to rethink soil management for food security in the LMRIA given the growing understanding of the importance of acid sulfate and salt-affected soils and how they degrade the productive capacity of the region.

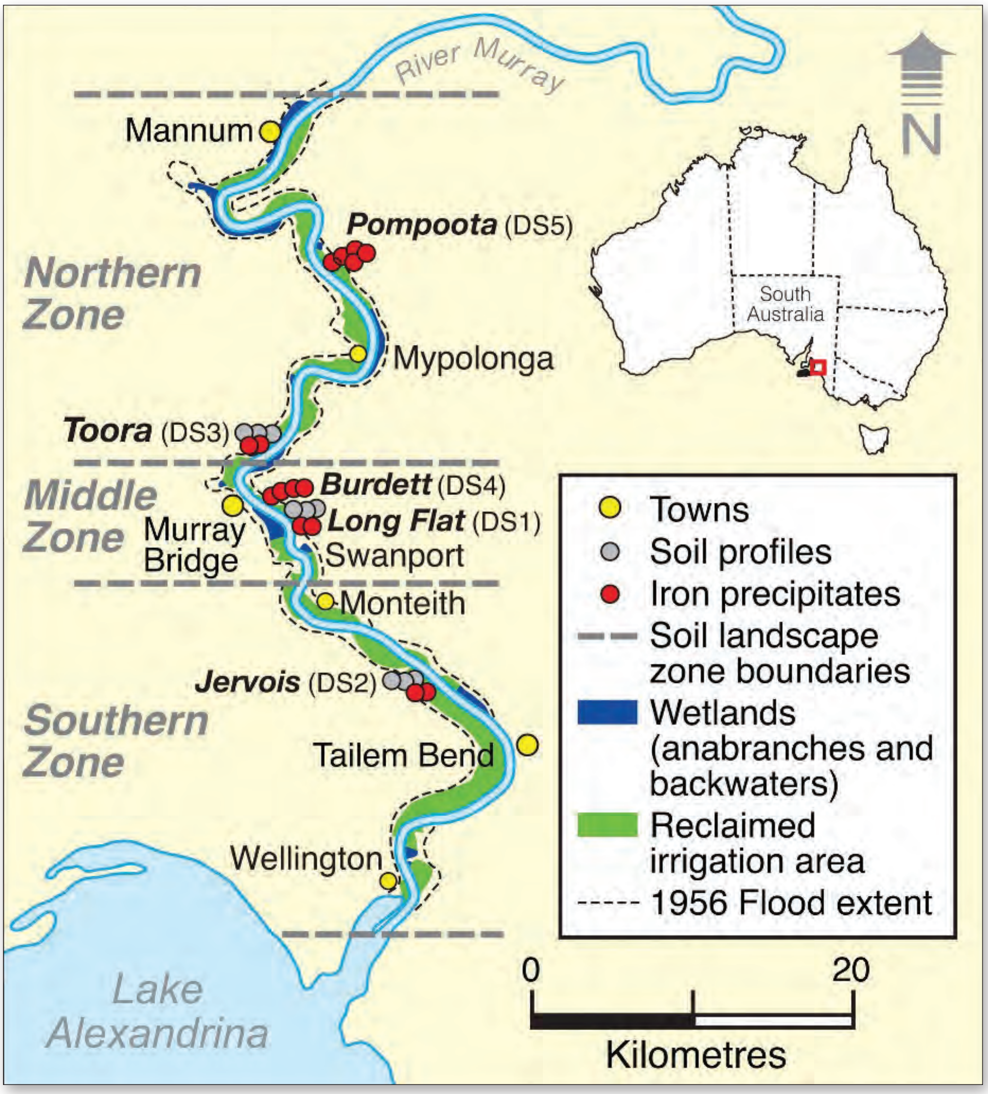


Figure 1-1. Map of the Lower Murray Reclaimed Irrigation Area (LMRIA) showing: (i) the distribution of three representative soil profile sites at Toora, Long Flat and Jervois, (ii) associated iron precipitates from drains at Pompoota, Toora, Burdett, Long Flat and Jervois, (iii) three soil landscape zone boundaries, and (iv) adjacent natural wetlands (anabranches and backwaters).

Source: Authors.

2

Background

The LMRIA is located on the historic floodplain of the River Murray between Mannum and Wellington (Figure 1-1). Between 1900 and 1930, 18 of the 22 natural swamps (5000 ha) between Mannum and Wellington had been 'reclaimed' for agricultural development (now referred to as the 'reclaimed irrigation area' in Figure 1-1 or LMRIA). In a virgin state the swamps typically encompassed a strip of elevated land along the river frontage with

1. low-lying ground consisting of dominantly *Phragmites australis* growing in standing water, and
2. rising high-lying ground behind the swamp. These swamps ranged in size from 25 to 1500 ha with subsoils that were generally either uniform black or mottled brown heavy clays with topsoils comprising variable organic matter content.

After reclamation, dairying was the dominant land use with permanent pastures favoured in the northern swamps and lucerne in the south.

Land was reclaimed by construction of a levee bank as close as practicable to the river frontage and pumping out standing water. This was followed by construction of a drainage system to maintain the water table at a sufficiently low level to permit agricultural development. However, the permanent raising of the river following construction of the LMRIA levee banks and barrages near the Murray Mouth also led to rising regional saline groundwater pressure that resulted in salt accumulation within the near surface soil profile. This was overcome by efficient drainage and regular gravity-fed flood irrigation with fresh water from the river.

Irrigation and drainage systems in the LMRIA generally comprise an irrigation channel that runs directly inside the levee bank and is gravity-fed via sluices or siphons from the river. Lateral drains are maintained at depths of approximately 0.7 m and a main salt drain at the end of the irrigation bays, which are maintained at a depth of approximately 1.2 m. Under ideal conditions, regular irrigation and maintenance of the drainage prevent saline water tables from rising to depths of less than 0.7 m, which limits the accumulation of salt within the root zone. Following construction of locks and weirs in the 1920s and 1930s, pool level below Lock 1 was maintained at approximately +0.75 m AHD for over 70 years. Within the LMRIA, irrigation and drainage systems were used to artificially maintain a shallow water table (≈ 0.7 m bgl). Increased sulfate from groundwater in irrigation mounds and irrigation return waters, combined with a ready supply of organic matter and prolonged reducing conditions, resulted in a progressive build-up of sulfidic material in soil profiles below the shallow water table (>1.0 m bgl) (Fitzpatrick et al. 2017b).

Approximately 4200 ha of this land was rehabilitated under the LMRIA rehabilitation project with approximately 1000 ha of land retired from farming and not rehabilitated (EPA 2008). Dairy production has now reduced from approximately 5000 ha to 1866 ha — a reduction of approximately 63% with a switch to beef production and some alternative cropping systems. The total area of 'productive' farms remaining in the LMRIA is estimated to be 3192ha (Philcox and Scown 2012).

The LMRIA has faced severe challenges over the past decade from the effects of the restructuring and rehabilitation of the area between 2003 and 2007 and the extreme period of the Millennium Drought from 2007 to 2010, which resulted in the lowest River Murray levels (1.75 m decline from average) in over 90 years of records. Groundwater levels also fell to their lowest in over 100 years. Coupled with restricted irrigation water allocations, there was very little irrigation water applied. This led to severe soil cracking to depths up to 4 m, salinisation and acidification (see Appendix 6) and severe socio-economic impacts. The result of this is that many irrigators have ceased or down-scaled their operations in the LMRIA. Irrigation has now become much patchier across the region with less commercial irrigation and dairy land use. Remaining irrigators have observed large water losses during irrigation due to lateral movement to adjacent irrigation bays and properties. This is likely due to the legacy of deep soil cracking, which provides preferential pathways for water flow and lower groundwater levels compared to pre-drought on adjacent irrigation properties (Figure 2-2). These losses increase drainage pumping costs and pollution returned to the River Murray. Due to more limited irrigation across the LMRIA and the drought, large areas of land have become strongly salinised, acidic (i.e. pH <4, due to formation of acid sulfate soils with sulfuric materials), sodic and eroded (see Appendices 3, 4, 5 and 6 for brief overviews of the nature and classification of salt-affected/acid sulfate soils). There is a high risk of these issues becoming more prevalent in the future given climate change projections for this region.

Over the last two decades the application of our work to solve real agricultural and environmental challenges associated with salt-affected/acid sulfate soils and water quality issues in Australia, Iraq, China and Brunei has occurred at several levels (for example, Fitzpatrick 2004, 2008, 2014, 2015; Fitzpatrick and Shand 2008; Grealish et al. 2011, 2014, 2015; Grealish and Fitzpatrick 2013, 2014). The general approach and procedure has been to

- identify the best set of soil-water and landscape field indicators for a region
- construct appropriate 3D and 4D (space and time) mechanistic models of soil-water processes that explain and predict the processes giving rise to a wide range of acid sulfate and salt-affected soils using schematic cross-section diagrams, which display sequences of soil-water features, soil types and water flow paths (i.e. integrate pedological, hydrological, geological, biogeochemical and mineralogical information)
- publish easy-to-use pictorial manuals and handbooks that incorporate field indicators on schematic cross-section diagrams, which display sequences of soil-water features, soil types and water flow paths. This information is used by land managers to help provide land-use options that will help prevent the spread of soil salinity and acid sulfate soils (Fitzpatrick et al. 1997; Cox et al. 1999). The paper by Fitzpatrick et al. (2003) highlights several case studies involving a wide range of types of salt-affected/acid sulfate soils in South Australia and Victoria.

What is the Handbook for?

This handbook shows farmers, land managers, agencies and service providers how to apply a user-friendly soil identification key (Appendix 4; Tables A4-1 and A4-2) to classify soil subtypes and landscape features that are indicators of ***acid sulfate, salt-affected and waterlogged soil conditions in the LMRIA***. These conditions are influenced by soil subtype, topography, hydro-geology, vegetation and climate. The procedures used in the handbook are in four steps.

1. Conduct an office assessment phase, which simply involves drawing transects on an aerial photograph.
2. Go onto the paddock to those areas marked on the aerial photograpH and recognise and map specific soil and landscape features across transects using as an aide the generalised schematic cross-section diagram displaying the sequence of soil-water features, soil types and water flow paths (Figure 2-2).
3. Undertake simple chemical measurements (for example, pH and dispersion tests) on selected soil samples brought back from the paddock to confirm the ***acid sulfate and salt-affected*** (salinity and sodicity) soil subtype.
4. Collate this information to produce a soil map with appropriate management options (for example, drainage).

The handbook is an aid to identify and map soil-water hazard classes (colour-coded maps using the RAG traffic light system: see Step 5 on p. 25). It in turn is used for property planning in the LMRIA.

This handbook shows how to observe and measure the presence or absence of key soil and landscape features. These options are targeted to specific parts of the landscape (for example, irrigated flat land, drains, levee banks and wetlands) and should be incorporated into farm management plans. All methods and procedures described in this handbook are simple and inexpensive.

Finally, soil interpretations are most often developed in response to various farmer land use needs (for example, irrigation); thus the development process has included input from various farmers and professionals from different disciplines. User feedback has been crucial in the iterative process of refining specific interpretations.

The LMRIA landscape has been highly modified and managed for decades, and at times has been highly stressed (see Appendix 6). The drainage of the swamps, construction of levee banks, and introduction of barrages and regulated water levels in the early to mid-part of the 20th century enabled extensive agricultural development and modification of the landscape. The modification of the landscape, while enabling agricultural production, has also created new soil and water issues, which require careful management to both sustain agriculture and protect the broader River Murray environment.

Figure 2-2 shows a generalised schematic cross-section diagram displaying the sequence of eleven (**11**) dominant soil-water landscape features in the LMRIA. Each soil-water landscape feature contains

1. a dominant geomorphological landscape unit (for example, back swamp, salt drain, floodplain, levee bank, riparian zone and ponds in the mixing zone of drain discharge into the River Murray)
2. a dominant soil subtype and related soil features (for example, salt efflorescences)

3. dominant water quality features (suspended iron-rich brownish precipitates) and water flow path/hydrology (for example, waterlogging and depth to water table).

The typical present topography of the irrigation areas is characterised by a constructed levee bank on the river's edge (Figure 2-2), a gradual slope extending from the levee bank to a large drainage channel (termed the 'salt drain', as it intercepts the regional saline water table), and rising again towards the highland region (Figure 2-2). Some irrigation areas have a back swamp area as shown in Figure 2-2 as (**1**), which usually has salinised and sodic soils. The bottom of the salt drain is the lowest topographic and hydrologic point in the local and entire regional Murray-Darling Basin catchment, creating a rising pressure for saline groundwater.

Large drains occur at the end of irrigation bays, which are generally referred to as 'salt' or main drains (**2** and **3**), which return saline groundwater, excess surface irrigation runoff and subsurface drainage (and occasionally stormwater runoff) to the river via large electric pumps (Figure 2-2). Lateral or 'side' drains are present alongside each irrigation bay, which flow into the salt drain. As well as being very salty, the salt drain can become contaminated with nutrients, iron-rich precipitates, acidity and bacteria. These drains were mostly filled with water or ponded (2) before and after the Millennium Drought and following reflooding (and after winter rains), and comprise sulfuric subaqueous clay soils with brownish iron-rich precipitates. During the Millennium Drought (and during summer months) most of these drains progressively dried out (3) and formed thin coatings of strong brown iron-rich precipitates and salt efflorescences, with overly black monosulfidic material (see Figure 2-2 and Figure A1-3). Soils in these drains classify mostly as sulfuric clay soils with iron-rich brownish precipitates/white salt efflorescences and monosulfidic material (see Appendix 4).

The end of the irrigation bays (**4**), especially in the northern and middle zones (Figure 1-1), is prone to strong waterlogging and salinisation if drain levels are not maintained well (>0.5 m) below the soil surface and irrigation is not conducted to leach salts. Soils in these degraded areas classify mostly as hypersulfidic (contain pyrite and would acidify to pH <4 if exposed to oxygen) cracking clay soils with salt efflorescences/brownish Fe-rich precipitates (Figure 2-2).

The main agricultural floodplain top (0-1 m depth) soils (**5**) are generally high in organic matter and nutrients and classify as hyposulfidic (contain insufficient pyrite to acidify) cracking clay soils. The soil type on the floodplain, especially in the northern and middle zones (Figure 1-1) comprise heavy clay soils with slickensides, which shrink and crack during dry/drought periods, and swell when wet (i.e. Vertosols or Vertisols).

The deeper (>3.5 m depth) clayey floodplain soils (**6**), which did not dry out during the Millennium Drought, and which hence did not acidify, are classified as hypersulfidic cracking clay soils (see Appendix 4).

The deeper (1-3.5 m depth) floodplain soils (7) are usually below the groundwater level. As discussed in more detail in Appendix 6, these soils dried and cracked during the Millennium Drought, resulting in oxidation of acid sulfate soils with hypersulfidic material to form sulfuric (pH <4) material (Figure 2-2). These soils classify as sulfuric cracking clay soils, displaying yellow masses of jarosite along old Phragmites root channels, cracks and faces of peds (Figure 2-2; Fitzpatrick et al. 2017b).

The deep (>3.5 m depth) organic-rich (peaty) soil (**8**) with hypersulfidic material, which occurs mainly in the southern zone (Figure 1-1), was below the groundwater level before the Millennium Drought. During the drought, 'desiccation cracks' developed in the peaty material resulting in oxidation of hypersulfidic material to sulfuric (pH <4) material (Figure 2-2). These soils classify as sulfuric organic soils and also display bright yellow masses of jarosite along old Phragmites root channels and cracks (Figure 2-2; Fitzpatrick et al. 2017b).

The compacted clayey levee banks (**9**) were constructed to enable the swamp/floodplain area to be drained and used for farming. These banks now protect the floodplain from uncontrolled flooding due to the regulated river level normally being well above the floodplain level. During irrigation events, a sluice gate or siphon in the levee banks is opened to allow water to be gravity-fed into an inlet channel, and then through an outlet onto the paddock/irrigation bay (Figure 2-2). During the Millennium Drought the levee banks, which comprise human-made soils (anthropogenic clay soils) were prone to cracking and subsidence (Figure 2-2).

The riparian area near the levee bank (**10**), due to subsurface seepage of the river water, can be moist and contain vegetation such as the common reed *Phragmites australis* and River Red gum. These soils classify as hypersulfidic organic soils.

The final soil-water landscape feature adjacent to the River Murray consists of 'ponds and wetlands in the mixing zone of drain discharge into the River' (**11**), which classify as hypersulfidic subaqueous clay soils with brownish precipitates (see Appendix 6). Water levels in these ponds are controlled by upstream flows and barrages in Lower Lakes. The River Murray provides both surface water (for irrigation) and groundwater (via seepage) to the floodplain. The level of the river determines whether gravity-fed flood irrigation can be used, which is the normal method of irrigation. During the Millennium Drought the river levels fell nearly 2 m from normal levels, which meant normal irrigation was impossible and groundwater levels fell. (The river provides a hydraulic pressure boundary on one side of the floodplain, along with the highland/regional groundwater on the other side; see Mosley et al. 2014a for more details.)

Summary and objectives of the handbook

The deep sulfuric clayey soils and adjacent acid iron-rich precipitates in drains in the LMRIA pose a major remediation challenge because of

1. the large volume and distribution (3500-5000 ha) of pyritic and acidic material in the deep clays
2. the relative lack of neutralising minerals in the deep clays
3. the low pH, complex biogeochemistry and hydrology of the acid drainage
4. iron-rich precipitates in drains (dominantly as schwertmannite), which sequester metals and acidify between reflooding, rainfall and irrigation events (see Appendix 6).

The same processes of deep oxidative weathering of pyrite are responsible for the acid drainage from coal mines and highway construction sites worldwide. The situation in the LMRIA, however, is perhaps more extreme because of the large area (~ 5000 ha), which is adjacent to the River Murray — with concerns for ongoing/long-term acid drainage leading to on-farm impacts and release of potentially toxic metals to the river environment.

The experience that sulfuric material with extensive retained acidity (jarosites) has persisted for a decade or longer in the LMRIA (Fitzpatrick et al. 2017b; Appendix 6) highlights the need to understand and integrate the dynamic interactions of pedology, hydrology, irrigation science and water quality via the development of a handbook, which will provide instruction on how to conduct soil investigations for the assessment and management of **acid sulfate and salt-affected soils** in order to avoid potentially negative environmental impacts such as poor water quality associated with the apparently irreversible formation of deep sulfuric clayey soils.

The handbook provides greatly improved knowledge of optimal irrigation and soil-water-landscape management in the LMRIA under changing land use and climate patterns.

Soil-water landscape feature No	**1** **Back-swamp area**	**2** **Salt Drain (ponded water) WINTER**	**3** **Salt Drain (dry) SUMMER**	**4** **(North/Mid zone) Bottom end of paddocks**	**5** **(North/Mid zone) Floodplain soils (0-1 m depth)**	**6** **(North/Mid zone) Floodplain soils (1-3-5 m depth)**
Soil & water problems	Waterlogging, salinity, sodicity	Acidification, water pollution, infrastructure damage	Acidification, salt efflorescences wind pollution	Salinity, sodicity, waterlogging acidification	Cracking, heaving, slumping, low fertility, salinization, water logging infrastructure damage	Compaction during drought
General soil-water description	Strongly waterlogged, saline and/or eroded	Main & side drains leading to drainage pump, level controlled by irrigation and pumping operation, Ponded after Millennium drought followed by reflooding or winter rains (saline, acidic, nutrient-rich)	Main & side drain systems: Drained / dry after Millennium drought &/or summer (salt efflorescences saline, acidic, nutrient-rich and monosulfidic material)	Cracking clays (Vertosols), hypersulfidic material with salt efflorescences and brownish precipitates	Cracking clays (Vertosols), hyposulfidic material (contain insufficient pyrite to acidity) with salt efflorescences and/or brownish precipitates	Cracking clays (Vertosols) hypersulfidic material (contain pyrite and would acidify to pH<4 if exposed to oxygen)
Soil-subtype (soil key)	Strongly waterlogged saline and sodic cracking clay soil	Sulfuric subaqueous clay soil with brownish precipitates	Sulfuric clay soil with brownish precipitates/salt efflorescences and monosulfidic material	Hypersulfidic cracking clay soil with salt efflorescences/ brownish precipitates	Hyposulfidic cracking clay soil	Hypersulfidic cracking clay soil

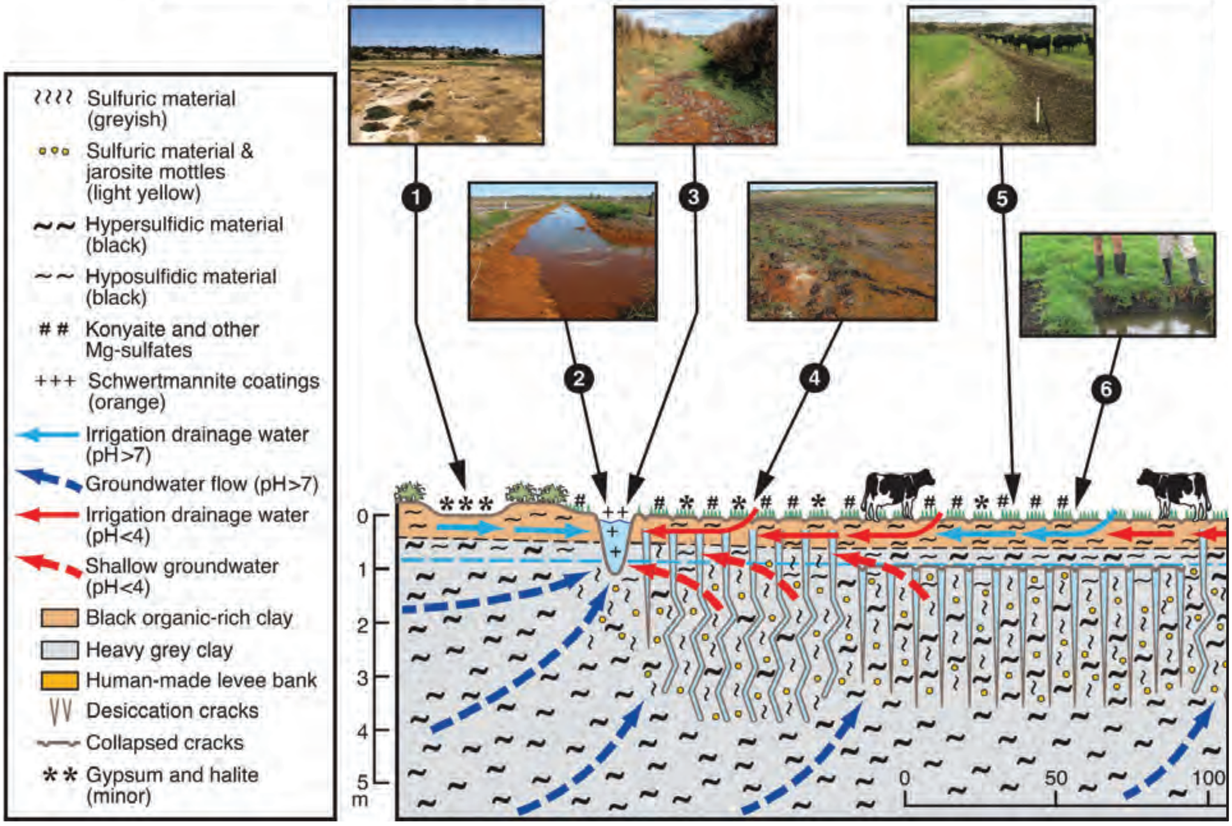
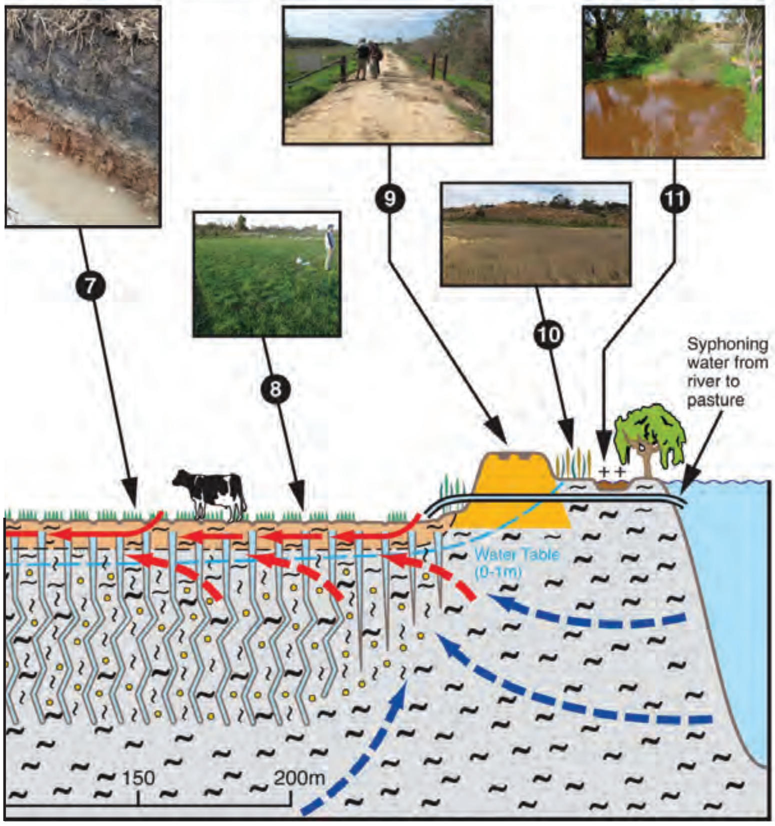


Figure 2-2. Generalised schematic cross-section diagram displaying the sequence of soil-water features, soil types and water flow paths in the LMRIA.

Source: Authors.

7 (North/Mid zone) Floodplain soils (>3.5 m depth)	8 (South zone) Floodplain soils (>3.5 m depth)	9 Levee Bank	10 Riparian zone (near river)	11 River Murray
Deep cracking, oxidation and acidification (during drought)	Deep organic-rich clayey soil; oxidation and acidification (during drought)	Cracking, slumping and leaking	Waterlogging, encroachment by vegetation	Low River Level (<0.5 m AHD) High salinity
Cracking clays (Vertosols), sulfuric material (pH<4 after millennium drought)	Organic-rich clayey soils with sulfuric materials (pH<4 after millennium drought)	Excavated an compacted clay material (human-made soil)	Organic-rich clayey soils with hypersulfidic material (contain pyrite and would acidify to pH<4 if exposed to oxygen)	River Murray – water level controlled by upstream flows and barrages in Lower Lakes. Ponds in the mixing zone of drain discharge into the River Murray.
Sulfuric cracking clay soil	Sulfuric organic soils (clayey and hydric)	Anthropogenic clay soil	Hypersulfidic organic soils (clayey and hydric)	Hypersulfidic subaqueous clay soil with brownish precipitates



3

The Soil Landscape Key

This key

- shows how to identify soil and landscape features that are indicators of acid sulfate, salt-affected, waterlogged and anthropogenic soil conditions in the LMRIA using as an aid the generalised schematic cross-section diagram displaying the sequence of soil-water features, soil types and water flow paths (Figure 2-2)
- suggests management options for improving productivity
- assists in identifying soil-water hazard classes used for property planning
- is presented in an easy-to-follow form as it covers an area of related soil subtypes, topography hydrology, geology and vegetation. Only selected features have been used, so as to simplify the key.

All methods and procedures required are simple and inexpensive. Implementing management options will minimise the off-site impact of salt and acidity movement into waterways and water supplies.

4

Where it applies

The key applies to all acid sulfate, salt-affected, waterlogged and other soils such as human-made (anthropogenic) soils on levee banks.

If you notice new occurrences of acid sulfate, salt-affected, waterlogged and other soil areas in summer in your paddock or farm, then this indicates that you need to use the key to investigate the problem more closely.

5

Before you start

What you will need

- a map or aerial photograpH of paddock/farm (for example, Figure 7), scale ranging from 1:1000 to 1:5000
- two clear sheet overlays (for example, acetate or tracing paper)
- tape or velcro to attach overlay to photograph
- coloured felt pens (or a pencil) to write on the overlays
- soil auger (post-hole auger), spade and knife
- plastic or paper bags for soil sample collection
- a blank recording sheet (see Table 7-1)
- rainwater
- 600 ml glass jars (for example, vegemite jars)
- CRC for Soil and Land Management sodicity meter (see Figure A2-2; Rengasamy and Bourne 1997)
- electrical conductivity meter
- pH strips or pH meter
- ruler.

6

Planning where to go

Office Assessment phase

On your property map or aerial photograpH select several paths or transects across the floodplain paddocks, drains, back swamps, riparian zone wetlands or ponded areas adjacent to the River Murray that are likely to have a problem (as an aide see Figure 2-2, which is a generalised schematic cross-section diagram displaying the sequence of soil-water features, soil types and water flow paths found in the LMRIA. These transects will usually be from east to west or west to east (towards the river).

Avoid transects that are not representative (for example, along fence lines or roadways).

Attach the overlay to the photograpH using the tape or velcro. Select 2 to 5 transects, which cut across suspected areas of salinity or waterlogging within paddock. Draw lines on the overlay for each transect as per Figure 6-1.

Mark transects on the first plastic overlay (for example, A-A' and B-B' in Figure 6-1).

NOTE: these two transects cover mostly the irrigated paddock but also adjacent drains and wetlands (i.e. at the A' and B' ends in Figure 6-1).

Figure 6-1. Transects marked on an aerial photograpH for Long Flat (see Figure 1-1).
Source: Authors.

7

Making observations in the field

Note

We propose that farmers and land managers undertake the field component described in this section alongside 'trained advisors' or with a 'facilitated discussion group'. It is possible that the ideal way to use this handbook would be to

1. train 'advisor(s)/facilitator(s)' in the field to easily observe soil-water indicators and process/es
2. conduct a series of 'facilitated discussion groups'.

Note that, as experience is gained, only some aspects of the Field Recording Checklist (below) need to be completed.

Field assessment phase

Go onto the paddock to those areas marked on the aerial photograph.

Key soil features in each paddock are identified on a Field Recording Checklist (Table 7-1) by using both the soil identification key (Appendix 4: Tables A4-1 and A4-2) and generalised schematic cross-section diagram displaying the sequence of soil-water features, soil types and water flow paths (Figure 2-2).

The field assessment should proceed by following Steps 1 to 5 set out below:

1. Obtain **Field Recording Checklist/Table** (see Table 7-1, which carries references to relevant appendices in this handbook) to record results noted in the field.
2. Commence **field inspections** at Site 1 along a typical transect at a point of concern and continue every 20 m where you see changes occur.
3. Mark this and subsequent points on an aerial photo and on Field Recording Checklist/Table.
4. **Auger** to rigid clay layers. (A gouge auger is ideal for this, as it drives easily into clayey swamp soils and provides a visual, complete and intact soil profile.)
5. Record the **soil profile features** on the field recording checklist. (See below.)

How to record the soil profile features

On the field recording checklist (Table 7-1), record the surface features, including gilgai and cracks when soil is dry (Appendix 1). Record the depth (mm) of main soil layers from the soil surface to where there is a change in

- **soil consistence** (Appendix 1: Table A1-4)
- **soil colour** (Appendix 1: Table A1-3) — Grey, Black, Brown, Red, Yellow or Mottled greyish to bluish colours
- **structure** (Appendix 1: Figure A1-1) — slickensides, peds or massive
- **texture** (Appendix 1: Tables A1-1 and A1-2) — heavy clay; medium clay; light clay; sandy clay; sandy clay loam; loam or sand (the test of soil texture is critical and applicable to each layer)
- **amount of roots** (Appendix 1: Table A1-5).

Soil fertility testing

While the LMRIA soils are considered highly fertile, periodic soil fertility testing is recommended in order to determine whether fertiliser application is required to maintain optimal production. Guidance can be obtained from Dairy SA at http://www.dairysa.com.au/soil-water-more.aspx.

Table 7-1. Field recording checklist/table

Date:	Site number:	Distance from start of route:

1. Surface features (see Appendix 1)		
Hard Rock or Large Calcrete fragments		
Hard rock/calcrete to restrict cultivation	NO	YES
Gilgai (mounds or depressions on soil surface)		
Zero or none (Z)	Low gilgai (L)	High gilgai (H)

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

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

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

Erosion		
Zero or none (Z)	Rill (R)	Gully (G)

Vegetation (classify according to headings below)					
Zero or none (Z)	Salt tolerant grasses *Samphire?*	Healthy pasture	Healthy crop	Reeds *Phragmites?*	Notes:

2. Soil Profile features (see Appendix 1)

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

Colour:

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

Structure:

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

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

Texture:

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

Consistence classes:

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

Root abundance:

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

3. Supplementary Testing (see Appendix 2 and 3)

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

Measure pH, Electrical conductivity (EC; salinity 1:5 soil:water ratio), dispersion test (sodicity) on collected samples back in the house or shed or laboratory and record the data in Table 7-2.

Table 7-2. Soil pH, EC and dispersion tests

Site (a1)	Depth (mm)	pH	Salinity (EC)	Sodicity (dispersion test)
a1.1	1-10 (surface)			
a1.2	10-100			
a1.3	100-500			
a1.4	500-1000			
a1.5	1000-1500			
Repeat above approximately every 30 m along each transect.				
Mark each subsequent point on the plastic overlay.				
Start new Field Recording Sheet for each transect.				

8

Soil types based on field observations and laboratory tests

Step 1

From information recorded on the Field Recording Sheets (Tables 7-1 and 7-2), allocate to each layer (a1.1, a1.2, etc.) the 'Key soil/water features and acid sulfate materials' (Table 8-1), using the question and answer format shown in Table 8-2 to the following 7 points relating to occurrences or interpretations of

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

Table 8-1. Key soil/water features and acid sulfate materials of layers

Soil/water features and materials	Code	Definitions
Subaqueous condition/soils	**W**	Surface water levels, 2.5 m below the surface water level
Hydric condition/soils	**Hyd**	Surface water levels, 0.50 m above the surface water level
Unsaturated condition/soils	**Uns**	Drained soils with water level below 0.50 m
Salt efflorescences	**Ef**	Fluffy salt accumulations (e.g. gypsum and halite)
Gypsum/Halite crusts	**Gyp**	See Glossary (Appendix 9)
Calcareous materials	**Ct**	See Glossary (Appendix 9)
Shells	**Sh**	Hard, protective outer layer created by an animal that lives in the sea or inland environments
Organic rich material/soil	**Or**	See Glossary (Appendix 9)
Clays	**Cy**	See Table A1-2
Sands	**Sa**	See Table A1-2
Loams	**Lo**	See Table A1-2
Sulfuric material/soil	**Su**	See Appendix 3
Hypersulfidic material/soil	**He**	See Appendix 3
Hyposulfidic material/soil	**Ho**	See Appendix 3
Monosulfidic material **wet**	**Mow**	See Appendix 3, Table A3-1 with n-Value greater than 1
Monosulfidic material **dry**	**Mod**	See Appendix 3, Table A3-1 with n-Value between 1 and 0.7
Reddish Fe-rich precipitates/gels	**Rp**	Reddish-yellow Fe-rich precipitates/gels (schwertmannite-rich)
Saline soils	**Sal**	See Appendix 2, Table A2-1
Sodic soils	**Sod**	See Appendix 2, Table A2-1

Table 8-2. Key soil features and acid sulfate materials for each soil layer

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

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

Step 2

The information recorded in Table 8-2 for the 'Key soil features and acid sulfate materials of **layers**' is used to classify the **soil subtype for each soil profile** (or sampling site — for example, a1) in accordance with the following procedure, as applied to the 'Soil identification key' (see Tables A4-1 and A4-2 in Appendix 4). This is based on the presence of the dominant acid sulfate soil material present, with the highest hazard ASS material keying out first, as follows:

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

As explained in Appendices 3 and 4, the classification of ASS materials (i.e. sulfuric, hypersulfidic, hyposulfidic or monosulfidic) is based mainly on the initial pH (pH at time zero) and after incubation for at least 16 weeks.

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

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

Finally, a soil profile that classifies as a '**hyposulfidic soil**' requires hyposulfidic material (i.e. decrease in pH to >pH 4 after incubation for at least 16 weeks) to be identified in a layer or horizon, which is at least 10 cm thick within 150 cm of the soil surface.

Step 3

Finally, additional key information recorded in Table 8-3 for the key soil features and acid sulfate materials of layers is also used to highlight presence of other dominant soil features present, with the highest hazard soil feature keying out first, as follows:

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

Table 8-3. Acid sulfate soil subtypes/other soils with additional key soil features for each soil profile

Profile No	Profile classification (Appendix 4: Table A4-2)	MAP UNIT CODE
A-A': a1	Sulfuric subaqueous clay soil with reddish Fe-rich precipitates	Su, W, Cy, Rp
A-A': a2	Sulfuric cracking clay soil with hydric and salt efflorescences	Su, Cy, Hyd, Ef
A-A': a3	Sulfuric cracking clay soil with hydric and salt efflorescences	Su, Cy, Hyd, Ef
A-A': a4	Sulfuric cracking clay soil with hydric, salt efflorescences and calcareous segregations	Su, Cy, Hyd, Ef, Ct
B-B': b1	Waterlogged soil with hydric and gypsum crusts	Hyd, Lo, Gyp
B-B': b2	Other soils (Unsaturated red sandy sodic soils)	Uns, Sa, Sod

Confidence level of soil classification

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

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

9

Soil map units

Step 4

As shown in Table 9-1, based on the information from **Steps 1 to 3**, allocate

- the dominant acid sulfate soil subtypes and non-acid sulfate soil subtypes with additional/related key soil features (for example, sulfuric clays with salt efflorescences)
- the associated Map Unit Code

to each soil profile or site (or sampling site — for example, a1), in order to map areas (i.e. polygons) on the plastic layer overlying the aerial image (see Figure 9-1).

Step 5

Based on the information from **Step 4**, allocate the soil hazard rating class (**High**, **Moderate** or **Low**) for each site, as shown in Table 9-1.

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

'The Red-Amber-Green system, also known as the 'RAG' or 'traffic light' system is a convenient method to facilitate easy visualisation in a manner that will be easily interpreted and identified on soil maps (see Figure 9-1).

Table 9-1. Soil map units and associated map unit codes and soil hazard rating classes

Profile No	Acid Sulfate Soil Subtypes (Table A4-2) Saline or Sodic Soil groups (Table A4-2) + Conditions and features (Table 8-1)	MAP UNIT CODE	Soil hazard rating classes	Index rating (Map unit)
A-A': a1	Sulfuric subaqueous clay soil with red precipitates	Su, W, Cy, Rp	High	8-10
A-A': a2	Sulfuric cracking clay soil + hydric salt efflorescences	Su, Cy, Hyd, Ef		
A-A': a3	Sulfuric cracking clay soil + hydric salt efflorescences	Su, Cy, Hyd, Ef		
A-A': a4	Sulfuric cracking clay soil + hydric salt efflorescences and calcareous segregations	Su, Cy, Hyd, Ef, Ct		
D-D': d1	Hypersulfidic subaqueous organic soil	He, W, Or	Moderate	6-7
D-D': d2	Hypersulfidic subaqueous clay soil	He, W, Cy		
D-D': d3	Hypersulfidic soil with shells	He, Sh		
D-D': d4	Hyposulfidic clay soil with salt efflorescences	Ho, Cy, Ef		
D-D': d5	Yellow clayey sodic soil	Uns, Cy, Sod		
D-D': d6	Red sandy sodic soil	Uns, Sa, Sod		
	Other soils (non-acid sulfate soil subtypes)			
E-E': e1	Hydric yellow loamy soil with gypsum crusts	Hyd, Lo, Gyp	Low	2-5
E-E': e2	Unsaturated red sandy sodic soils	Uns, Sa, Sod		

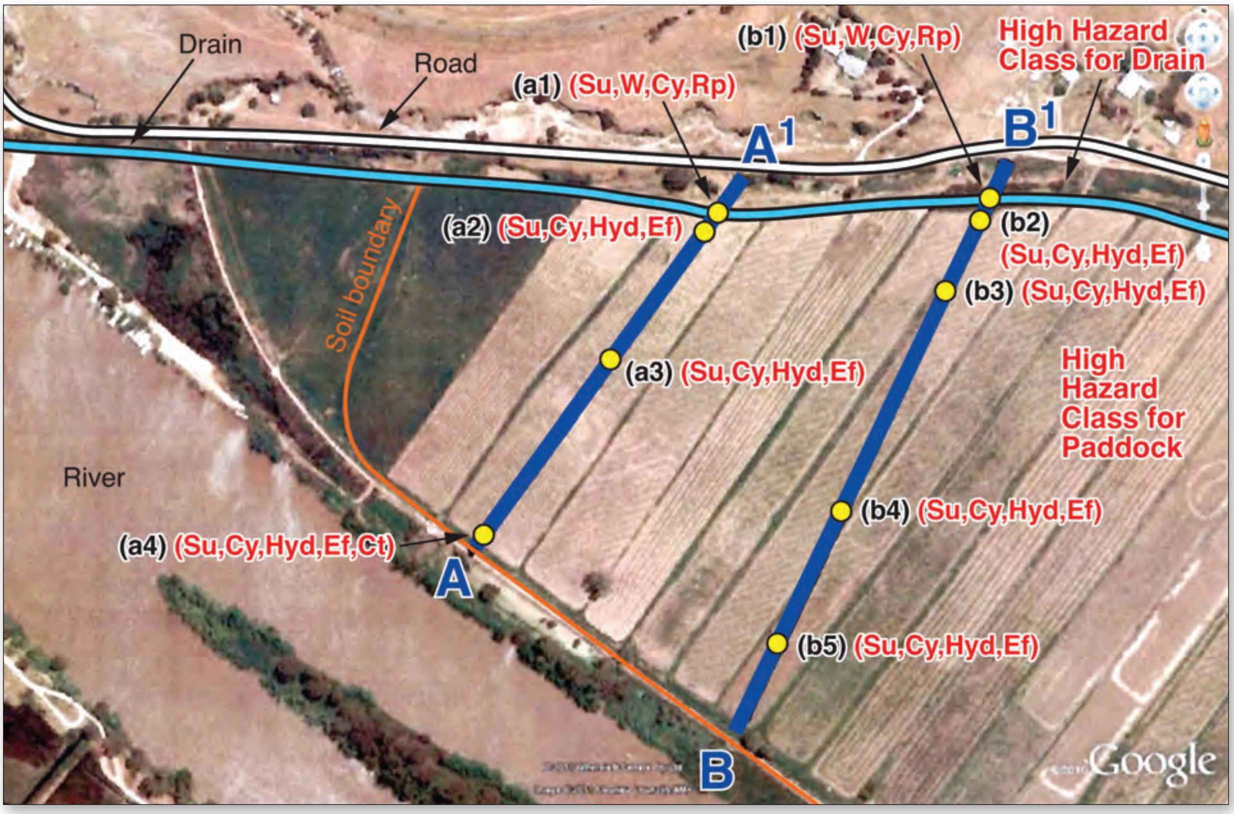


Figure 9-1. Soil subtypes with associated soil hazard rating classes along transects A-A' and B-B' and boundaries entered on the aerial photograpH for drain and paddock at Long Flat (Figure 1-1).

Source: Authors.

10

Drain Water Quality Assessment in soil map unit

Drainage is essential in the LMRIA to keep the rising saline regional groundwater table out of the pasture root zone and to remove salt from the landscape. Drainage water is typically returned to the River Murray via a network of drains and large pumps. This can create water quality impacts in the River Murray (Mosley and Fleming 2010). Drainage volume should therefore be minimised via efficient irrigation and recycling of water where practical and drain water quality should be maximised via employing best management practices on farms to minimise pollutant inputs to drains (for example, preventing surface runoff directly into drains). Drains can also indicate what is happening on the farm, in particular their level and colouration.

Assess and record information on drainage operations and infrastructure, and on drain water quality.

Appendix 7 provides background on drainage and drain water quality in the LMRIA.

The following field sheet checklist (Tables 10-1 to 10-3) can be used to record information on drainage indicators that can be used, in conjunction with other indicators, to ensure protection of top soil and pasture condition in the LMRIA.

Table 10-1. Drainage field recording checklist table

Date	Site description (e.g. salt drain at pump shed))	Drainage pump operating (Y/N)	Drains clear of dense vegetation that could restrict flow (Y/N)	Drainage pump operating to keep drain/ groundwater level at least 0.5 m below paddock surface (Y/N)	Drain pump switched on during irrigation or immediately after irrigation completed to ensure rapid drainage (Y/N)

Check: If you answered NO to any of the above, then it is likely that a less than optimal drainage system or operating procedure could be present.

Table 10-2. Acid drainage indicator checklist table

Date	Site description (e.g. salt drain at pump shed)	Orange-brown precipitates/colour in drain water (Y/N)	Corrosion of metal pipes and pumps in drainage system (Y/N)

Check: If you answered YES to one or more of the above, then acid drainage is likely to be present at the site.

Table 10-3. Drainage water quality — pH and salinity (EC)

Site #	Site description (e.g. salt drain at pump shed)	Salinity/EC*	pH*
1			
2			
3			
4			
5			
6			
7			
8			

Check: pH should be in the range of 6.5-9.0. pH <6.5 indicates that acid sulfate soil impacts are very likely present and there is a high corrosion risk. High metal levels will also be present if pH is less than 6.5. Drainage salinity/EC will vary according to seasons and irrigation events, and there is no specific guideline for this. If reuse of drainage water is conducted, then ideally the drain water should be diluted/shandied so that EC goes below about 1000-1500 µS/cm before reuse on pasture. pH and EC can be measured with calibrated hand-held instruments or in a laboratory.

11

Irrigation Assessment in soil map unit

Irrigation in the LMRIA is **mandatory** in order to prevent land salinisation, soil cracking and acidification (during drought). Irrigation and drainage can also restore currently salinised land to an improved state.

Appendix 7 provides background on irrigation in the LMRIA.

The following field sheet checklists (Tables 11-1 to 11-4) can be used to

- record information on irrigation volumes and timescales
- examine irrigation infrastructure
- check soil and water indicators that may indicate insufficient irrigation or drainage is occurring.

If used in conjunction with other indicators, the checklists can ensure that irrigation can be successfully used to sustain soil condition in the LMRIA.

Tables 11-1 to 11-4. Irrigation field recording checklist table

Date: **Irrigation bay ID/Number:**

Table 11-1. Irrigation efficiency calculations

Irrigation date	Irrigation bay #	Bay name	Bay area (ha)	Watering time (hours)	Watering amount (ML)	Watering efficiency* (ML/ha)	Comments

*The Watering amount column divided by the Bay area gives the Watering efficiency. It is useful to assess this over several irrigations to gain an understanding of average efficiencies, as different soil moisture and river level conditions can influence individual irrigation results.

Check: Watering efficiency should be <1.0 ML/ha/watering and irrigations should in general be completed within 8 hours. More than three ELMA irrigations (and preferably more than 5) should be applied where possible per annum during extreme drought conditions.

TABLE 11-2. IRRIGATION BAY INFRASTRUCTURE CHECKLIST

Irrigation date	Irrigation bay #	Bay name	Irrigation siphon/ sluice in good condition (Y/N)	Inlet channel in good condition and clear or dense vegetation (Y/N)	Irrigation bay outlets present and in good condition (Y/N)	Irrigation bay laser levelled (Y/N)

CHECK: If you answered NO to one or more of the above, then irrigation efficiency is likely to be much less than optimal.

TABLE 11-3. IRRIGATION BAY INDICATOR CHECKLIST

Irrigation date	Irrigation bay #	Bay name	Pasture has uneven distribution across bay (Y/N)	Soil cracks present* (Y/N)	Salt tolerant vegetation present (Y/N)	Salt efflorescences present (Y/N)

*Small surface cracks (less than approximately finger width) are tolerable, but cracks deeper than about 10 cm and wider than 1 cm should be avoided.

CHECK: If you answered YES to any of the above, then it is likely that irrigation is either insufficient or being unevenly applied to the irrigation bay, possibly due to poor infrastructure (see above).

Table 11-4. Irrigation water quality — pH, salinity (EC) and sodium absorption ratio (SAR)

Site #	Site description (e.g. salt drain at pump shed)	Salinity (EC)	pH*	SAR*
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				

Check: pH should be in the range of 6.5-9.0, salinity/EC should ideally be below approximately 1000 µS/cm for sensitive pasture species, and SAR should be below approximately 18 for clover and other grasses (ANZECC and ARMCANZ 2000). pH and EC can be measured with calibrated hand-held instruments, but SAR is required to be measured by a laboratory. Generally, the River Murray has a near neutral pH (approx. 7) and a low SAR (<2), hence testing for pH and SAR would generally only be required if non-river sources of water is being used or if 'shandying' of drain water for irrigation is being conducted. River water EC values are available on the DEWNR and MDBA websites.

12

Using soil-water landscape maps for farm management planning

Based on the soil-water landscape map units and associated soil hazard rating classes displayed in Table 9-1 and on the map overlay (Figure 9-1), management options can be made as part of a farm property management plan for each map unit, as displayed in the cross-section in Figure 12-1.

For example, management options can be made for each of the map units and associated soil hazard rating classes in the paddock and salt drain at Long Flat shown on the map overlay shown Figure 9-1.

Paddock management of floodplain soils

(Soil-water landscape feature Nos. 4, 5, 6, 7 and 8 as shown in Figure 12-1)

The sections below provide detailed background information and advice on how best to manage the floodplain soils in paddocks (i.e. Soil-water landscape feature Nos. 4, 5, 6, 7 and 8: as displayed in Figure 12-1). A brief summary of major management options is also provided in Figure 12-1.

Soil acidity management

Flushing of acidity built up over a long period of time

The predictive and generalised conceptual models presented in Figures A6-1, A6-2 and A6-3 illustrate how the lowering of the water table under the LMRIA during an unprecedented hydrological drought allowed oxidation sulfides in previously waterlogged, anaerobic hypersulfidic material between approximately 1-3 m below ground level (blg). Hypersulfidic material previously had built up in the saturated zone below approximately 50 cm due **to stable water level conditions** and an availability of sufficient iron, sulfate and organic material. Under these saturated conditions (pre-drought), the hypersulfidic material did not pose a threat, but once allowed to oxidise (during drought), sulfuric acid was produced, predominantly in the 1-3 m bgl zone (Figure A6-2).

Oxidation and acidification between 1 and 3 m of the hypersulfidic cracking clay soil profile was enhanced due to formation of large cracks up to 3.5 m deep (Figure A6-2). However, the topsoil layers (~<0.5 to 1 m) in these sulfuric cracking clay soils was likely prevented from forming significant

Soil-water landscape feature No	1 Back-swamp area	2 Salt Drain (ponded water) WINTER	3 Salt Drain (dry) SUMMER	4 (North/Mid zone) Bottom end of paddocks	5 (North/Mid zone) Floodplain soils (0-1 m depth)	6 (North/Mid zone) Floodplain soils (1-3-5 m depth)
Summary of major management options	Keep drainage infrastructure operating effectively. Irrigate if possible Fence to exclude stock. Plant salt tolerant grasses. Add lime to areas that that are strongly hypersulfidic	Keep the main drain water level around 0.5 to 0.75 m below paddock surface. Maintain banks and infrastructure Keep drains clear of vegetation Limestone dosing (if acidic)	Limestone dosing Keep the main drain water level > around 0.75 m below paddock surface. Maintain banks and infrastructure	Plant perennial pasture tolerant to salinity and waterlogging. Plant moderately salt tolerant Agroforestry. Remove stock in wet periods. Apply gypsum or limestone (if required)	Maintain height of water in the river at +0.5m AHD or greater to enable flood irrigation. Maintain irrigation efficiency	Soil cracking & land subsidence management
Soil & water problems	Waterlogging, salinity, sodicity	Acidification, water pollution, infrastructure damage	Acidification, salt efflorescences wind pollution	Salinity, sodicity, waterlogging acidification	Cracking, heaving, slumping, low fertility, salinization, water logging infrastructure damage	Compaction during drought
General soil-water description	Strongly waterlogged, saline and/or eroded	Main & side drains leading to drainage pump, level controlled by irrigation and pumping operation. Ponded after Millennium drought followed by reflooding or winter rains (saline, acidic, nutrient-rich)	Main & side drain systems: Drained / dry after Millennium drought &/or summer (salt efflorescences saline, acidic, nutrient-rich and monosulfidic material)	Cracking clays (Vertosols), hypersulfidic material with salt efflorescences and brownish precipitates	Cracking clays (Vertosols), hyposulfidic material (contain insufficient pyrite to acidity) with salt efflorescences and/or brownish precipitates	Cracking clays (Vertosols) hypersulfidic material (contain pyrite and would acidify to pH<4 if exposed to oxygen)
Soil-subtype (soil key)	Strongly waterlogged saline and sodic cracking clay soil	Sulfuric subaqueous clay soil with brownish precipitates	Sulfuric clay soil with brownish precipitates/salt efflorescences and monosulfidic material	Hypersulfidic cracking clay soil with salt efflorescences/ brownish precipitates	Hyposulfidic cracking clay soil	Hypersulfidic cracking clay soil

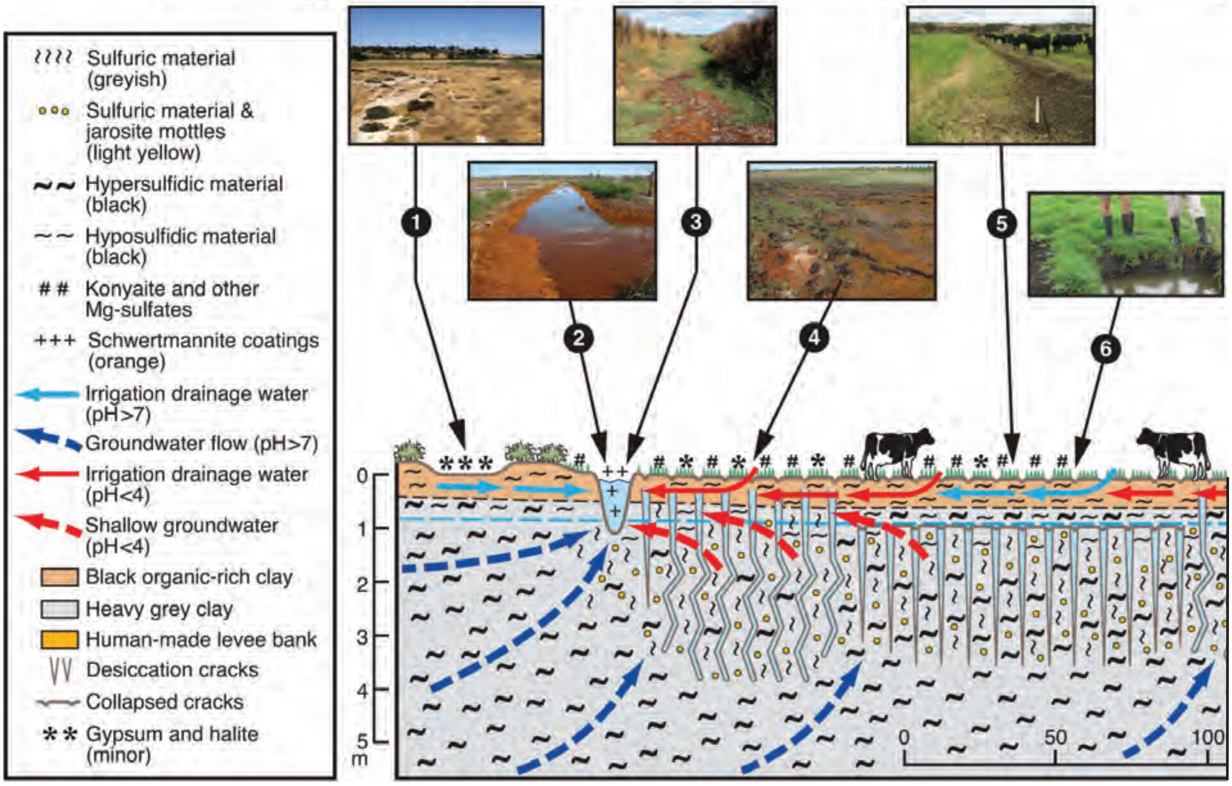
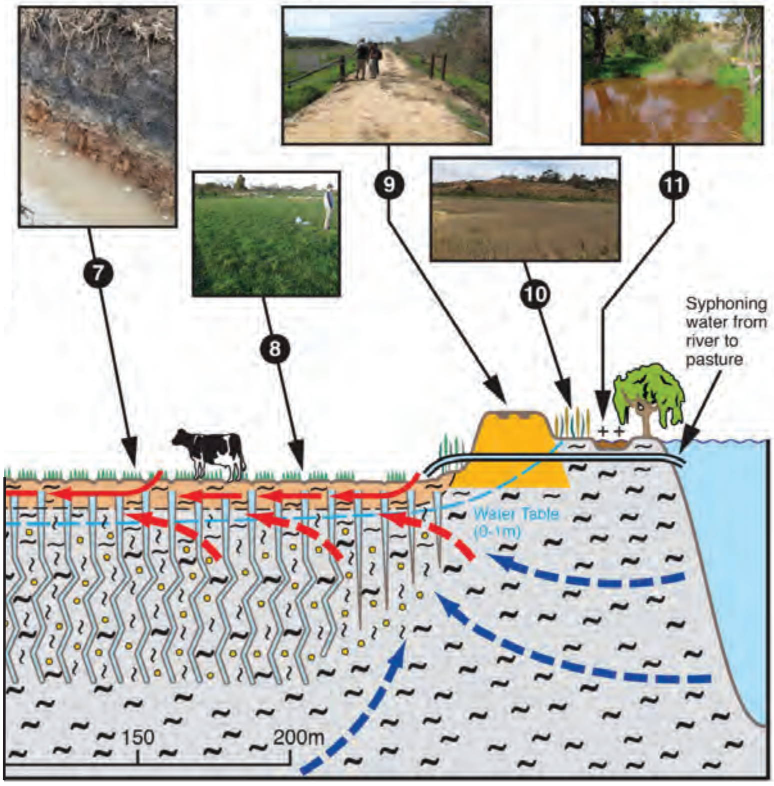


Figure 12-1. Generalised schematic cross-section diagram displaying the sequence of soil-water features, soil types, water flow paths and management options found in the LMRIA.

Source: Authors.

7 (North/Mid zone) Floodplain soils (>3.5 m depth)	8 (South zone) Floodplain soils (>3.5 m depth)	9 Levee Bank	10 Riparian zone (near river)	11 River Murray
Soil cracking & land subsidence management. Flushing of acidity	Soil cracking & land subsidence management	Maintain river levels to prevent bank cracking & subsidence. Repair and maintain banks. Maintain irrigation infrastructure	Maintain wetland vegetation. Minimise drainage volumes and water quality impacts	Maintain suitable river levels (>0.5 m AHD) and salinity (<1,000 EC)
Deep cracking, oxidation and acidification (during drought)	Deep organic-rich clayey soil; oxidation and acidification (during drought)	Cracking, slumping and leaking	Waterlogging, encroachment by vegetation	Low River Level (<0.5 m AHD) High salinity
Cracking clays (Vertosols), sulfuric material (pH<4 after millennium drought)	Organic-rich clayey soils with sulfuric materials (pH<4 after millennium drought)	Excavated an compacted clay material (human-made soil)	Organic-rich clayey soils with hypersulfidic material (contain pyrite and would acidify to pH<4 if exposed to oxygen)	River Murray – water level controlled by upstream flows and barrages in Lower Lakes. Ponds in the mixing zone of drain discharge into the River Murray.
Sulfuric cracking clay soil	Sulfuric organic soils (clayey and hydric)	Anthropogenic clay soil	Hypersulfidic organic soils (clayey and hydric)	Hypersulfidic subaqueous clay soil with brownish precipitates



amounts of sulfuric material due to the continuous wetting and drying cycles associated with flood irrigation **over the last 80 years**. Acidic topsoil layers (<50 cm) were not present pre-drought in the hypersulfidic clayey soils in the LMRIA after construction of the barrages and levee banks (Fitzpatrick et al. 2009). However, Taylor and Poole (1931) provided some evidence of acidification of these topsoils during the early development of these river floodplains for agriculture (dairy, beef and fodder production **between 1881 and 1940**, i.e. before the barrages were constructed). It is likely that there was hypersulfidic material present at the soil surface that oxidised during the initial drainage and reclamation of the LMRIA to form sulfuric soils. However, over several decades of continuous irrigation it is likely that any acidity present at the surface was flushed, and limestone added as a typical agricultural practice, to produce the circum-neutral top soil pHs presently found in the LMRIA.

As a consequence, the ELMA (Environmental Land Management Allocations) water allocation for the LMRIA (see Appendix 8) must be retained as follows:

- Where practicable, on properties with only an ELMA water allocation, ensure that ELMA is applied in full, annually, to **maintain soil health** (prevention of cracking and slumping, salinisation and acid sulfate soil exposure).
- The ELMA allocation should not be a part of carryover water.
- The ELMA water allocation should be exempt from water restrictions during drought conditions.
- Use your ELMA water — At least one, but preferably 3-6, ELMA irrigations a year can help prevent soil problems such as further formation of sulfuric soils at depth, soil structure collapse (soil cracking — see Figure 12-2) and loss of all important organic matter.
- Ensure that drainage channels, reuse drains and pumps are operating efficiently to keep the saline, and now acidic in many areas post the Millennium Drought, groundwater table below the root zone (>0.5 m below ground level) where practical.

Irrigation efficiency

- Provided drainage is adequate, irrigation should be beneficial, as this will provide acid-neutralising/alkalinity, push acid down out of the root zone, and re-establish saturated conditions in the soil. On farms with only an ELMA allocation, ensure this water is applied in full, annually, where possible.
- Maximise irrigation efficiency on your farm to minimise acid drainage volumes. Provided drainage is adequate, efficient irrigation should be beneficial, as this will provide acid-neutralising alkalinity, leach acid down out of the root zone, and re-establish saturated conditions in the soil.
- Maximise irrigation efficiency on your farm to minimise acid drainage volumes. Provided drainage is adequate, efficient irrigation should be beneficial, as this will provide acid-neutralising alkalinity, leach acid down out of the root zone, and re-establish saturated conditions in the soil.
- In order to achieve efficient irrigation, re-establish pastures, repair delivery channels, rotary hoe and laser level.

- Use mole drains only where drainage is a problem — in slow-draining paddocks or wet boggy areas in paddocks.

Fertiliser management

- Use only the fertiliser you need — save money and water quality.
- Don't water the fertiliser in, especially nitrogen. Apply fertiliser after water as soon as you can get it on the paddock, because it will diffuse into the soil.

Organic matter management

- Grow feed, lots of it — lots of feed uses lots of fertiliser and water, feeds lots of livestock and puts lots of **organic matter** back into the soil for better drainage. (It also helps prevent formation of sulfuric material soil and other soil problems.) Green feed can be anything you can grow — pasture, lucerne, Sulla, paspalum, kikuyu, medic, summer crops — so try different rotations.
- Use feed supplements to run more livestock and feed them better throughout the year.

Water loss management

- Apply the correct flow rate and volume of water to minimise water use and prevent runoff.
- Correct use of soil moisture monitoring equipment will maximise the benefit of water available for irrigation.
- Water short as the last portion of the bay accumulates fertiliser and manure and consequently has very high nutrient levels.
- Use a marker or alarm to indicate when water should be turned off to prevent generating runoff from the end of the irrigation bay ('watering short').

Soil cracking and land subsidence management

Cracking leads to loss of use of the land, as animals can be injured (Figure 12-2). Reduced irrigation efficiency may also occur, because water moves preferentially through the cracks rather than across the soil surface.

- Paddocks with severe deep cracking (Figure 12-2) that received little or no water during the drought require different treatment: deep rip across the bays (to reduce continuity of the crack), cultivation with a chisel plough or similar, rotary hoe, laser level and a roll, prior to sowing. The aim is to break up and fill deep cracks with soil particles, which will wet up and prevent the surface water from running freely down the cracks. Alternatively, change to spray irrigation and prevent water by not having ponded water on the surface.
- Paddocks with small shallow cracking that received some water during the drought may be treated with a light rip and rotary hoe and laser levelled for the purpose of improving irrigation efficiency prior to shallow sowing.

Figure 12-2. Photographs of large soil cracks formed during Australia's Millennium Drought, which commenced in 2007 (see also Figure 2-2).

Source: Authors (top), *Murray Valley Standard* (bottom).

- There may be a need for further laser levelling as the soil settles and swells in following seasons, so returning to permanent pasture initially may not be advisable. A rotation that includes either winter mix or a cereal with millet sown in summer may be necessary.
- For paddocks in good condition, maintenance of soil hydration is essential to minimise the risk of **soil cracking**, **slumping** and generation of acid sulfate conditions. The use of ELMA and irrigation water (however limited) will provide beneficial outcomes. During the drought, some irrigators also found benefits in maintaining their salt drain level high (i.e. instead of pumping) to prevent soil cracking. The downside to this may be some soil salinisation, and it is not recommended if acidic groundwater is present.
- Where practicable, on properties with only an ELMA water allocation, ensure that ELMA is applied in full, annually, to **maintain soil health** (prevention of cracking and slumping, salinisation and acid sulfate soil exposure).

Runoff management

- Plant buffer strips around and/or between laneways, walkways, channels and roads to minimise contamination of runoff and the receiving environment. Buffer strips may include trees, shrubs, groundcovers and grasses appropriate for the site conditions.
- Manage runoff from dairy and calf rearing areas to ensure this does not enter drains leading to the river.
- Manage runoff and leaching from farm dumps and chemical (including fuel) storage, and mixing/use areas, by adhering to legislative guidelines. For example, use bunds or banks to confine runoff in case of accidental spillage; dispose of containers appropriately; and do not dispose of chemical or fuel containers in farm dumps.
- Where bunded runoff areas are used for excess water, plant appropriate species for the conditions.

Drain water quality monitoring and management

(Soil-water landscape feature Nos. 2 and 3 as shown in Figure 12-1)

The sections below provide detailed background information and advice on how best to monitor and manage the drains. A brief summary of major management options is also provided in Figure 12-1.

Understand what is happening on your farm — undertake constant visual observations and test the salinity/EC and pH levels in your drainage water and soil.

Key references

- EPA Guidelines for Lower Murray Reclaimed Irrigation Area (EPA 2014).
- EPA factsheet No 05/18825: Acid sulfate soils issue in the LMRIA and the involvement of the EPA in its management. February 2013.
- Lower Murray Irrigation Information Sheet Number 1: Laser levelling.
- Lower Murray Irrigation Information Sheet Number 2: Irrigation scheduling.

- Lower Murray Irrigation Information Sheet Number 4: Nitrogen fertiliser for the Lower Murray.
- Lower Murray Irrigation Information Sheet Number 5: Phosphorous for the Lower Murray.
- Lower Murray Irrigation Information Sheet Number 6: Mole drainage in the Lower Murray for poorly drained soil.
- Lower Murray Irrigation Information Sheet Number 8: 10 'Commandments' for Swamp Management.

Note that all of the above Information Sheets can be found at the following URL: http://fertsmart.dairyingfortomorrow.com.au/getting-it-right/case-studies/#lower-murray.

Salt drain management

Formation of acid water reddish-yellow suspended/gelatinous precipitates

Prior to Australia's Millennium Drought, which commenced in 2007, the LMRIA was actively farmed mainly as dairy enterprises (>80 years). During this extensive pre-drought period, surface water tables were maintained from irrigation, river and groundwater flows, which kept the subsoils saturated (i.e. high water table level of 0-1 m below ground level). At the end of the Millennium Drought in 2010, a drop in the water table level of up to 3 m from pre-drought levels led to the previously saturated soils being exposed to air for the first time, causing severe soil cracking to depths of up 3.5 m and oxidation of pyrite in the subsoils, which contain high amounts of hypersulfidic material. This process enabled hypersulfidic material to transform to sulfuric material with the consequent formation of

1. deep 'sulfuric clayey soils'
2. schwertmannite in bright reddish-yellow suspended/gelatinous precipitates in acidic drains (see Figures A6-3, 12-2) (Fitzpatrick et al. 2012b; 2017a).

In the Long Flat salt drain (Figure 12-3), schwertmannite has been found to occur in

1. brownish-yellow hard/cemented crusts and nodules
2. roots and stems with coatings of schwertmannite on *Phragmites australis*.

Limestone dosing of salt drain

- Treatment of the acidic water in the drainage channels may be achieved by introducing a neutralising limestone slurry prior to discharge to the River Murray. Previous results by EPA showed that the acidic drainage can be successfully treated using this method. A neutral pH was achieved and acidity and associated soluble metals were reduced to acceptable levels before discharge to the River Murray.
- Although this is an effective and efficient method of neutralising acid drainage water prior to discharge, it is expensive, and does not treat the problem at the source (i.e. in the soils under the irrigation bays). This treatment method would have to be in place at each LMRIA discharge for a long time, and it fails to address the potential build- up of metal precipitates within the drains.

Figure 12-3. PhotograpH of salt drain at Long Flat site showing brownish-yellow iron precipitates and white salt efflorescences on dead grass along the side of drain in foreground; in background is a view of the shovel used to excavate (i) brownish-yellow hard/cemented crusts and nodules with schwertmannite and (ii) roots and stems with coatings of schwertmannite on *Phragmites australis*.

Source: Authors.

Water level in salt drain

- Keep the main drain water level around 0.75 m below paddock level if possible, or a minimum of at least 0.5 m.
- All drains and channels should be kept clean and free flowing.
- Only apply the water you need — use Irrigauges and turn water off in time. Do not overwater — wet boggy soil does not grow feed.

Banks and infrastructures in salt drain

- Ensure all check banks are kept intact. Use a double fence. Keep stock off. These things will ensure no leakage of surface water to side drains.
- Ensure that livestock is kept away from drains containing acid water. If animals come into contact with acid water, rinse them off. If they fall ill, call for veterinary advice.
- Where practical, keep acid water away from metal and masonry infrastructure.

Where salt drain reuse systems are in use

- The salt drain is not to be pumped out to the river when it contains any irrigation runoff water (which is required to be reused on the farm), even if it accumulates saline seepage.
- Water can be used from the salt drain for irrigation, subject to metering requirements by the Department of Environment, Water and Natural Resources.
- The drain water quality, in particular salinity/EC and pH, should be checked prior to reusing for irrigation and the drain water 'shandied' with fresh irrigation water performed as required in order to produce suitable quality water for irrigation.

- Regular flushing of areas where reuse water is applied with fresh irrigation water is recommended.

For all shared salt drain management

- No blocks are allowed in the salt drain, except where approval has been given by the Environment Protection Authority (EPA).
- Seepage water (high salinity) accumulating in the salt drain can be pumped out when required.
- Salt drain water levels should be kept as low as possible to maximise storage capacity for rainfall events.
- During large rainfall events, the capacity of the reuse system may be exceeded and may overflow into the salt drain. The salt drain can then be pumped out when the water level starts to affect the water table in the paddock by artificially raising the groundwater. The remaining water should be held for a minimum of two weeks before release or irrigation elsewhere.
- Check salinity levels to manage damage to crops and pastures.
- All water in the salt drain must be allowed to freely flow between neighbours to the river.

References

- Lower Murray Irrigation Information Sheet Number 3: Reducing drainage costs and impacts http://fertsmart.dairyingfortomorrow.com.au/getting-it-right/case-studies/#lower-murray.

Back swamp area

(Soil-water landscape feature No. 1 as shown in Figure 12-1)

Maintaining land condition in the back swamp area is more difficult, due to the inflow of saline groundwater to this region and the difficulty in applying irrigation water. Nevertheless, some general management advice is to

- keep drainage infrastructure operating effectively using the guidelines above
- irrigate periodically if possible to flush salt from the soil profile
- fence to exclude stock from areas
- plant salt tolerant vegetation
- apply gypsum if soil structure has been damaged due to sodicity
- add lime to areas that that are hypersulfidic or sulfuric.

Levee banks

(Soil-water landscape feature No. 9 as shown in Figure 12-1)

To maintain levee banks in suitable conditions, farmers and levee bank managers should

- maintain river levels to prevent bank cracking and subsidence — major impacts occurred as a result of the river level dropping in the Millennium Drought, leading to levee banks drying, cracking and slumping

- repair and maintain banks — banks should be inspected regularly and repaired or 'topped up' with compacted clay as required; vegetation on the levee banks should also be managed by slashing or spraying, so banks can be inspected easily and weeds and trees do not establish on them
- maintain irrigation infrastructure on the bank so that leakage is minimised. Irrigation water delivery channels at the toe of the bank should also be maintained in good condition to enable water to be delivered, which also assists in maintaining the levee bank soil conditions.

Riparian zone

(Soil-water landscape feature No. 10 as shown in Figure 12-1)

The riparian zone adjacent to the River Murray provides important functions for the river and acts as a 'buffer' against the impacts of drainage discharges. In general, in order to protect this area

- wetland vegetation should not be cleared unless necessary and with the required permits (for example, dredging for maintaining irrigation channel)
- drainage volumes should be minimised by efficient irrigation practices and drainage water quality impacts also minimised via following best management practices on farm (see above).

River Murray including adjacent ponded and wetland areas

(Soil-water landscape feature No. 11 as shown in Figure 12-1)

Maintain height of water in the river at +0.5 m AHD

To prevent acidification by maintaining the groundwater table and to retain the ability to apply irrigation water effectively via flood-irrigation, the river level should preferably be maintained at greater than +0.5 m AHD. At no times should the river level decline below zero m AHD as stated in the Murray-Darling Basin Plan. Where possible, any decrease in level below 0.5 m AHD should occur outside of the main irrigation season (October-March).

Maintain river salinity <1000 EC (µS/cm)

Where possible, river salinity should be maintained <1000 EC (µS/cm) to prevent salt impacts on sensitive pasture and crop species.

Maintain and apply ELMA water during drought

There are policy and operational management revisions required surrounding the use of ELMA to protect the LMRIA in future droughts. The recent discussion paper 'Environmental Land Management Allocations (ELMA) and the Water Allocation Plan for the River Murray Prescribed Watercourse' (Appendix 8) outlines these. In relation to maintaining soil condition to prevent severe cracking and acidification it is considered critical that ELMA is retained and applied at its highest level during drought conditions. The application of ELMA should be mandatory under these conditions and support given to irrigators where required (for example, fuel subsidies, access to portable pumps and travelling irrigators) under extreme drought conditions.

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APPENDIX 1

CLUES OBTAINED FROM FIELD OBSERVATIONS

CLUES FROM SURFACE FEATURES

Salt efflorescences

Figure A1-1. Photographs of soft coatings of strong brown iron-rich precipitates with associated white salt efflorescences on soil and vegetation surfaces at Long Flat [(a) and (b): samples DSb01-D, E] and Toora [(c) and (d): samples DSb03-D and DSb03-E] in uncultivated fields belonging to SA Water, showing strong brown iron-rich precipitates (comprising schwertmannite) and white salt efflorescences (comprising Konyaite: $Na_2Mg(SO_4)_2$. $5H_2O$ and Hexahydrite: $MgSO_4$ $6H_2O$) on dead grass.

Source: Fitzpatrick et al. 2017a.

Figure A1-2. Photographs of hard iron-rich cemented crusts/aggregates in *Phragmites australis* roots/stems excavated under water in the salt side drain at Long Flat.

(a) and (b) show the strong brown iron-rich cemented crusts/aggregates (DSa01F, c, d) being excavated under water using a shovel

(c) close-up view of wet freshly excavated strong brown cemented crusts/aggregates tipped from the shovel onto the dried *Phragmites* vegetation (light brown colour)

(d) close-up view of *Phragmites* roots/stems in water showing the thickened cemented crusts/aggregates at the air-water interface in the salt drain (DSa01F, c, d).

Source: Fitzpatrick et al. 2017a.

Iron precipitates on soil surfaces

Figure A1-3. Photographs of **moist coatings or pastes of** reddish-yellow coloured **iron-rich precipitates** and associated salt efflorescences located in progressively drying ponds and drains in:

(a) **Burdett** drain in May 2013 (looking west towards the River Murray showing pump station in distance)

(b) **Burdett** drain in May 2013 of close-up view of precipitate overlying black monosulfidic material

(c) and (d) in **Pompoota** side drain (looking west towards the River Murray with pump station in far distance) showing wet coatings on dead grass viewed in the top LHS (DSa05-5)

(e) **Pompoota** side drain of a close-up view of thin surface crusts/coatings (DSa05-6) on the carbonate nodules (DSa05-7)

(f) **Jervois** evaporation pond in drained section (DSb02-D).

Source: Fitzpatrick et al. 2017a.

Suspended iron precipitates in drains and ponds

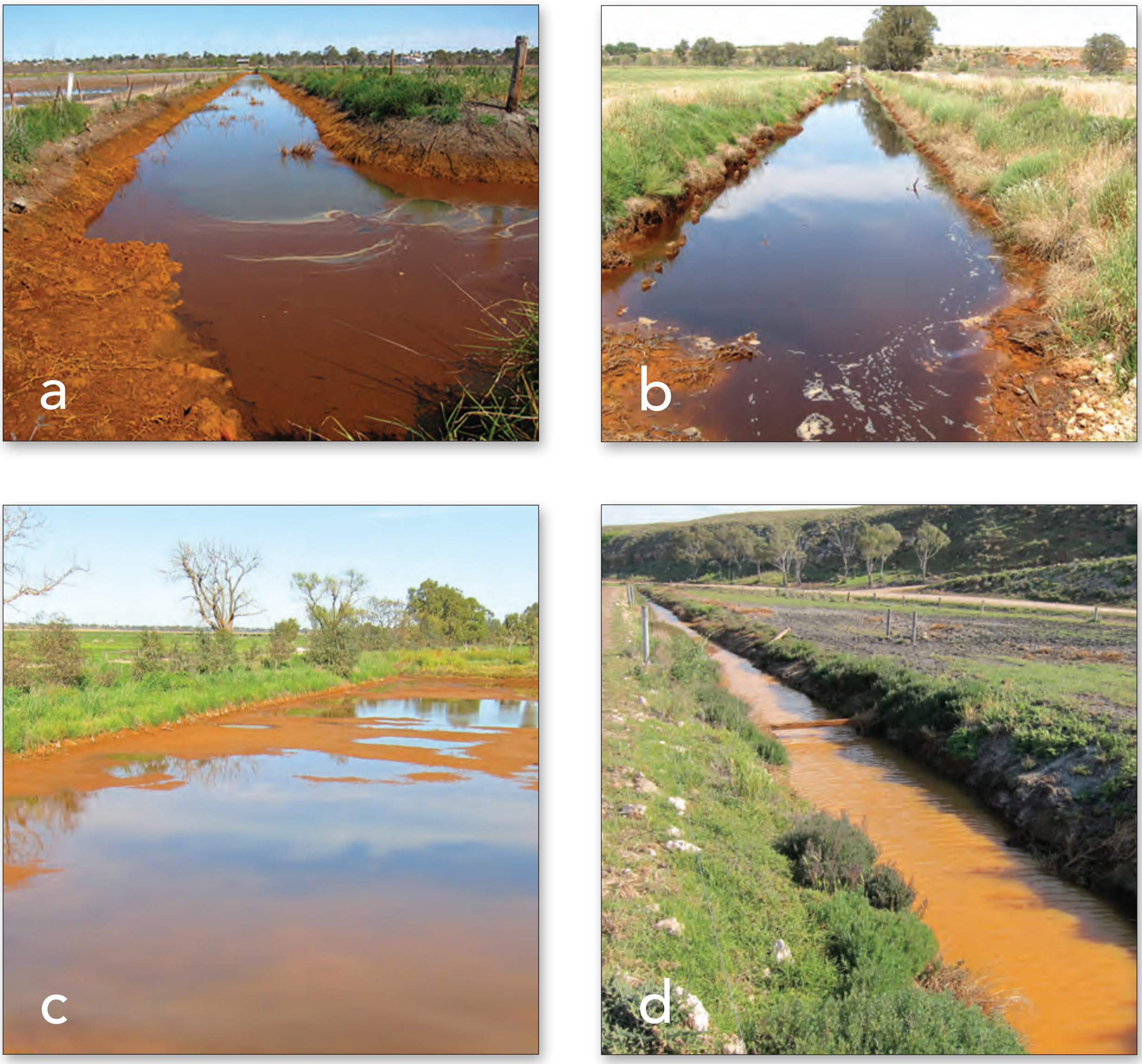


Figure A1-4. Photographs of suspended strong brown coloured iron-rich precipitates in drains filled with water in:

(a) **Burdett** drain on 2 September 2011 (looking west towards the River Murray showing pump station in distance) (DSb04-D)

(b) **Pompoota** drain on 17 November 2011 (looking west towards the River Murray showing pump station in distance) (DSa05-4)

(c) **Jervois** irrigation retention/reuse/evaporation pond on 2 September 2011 (DSb02-E)

(d) **Toora** side drain (DSb03-G)

(e) **Myponga** salt drain on 30 October 2015.

Source: Fitzpatrick et al. 2017a.

Gilgai

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

However, there are essentially two broad groupings of gilgai:

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

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

Figure A1-5. PhotograpH of high gilgai (i.e. melon-hole gilgai) on grey clays or Grey Vertosol with high shrink-swell potential showing ponding of water in closed depressions near Narrabri along the Newell highway.
Source: Fitzpatrick 2015.

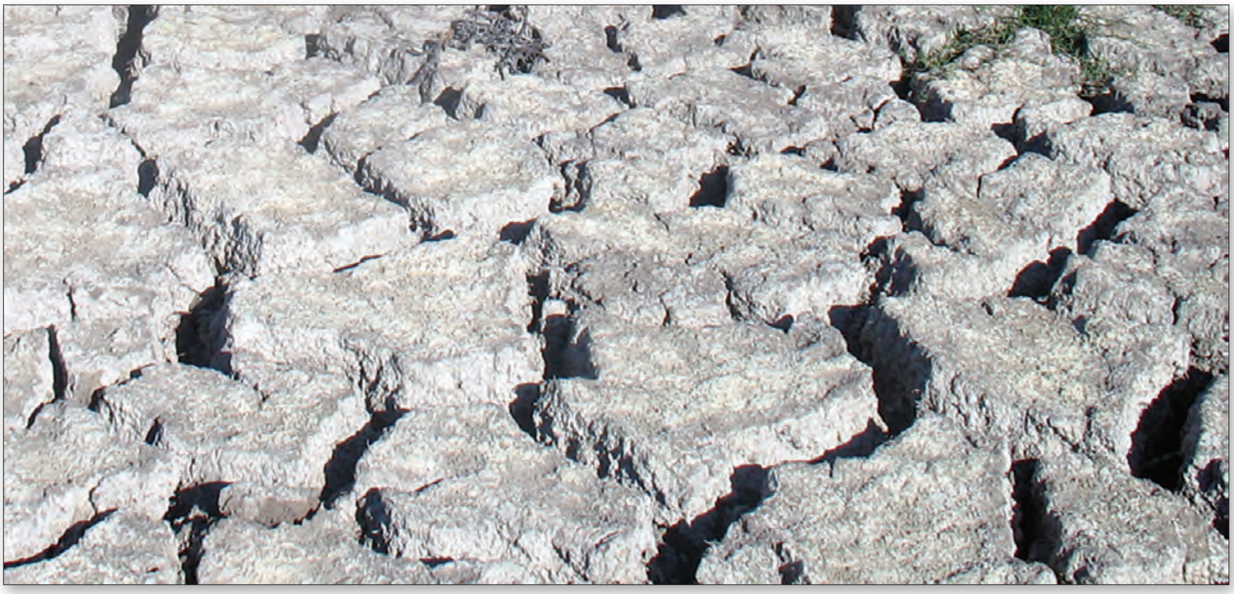


Figure A1-6. Cracks greater than 40 mm wide to a depth of 1 m in a deep clay soil, which shrinks and swells during seasonal wetting and drying cycles, in Hughenden, north Queensland.

Source: Fitzpatrick et al. 2014.

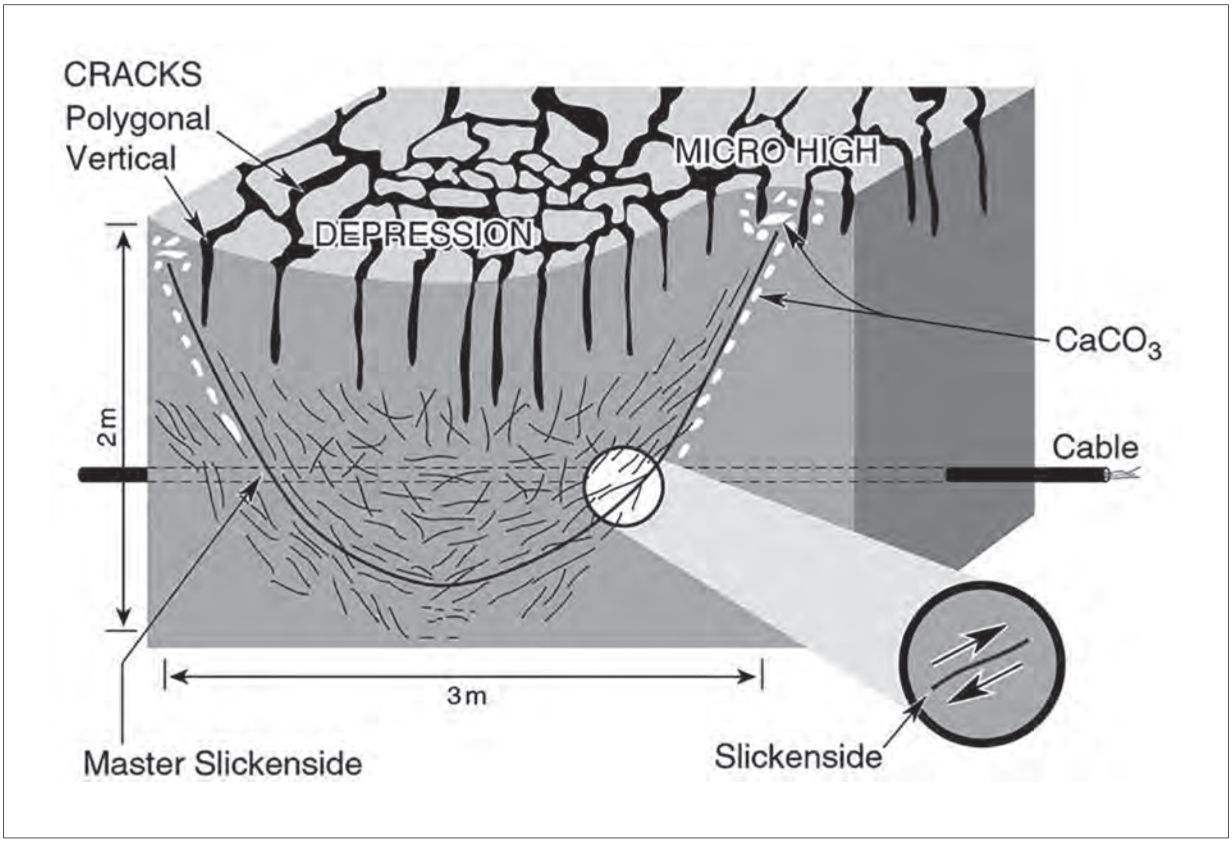


Figure A1-7. Schematic section through a swelling clay soil or Vertosol showing micro relief (gilgai), crack zones with slickensides (shearing zone), where cable distortion occurs due to soil movement (shearing action).

Source: Fitzpatrick et al. 2014.

Shrinkage cracks

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

Lime/gypsum

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

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

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

Clues from soil profile features

Clues from a road cutting, soil pit or auger hole

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

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

Cleaning the profile or auger hole face

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

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

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

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

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

Sketch of the profile (optional)

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

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

Colour

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

Table A1-1. Interpreting soil colour

Colour pattern of material in surface & subsurface layers	Accessory indicators Texture/ Depth	Soil indicator	Environmental indication
Uniform coloured surface & subsurface	Sandy/ shallow (25-50cm)	Uniform coloured[1] brown and red sand	**Excessively drained**: Water is drained very rapidly. Groundwaters are deep. Soils are commonly very coarse or sandy textured, rocky or shallow.
Uniform coloured surface & subsurface	Loams/very deep	Uniform coloured[1] brown and red loam (L) to sandy clay loam (SCL).	**Well drained**: Water is drained from the soil readily but not rapidly. Internal free water occurrence is very deep. Water is available to plants during most of the growing seasons and soil wetness does NOT inhibit growth.
Uniform coloured surface (0-30 m) mottled subsurface	Loams/ deep (>100cm)	Uniform coloured[1] brown and red L to SCL. Low chroma[4] mottling between 30 to 100 cm and no yellowish soil matrix hues or neutral colours within 150 cm	**Moderately well drained**: Water is drained from the soil slowly during some periods of the year. Internal free water occurrence is moderately deep (0.5-1 m). The soils are wet for only a short period of the growing season for mesophytic crops to be affected. Soils commonly have a slowly pervious layer within the upper 1 m, and periodically receive high rainfall.
<20% grey and bluish mottling in surface & subsurface	Loams and clays moderately deep (0-75cm)	<20% grey or bluish mottling[4] and >20% yellowish or red mottling[3] between 0-75 cm. (Few[6] to common[7] grey, bluish mottles[4])	**Somewhat poorly drained**: Water is drained from the soil slowly enough that the soil is wet at shallow depth for significant periods during the growing season. Internal free water occurrence is shallow (25-50 cm) and commonly transitory. Wetness restricts growth of mesophytic crops unless drained. Soils commonly have a slowly pervious layer and high water table, and can receive additional water from seepage or very high rainfall.

>20% grey and bluish mottling in surface & subsurface	Shallow (25-50cm) surface & subsurface	>20% grey or bluish mottling[4] and <20% yellowish or red mottling[3] between 0-75 cm. Many[8] grey, bluish or black mottles[4] Many[8] grey bluish mottles[3]	**Poorly drained**: Water is drained very slowly so that the soil is wet at shallow depths periodically during the growing season. Internal free water occurrence is shallow (25-50 cm) or very shallow (<25 cm) and common or persistent. Free water is commonly at or near the surface long enough for most mesophytic crops not to grow unless drained. The soil is NOT continuously wet directly below the plough-depth, but free water is usually present at shallow depth because of: (i) slowly pervious layers (ii) very high water tables and (iii) additional water from seepage or very high rainfall.
Uniform grey or bluish material in surface & subsurface	Very shallow (<25cm) surface & subsurface	Uniform grey or bluish material[2] throughout the soil and with many[8] grey, bluish or black mottles[4]	**Very poorly drained:** Water is drained very slowly. The soil remains wet at or very near the ground surface during most of the growing season. Internal free water occurrence is very shallow (<25 cm) and common or persistent. Free water is commonly at or near the surface long enough so that most mesophytic crops will not grow unless drained. The soils are on level land and are continuously wet and frequently ponded.

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

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

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

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

5. Very few = <2%.

6. Few = 2-10 %.

7. Common = 10-20%.

8. Many = 20-50%.

Source: Fitzpatrick 1996; Fitzpatrick et al. 1999.

Structure

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

(i) Slickensides (ss)

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

Cautionary note:

1. Do not confuse slickenside surfaces with the shiny smeared surfaces caused by implements (for example, by tools or tillage implements).
2. Slickenside surfaces can be obscured by the tools used to dig pits, hence the importance of observing a cleaned pit surface. When using an auger, it is more difficult to observe slickensides, and for this reason it is critical to always observe such features at the bottom of the auger.

Figure A1-8. Slickensides (also known as 'shiny backs') are shear planes found at depth in heavy shrink-swell clays. They characteristically form in all planes with the production of lenticular or wedge-shaped structures. Slickensides can be polished, grooved or fluted, and when the soil dries they crack and have a dull lustre.

NOTE: The majority of slickensides are small (for example, thumb-nail size), as shown in the upper part of the photograph.

Source: Fitzpatrick 2015.

(ii) Peds (p)

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

(iii) Massive (m)

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

Texture

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

How to determine soil texture

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

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

Figure A1-9. Photographs showing: (i) clayey soil with ped structures, (ii) loamy soil with massive structure (i.e. with no peds), and (iii) sandy soil with massive structure (i.e. with no peds).

Source: Authors.

Figure A1-10. Photographs showing the length of the ribbon produced by pressing out between thumb and forefinger to characterise: (i) a clayey soil texture with ribbon length >75mm and (ii) a sandy soil texture with no ribbon.

Source: Authors.

Table A1-2. Interpreting soil texture from the behaviour of a moist bolus (ball)

Texture*	Ribbon (mm)	Ball	Feel	Environment indication
Sand (S)	nil	coherence nil to very slight	Cannot be moulded. Clay is <5%.	No restriction on root growth for annuals and perennials but has a moderate susceptibility to mechanical compaction. No restriction on water movement but periodic soil moisture stress occurs because water is drained very rapidly.
Loamy sand (LS)	5	coherence nil to very slight	Cannot be moulded. Clay is 5-10%.	As above.
Clayey sand (CS)	5-15	coherence very slight	Cannot be moulded. Clay is 5-10%.	As above.
Sandy loam (SL)	15-25	coherence slight	Sandy to touch. Clay is 10-20%.	Root growth of annuals and perennials is not restricted but has a high susceptibility to mechanical compaction. Very slight restriction on water movement; soil water is available to most crops and trees. Water is drained from the soil readily but not rapidly.
Loam (L)	25	coherent and rather spongy	Smooth feel when manipulated but with no obvious sandiness; may be greasy to touch if organic matter is present. Clay is about 25%.	Root growth of annuals and perennials is not restricted, with moderate susceptibility to mechanical compaction. Very slight restriction on water movement; soil water is available to most crops and trees.
Sandy clay loam (SCL)	25-40	strongly coherent	Sandy to touch; medium-size sands grains visible in finer matrix. Clay is about 20%-30%.	As above.
Clay loam (CL)	40-50	coherent plastic	Smooth to manipulate. Clay is about 30-35%.	As above.

Light clay **(LC)**	50-75	plastic	Smooth to touch; slight to shearing between thumb and forefinger. Clay is about 35-40%.	Root growth of annuals and perennials is frequently restricted, with moderate susceptibility to mechanical compaction. Some restriction on water movement; soil water is available to most crops and trees. Water flow is restricted, contributing to periodic waterlogging.
Medium clay **(MC)**	>75	smooth plastic	Handles like plasticine and can be moulded into rods without fracture; has some resistance to ribboning shear. Clay is about 45-55%.	Root growth of most species is severely restricted but with low susceptibility to mechanical compaction. Water is drained very slowly. This does not apply to self-mulching or sub-plastic clay properties.
Heavy clay **(HC)**	>75	smooth plastic	Handles like stiff plasticine; can be moulded into rods without fracture; has firm resistance to ribboning shear. Clay is about >55% .	As above.
The Texture Groups according to Northcote and Skene (1972):				
1. **The Sands** = sand (**S**), loamy sand (**LS**), clayey sand (**CS**).				
2. **The Sandy Loams** = sandy loam (**SL**), fine sandy loam (**FSL**).				
3. **The Loams** = loam (**L**), sandy clay loam (**SCL**).				
4. **The Clay Loams** = clay loam (**CL**), silty clay loam (**ZCL**), fine sandy clay loam (**FSCL**).				
5. **The Light Clays** = sandy clay (**SC**), silty clay (**ZC**), light clay (**LC**), light medium clay (**LMC**).				
6. **The Medium-Heavy Clays** = medium clay (**MC**), heavy clay (**HC**).				

Source: Fitzpatrick 1996; Fitzpatrick et al. 1999.

Soil consistence

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

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

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

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

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

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

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

Table A1-3. Interpreting soil consistence

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

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

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

Source: Fitzpatrick 1996; Fitzpatrick et al. 1999.

Effective root depth

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

Effective root depth is estimated in the following manner:

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

Table A1-4. Interpreting effective root depth

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

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

Source: Fitzpatrick 1996.

Appendix 2

Saline and sodic soil tests and interpretation of results

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

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

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

1. This is a simple test that can be done by placing a sample of air-dried soil (i.e. thinly spread soil exposed to air for two days) in rainwater and leaving it to stand overnight. The test can be carried out on soil sampled either from a pit or auger hole. When using an auger, make sure that it is of large diameter, and take the soil sample for testing from the middle of the core. This is to avoid sampling remoulded soil that tends to disperse more readily.
2. If necessary, dry the soil sample in air for several days before gently breaking down large clods. Do not crush any rocks or fragments of lime.
3. Following a modified SASKIT method (after Rengasamy and Bourne 1997)
    i. Weigh 100 g of soil (do not include clods more than 1 cm in width) into a clean 600 ml or larger glass jar.
    ii. Pour rainwater gently down the side of the jar without disturbing the soil on the bottom. Gently add 500 ml of rainwater down side of the jar, without disturbing the soil at the bottom. This gives a **1:5 soil:water ratio**. If you do not have a balance, then place 4 scoops of soil to 30 scoops of rainwater (for example, coffee scoop or tea spoon).
    iii. Replace the lid and gently invert. Rotate the jar while it is upside down, on an angle of 45 degrees, until the soil detaches itself from the base of the jar. Let jar with sample stand in a secluded place (out of reach of children, pets, etc., with no vibrations or bumping) for 4 hours.
4. **Sodicity** (dispersibility) (modified from Fitzpatrick et al. 1997)
    i. After **4 hours**, without moving the jar, gently stir the liquid for 5 seconds so that only the dispersed clay on top of the sediment is agitated (i.e. do not disturb the whole soil sediment on the bottom of the jar!).

ii. Describe whether the solution above the soil sediment is 'clear', 'murky' or 'densely opaque' (see Figure A2-1) on the analysis sheet (Table A1-1).

5. **Soil salinity** (electrical conductivity)

   i. Completely stir the whole soil sediment vigorously for 15 seconds.

   ii. Measure the electrical conductivity (EC) of solution after 10 minutes. Record the EC measurement ($EC_{1:5}$) in the unit of dS/m as shown in Table A2-1.

6. **Gypsum**

   i. Determine presence of gypsum by mixing approximately 20 ml of solution with 20 ml of acetone. If a white precipitate develops, then gypsum is present.

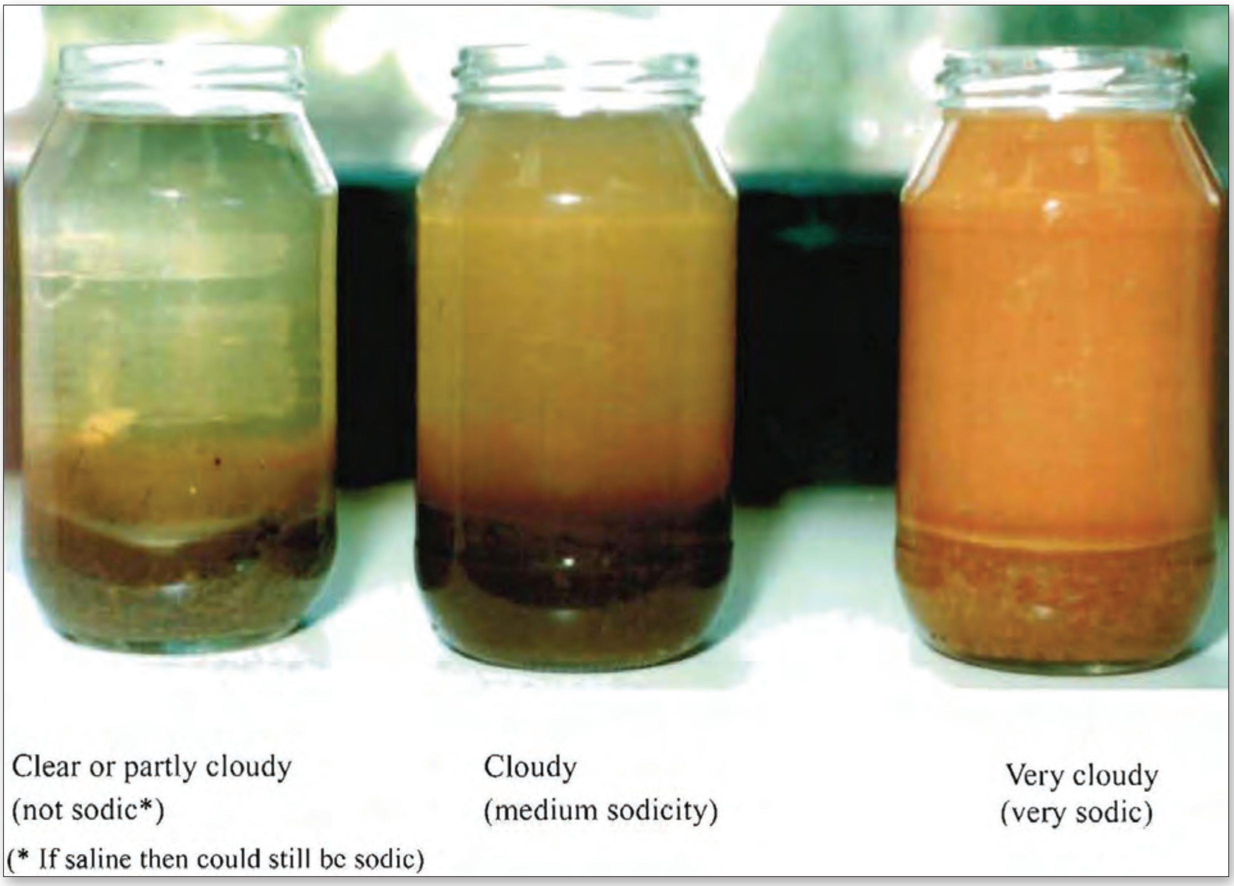


Figure A2-1. Estimating turbidity or cloudiness (soil sodicity) in a 1:5 soil/water suspension.
Source: Fitzpatrick et al. 1997.

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

Date of Soil Sampling:

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

If EC is less than 0.7 dS/m and liquid is **clear**	Soil is non-saline and non-sodic.
If EC is 0.7-1.4 dS/m and liquid is **clear**	Soil is moderately saline.
If EC is 1.4->3.5 dS/m and liquid is **clear**	Soil is severely saline.
If EC is less than 0.7 dS/m and liquid is **murky**	Soil is non-saline and moderately sodic.
If EC is less than 0.7 dS/m and liquid is **densely opaque**	Soil is non-saline and severely sodic.
If a white precipitate develops in acetone	Gypsum is present.

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

1. After 4 **hours**, check the suspension above the sediment at the bottom of the jar and estimate the amount of cloudiness using the sodicity meter. Lower the meter with the white disc at the bottom of the plastic tube into the suspension, until the disc is no longer visible when viewed from the top (Figure A2-2 A). Place a moistened finger over the top of the tube and withdraw the meter with a level of liquid in the tube. The level can be read against the coloured scale, which corresponds with the photographs and indicates whether the soil is non-sodic, sodic or highly sodic (Figure A2-2 B).
2. After checking for sodicity, invert the jar vigorously 15 times and allow to stand for a further 15 minutes. If you previously scored the jar clear and so non-sodic, but it now remains cloudy, the soil is likely to disperse not due to high sodium, but from structural breakdown due to mechanical cultivation.
3. Record the level of sodicity or mechanical dispersion on the Field Recording Sheet.

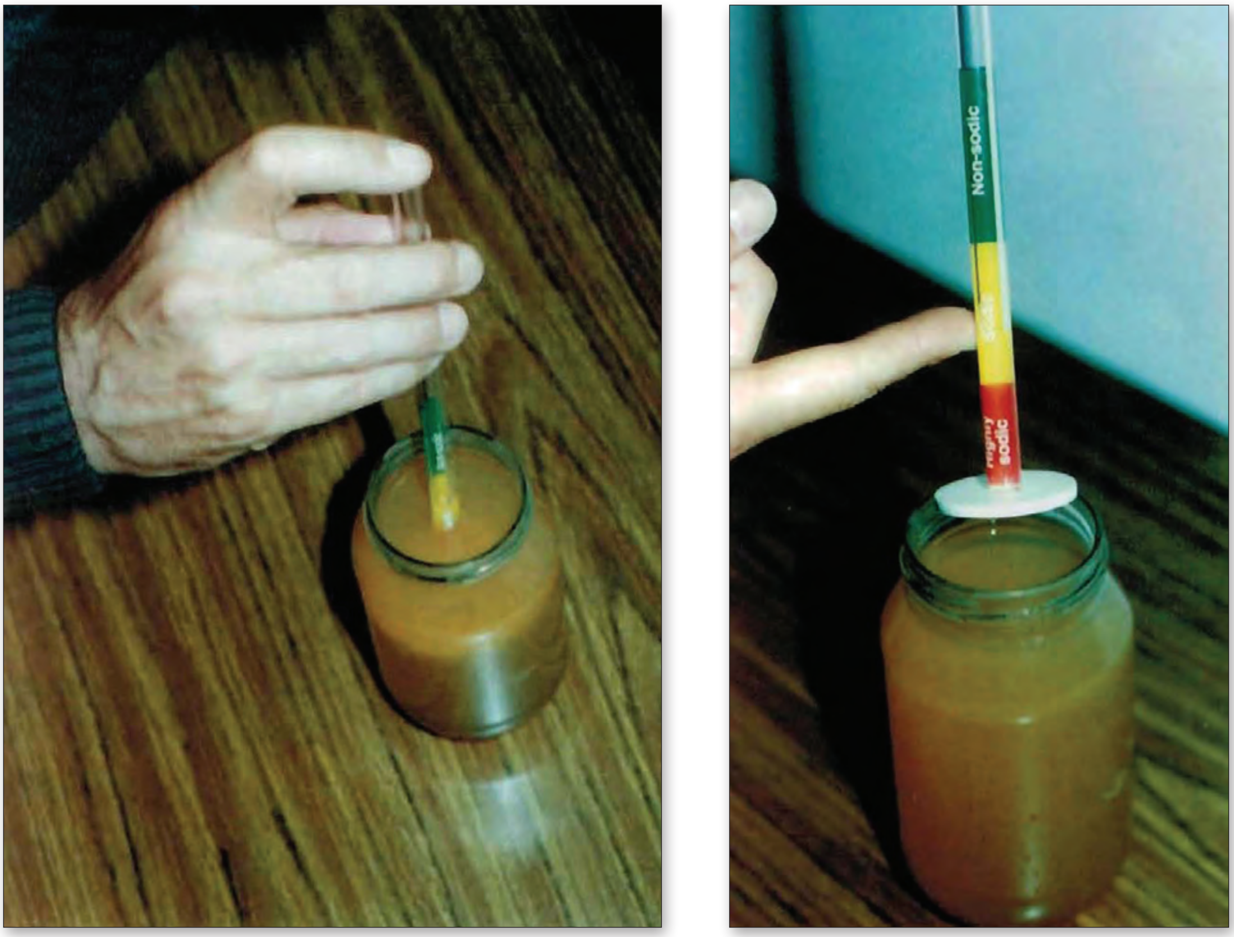


Figure A2-2.

A. Left: Lowering the meter into the soil/water suspension until the white disc is no longer visible.

B. Right: Reading the water level against the scale.

Source: Cox et al. 1999.

Saline and sodic soil hazard

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

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

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

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

Managing sodic soils

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

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

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

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

Appendix 3

Acid sulfate soil materials and pH tests

Acid sulfate soil materials

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

1. potential
2. actual (or active)
3. post-active ASS

which are the three broad generic soil types that continue to be recognised (for example, Fanning 2002; Fanning et al. 2017). However, definitions of these broad generic types of ASS can be confusing and the Acid Sulfate Soil Working Group of the International Union of Soil Sciences agreed to adopt changes to the classification of ASS materials (Sullivan et al. 2010). This was also adopted

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

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

Sulfuric material

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

Sulfidic materials

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

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

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

Hypersulfidic material is a sulfidic material that has a field pH of 4 or more and is identified by experiencing a substantial* drop in pH to <4 (1:1 by weight in water, or in a minimum of water to permit measurement) when a 2-10 mm thick layer is incubated aerobically at field capacity. The duration of the incubation is either:

1. until the soil pH changes by at least 0.5 pH unit to below 4; or
2. until a stable** pH is reached after at least 8 weeks incubation.

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

**A stable pH is assumed to have been reached after at least 8 weeks of incubation when either the decrease in pH is <0.1 pH unit over at least a 14-day period, or the pH begins to increase.

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

Hyposulfidic material is a sulfidic material that

1. has a field pH of 4 or more
2. does not experience a substantial drop in pH to <4 (1:1 by weight in water, or in a minimum of water to permit measurement) when a 2-10 mm thick layer is incubated aerobically at field capacity. The duration of the incubation is until a stable pH is reached after at least 8 weeks of incubation.

Monosulfidic materials

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

Non-acid sulfate soil materials

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

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

1. **Other acidic soil materials** — either
   i. non-sulfidic soil materials that acidify by at least a 0.5 pH_w unit to a pH_w of <5.5 during moist aerobic incubation; or
   ii. soil materials with a $pH_w \geq 4$ but <5.5 in the field.
2. **Other soil materials** — soils that do not have acid sulfate soil (or other acidic) characteristics.

Testing for presence of soil carbonates

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

Field pH test (pH_F)

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

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

Procedural outline for field pH_F testing

Incubation (ageing) testing

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

- Bulk soil samples (typically >500 g) should be placed in pre-labelled, thick, sealable plastic bags and mixed for pH analysis and bulk storage.
- Two sub-samples from the layers should be placed in two separate chip-trays (Fitzpatrick et al. 2010a).
- One chip-tray should be used to display morphologically representative aggregates for each of the sampled layers (compartments filled to ¾ full with preferably undisturbed clods/samples) for later visual reference (Figure A3-1).
- The second chip-tray for the acid sulfate soil incubation test ($pH_{incubation}$) should be stored in the shed or laboratory (compartments filled to ⅓ full with disturbed crushed samples and moistened with distilled or deionised water).
- Each compartment is to be adjacently labelled (on the inside of the lid) with the layer sample ID, and on the outside of the chip-tray labelled with survey locations and collection date (Figure A3-2).

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

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

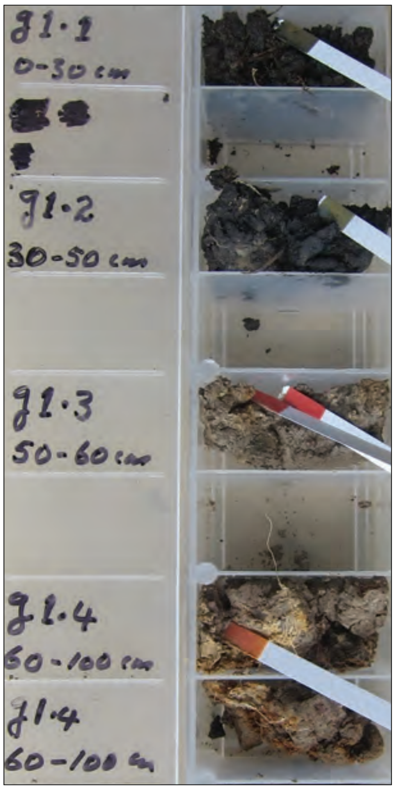
<table>
<tr><th>PhotograpH of soil profile from Mobilong</th><th>Depth (cm)</th><th>ID No</th><th>Chip-tray displaying representative soil aggregates with Merc strips</th></tr>
<tr><td rowspan="5"></td><td>0-30</td><td>g1.1</td><td rowspan="5"></td></tr>
<tr><td>30-50</td><td>g1.2</td></tr>
<tr><td>50-60</td><td>g1.3</td></tr>
<tr><td>60-80</td><td>g1.4</td></tr>
<tr><td>80-100+</td><td></td></tr>
</table>

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

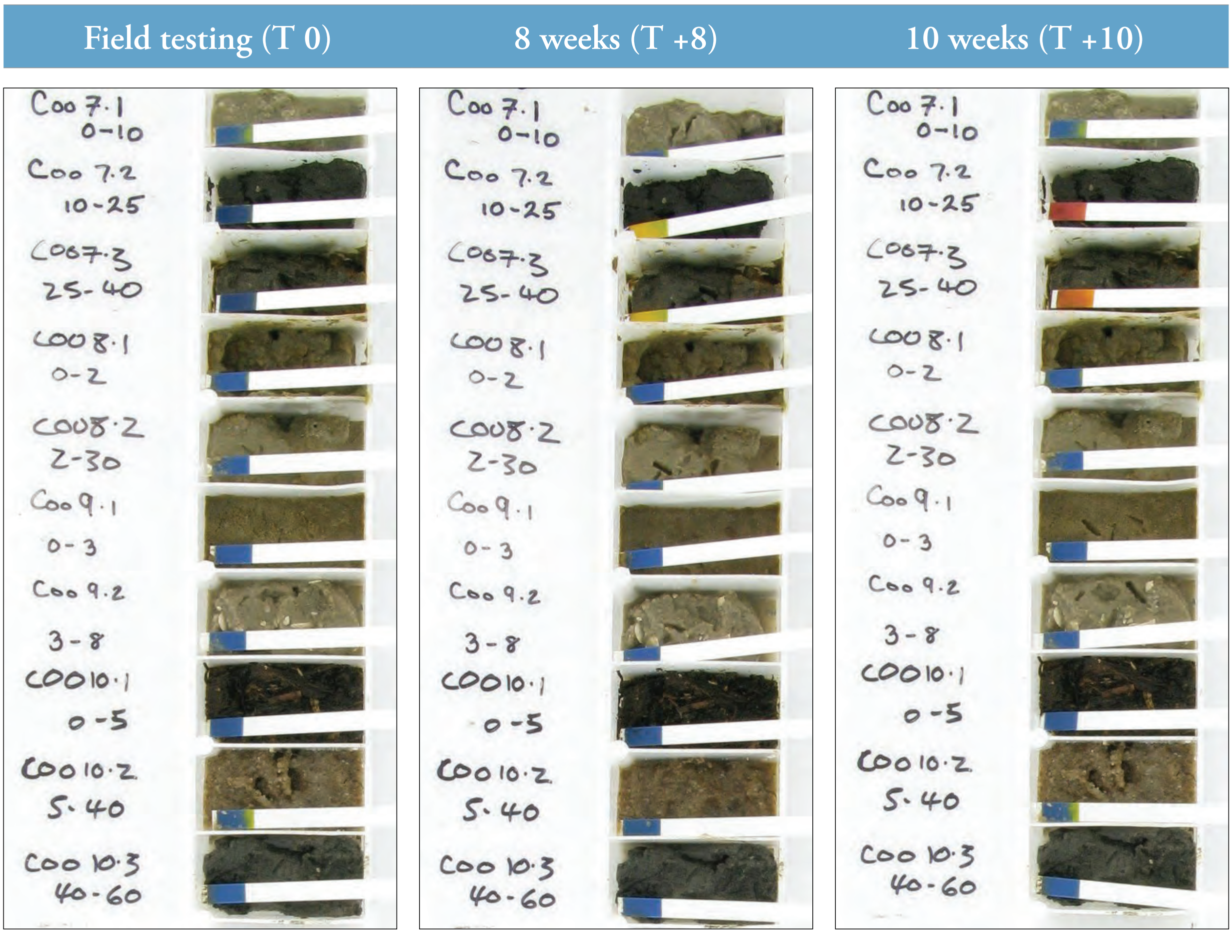


Figure A3-2. Time sequence (T 0, T +8, T +10) for a chip-tray of soils from the Coorong in South Australia undergoing incubation. Each photograpH shows soil pH as indicated by Merck pH strip colours:

(i) at T 0, at sampling in the field

(ii) at T +8, after incubation for 8 weeks

(iii) at T +10, at 10 weeks.

Here pH indicator strip colours indicate that most samples remain alkaline or neutral (blue colour >pH 7) with only two becoming acid after incubation for 10 weeks (red or pink colour - pH 3.9 to 4) (Fitzpatrick et al. 2008b).

NOTE: The preferred method is to measure the pH of the whole soil using a calibrated pH meter.

Source: Fitzpatrick et al. 2008b.

Field pH meter

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

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

The n-Value via the index of squishiness is a field estimate of mechanical properties that describes the ability of a saturated soil to support a load. The n-Value (sometimes referred to as 'index of squishiness') concept was developed by Pons and Zonneveld (1965) to define the degree of physical ripening of soft sediments (i.e. '**pelagic ooze**' materials) as they dewater. It is a measure of the physical bearing capacity of a soil material. The following definition has been modified from Fanning and Fanning (1989) and Soil Science Division Staff (2017, pp. 189-190). It is mathematically defined for Soil Taxonomy for soil materials that are not thixotropic as follows:

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

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

R = % silt + sand;

L = % clay (<2 μm);

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

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

Figure A3-3. Professor JL Pons undertaking the 'index of squishiness' or n-Value test in the Mekong Delta, Vietnam, in 1992 during the 4th International Acid Sulfate Soil Conference.

Source: Authors.

Table A3-1. Index of squishiness classes or n-Values

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

References

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

Pons JL and Zonneveld, IS. (1965). Soil ripening and soil classification. Initial soil formation in alluvial deposits and classification of the resulting soils. Inst. Land Reclam. and Impr. Pub. 13. Wageningen, The Netherlands. 128 pp.

Appendix 4

Soil identification key

Acid sulfate and salt-affected soils

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

Groundwater associated salinity (GAS)

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

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

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

Non-groundwater associated salinity (NAS)

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

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

Irrigation associated salinity (IAS)

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

Inland and coastal acid sulfate soils (ASS)

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

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

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

Classification of acid sulfate and salt-affected soils

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

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

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

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

The key consists of a systematic arrangement of soils into 5 broad acid sulfate soil types, each of which can be divided into up to 6 soil subtypes. The key layout is bifurcating, being based on the presence or absence of particular soil profile features (i.e. using a series of questions set out in a key). A soil is allocated to the first type whose diagnostic features it matches, even though it may also match diagnostic features further down the key. The key uses a collection of plain-language names for types and subtypes of ASS in accordance with the legend for the Atlas of Australian Acid Sulfate Soils (Fitzpatrick et al. 2010b; Fitzpatrick 2013). It recognises the following 6 acid sulfate, salt-affected and anthropogenic soil types (Table A4-1):

1. Subaqueous soils
2. Organic soils
3. Cracking clay soils
4. Sulfuric soils
5. Hypersulfidic soils
6. Hyposulfidic soils
7. Strongly waterlogged sodic soils
8. Strongly waterlogged saline & sodic soils
9. Strongly waterlogged saline soils
10. Anthropogenic soils
11. Other soils

These are further subdivided into 21 soil subtypes (Table A4-2) based on occurrence of sulfuric material, hypersulfidic material, clayey or sandy layers; monosulfidic material, firmness, sodicity and salinity.

Table A4-1. Soil identification key for soil types in the LMRIA.

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

Does a sulfuric layer (pH <4) occur within 150 cm of the soil surface,

AND is the subsoil uniformly grey coloured (poorly drained)?

NO ↓

YES →

Sulfuric soil

Does sulfidic material (pH >4 which changes on ageing to pH <4) occur within 150 cm of the soil surface,

AND is the subsoil uniformly grey coloured (poorly drained)?

NO ↓

YES →

Hypersulfidic soil

Does sulfidic material (pH >4 which does not change on ageing to pH <4) occur within 150 cm of the soil surface,

AND is the subsoil uniformly grey coloured (poorly drained)?

NO ↓

YES →

Hyposulfidic soil

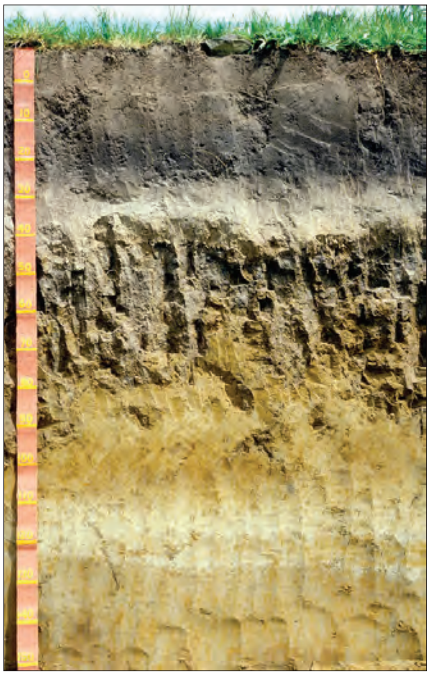
Does the Top Layer have: (i) uniform grey colour with grey (bleached) mottles?

Does Bottom Layer 1 have: (i) uniform yellow colour with or without some carbonate accumulations (ii) Test sample for dispersion to indicate sodicity (Appendix 2)?

Does Bottom Layer 2 have: (i) yellowish brown colour with bluish-grey mottles, slickensides and/or carbonate accumulations?

NO ↓

YES →



Strongly waterlogged sodic soil

Does the Surface Layer have features that indicate salinity such as white salt stains when dry, presence of sea barley grass or samphire?

Does the Top Layer have: (i) uniform grey colour with red stains and/or grey (bleached) mottles, (ii) EC meter reading is more than 0.7 dS/m?

Does Bottom Layer 1 have: (i) dark grey colour with yellow and some red mottles, (ii) EC meter reading is more than 0.4 dS/m, (iii) Test sample for dispersion to indicate sodicity (Appendix 2)?

Does Bottom Layer 2 have: (i) Bluish-grey colour with yellow mottles and/or carbonate accumulations, (ii) EC meter reading is more than 0.7 dS/m (Appendix 2)?

NO ↓

YES →

Strongly waterlogged saline & sodic soil

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

After finding the soil type, use Table A4-2 to find the soil subtype.

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

<table>
<tr><th>Soil type</th><th colspan="2">Diagnostic features for soil subtype</th><th>Soil subtype</th></tr>
<tr><td rowspan="6">Subaqueous soil
YES →
NO ↓</td><td>Does sulfuric material occur within 150 cm of the soil surface?
YES →
NO ↓</td><td>Does the upper 80 cm of soil consist of more than 40 cm of organic material (peat)?
YES →
NO ↓</td><td>Sulfuric subaqueous organic soil</td></tr>
<tr><td rowspan="2">NO ↓</td><td>Does a clayey layer with slickensides occur within 150 cm of the soil surface?
YES →
NO ↓</td><td>Sulfuric subaqueous clay soil</td></tr>
<tr><td>YES →</td><td>Sulfuric subaqueous soil</td></tr>
<tr><td>Does hypersulfidic material (pH >4 which changes on ageing to pH <4) occur within 150 cm of the soil surface?
YES →
NO ↓</td><td>Does the upper 80 cm of soil consist of more than 40 cm of organic material (peat)?
YES →
NO ↓</td><td>Hypersulfidic subaqueous organic soil</td></tr>
<tr><td rowspan="2">NO ↓</td><td>Does a clayey layer with slickensides occur within 150 cm of the soil surface?
YES →
NO ↓</td><td>Hypersulfidic subaqueous cracking clay soil</td></tr>
<tr><td>YES →</td><td>Hypersulfidic subaqueous clay soil</td></tr>
</table>

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

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

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

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

Appendix 5

Soil and landscape field indicators

Field indicators linked to landform elements are useful for identifying salt- and acid-affected soils and increasing awareness of the extent of salinity among landholders and regional advisers. Standard descriptive soil indicators such as visual indicators (for example, colour) and consistency are often used by farmers, regional advisers and scientists in the field to identify and report attributes of soil quality (Fitzpatrick et al. 1999). For example, soil colour can provide a simple means to recognise or predict salt-affected wetlands caused by poor drainage, providing an alternative to the difficult and expensive process of documenting saline water table depths to estimate water duration in soils. Visual indicators of salinity may be obvious (for example, white salt accumulations on soil surfaces, salt tolerant vegetation present) or subtle (for example, subsoil mottling patterns, strong pedality). Similarly, visual indicators of acid sulfate soil impacts may be readily apparent (for example, orange-brown precipitates on soil surface or in drain waters). Basic analytical indicators include electrical conductivity (salinity), dispersion (sodicity), and pH (acid sulfate soils). Combining descriptive and analytical indicators has provided vital information about soil-water processes, leading to improved management and remediation of saline land, as demonstrated in several case studies from Australia, China and Iraq (for example, Fitzpatrick and Shand 2008).

Soil management based on soil type and natural processes: Handbooks for land management planning

The sequence of steps used to develop this handbook for identifying soil indicators, land use options and best management practices in the LMRIA is shown in Figure A5-1.

Steps 1-5 describe soil layers and construct them in hydro-toposequences (schematic cross-section diagram with colour photographs of soil-water features, soil profiles and water flow paths), which are used to help map soil types in areas with variable geochemistry (Fitzpatrick et al. 2003).

Steps 6-9 involve local communities in developing the handbook by integration and adoption, where knowledge of the hydrological and soil-regolith process models (bottom half of Figure 2-2) and production systems is bought together in recommendations for appropriate best management practices (see Chapter 12).

For example, in the Mount Lofty Ranges in South Australia (Fitzpatrick et al. 1997, 2003) and Woorndoo region in Victoria (Fitzpatrick et al. 1997, 2003; Cox et al. 1999), fencing protecting saline-sulfidic wetlands from physical disturbance (i.e. cattle) has

- facilitated the re-establishment of more reducing soil conditions in the surface (A) horizon
- decreased the amount of pyrite oxidation

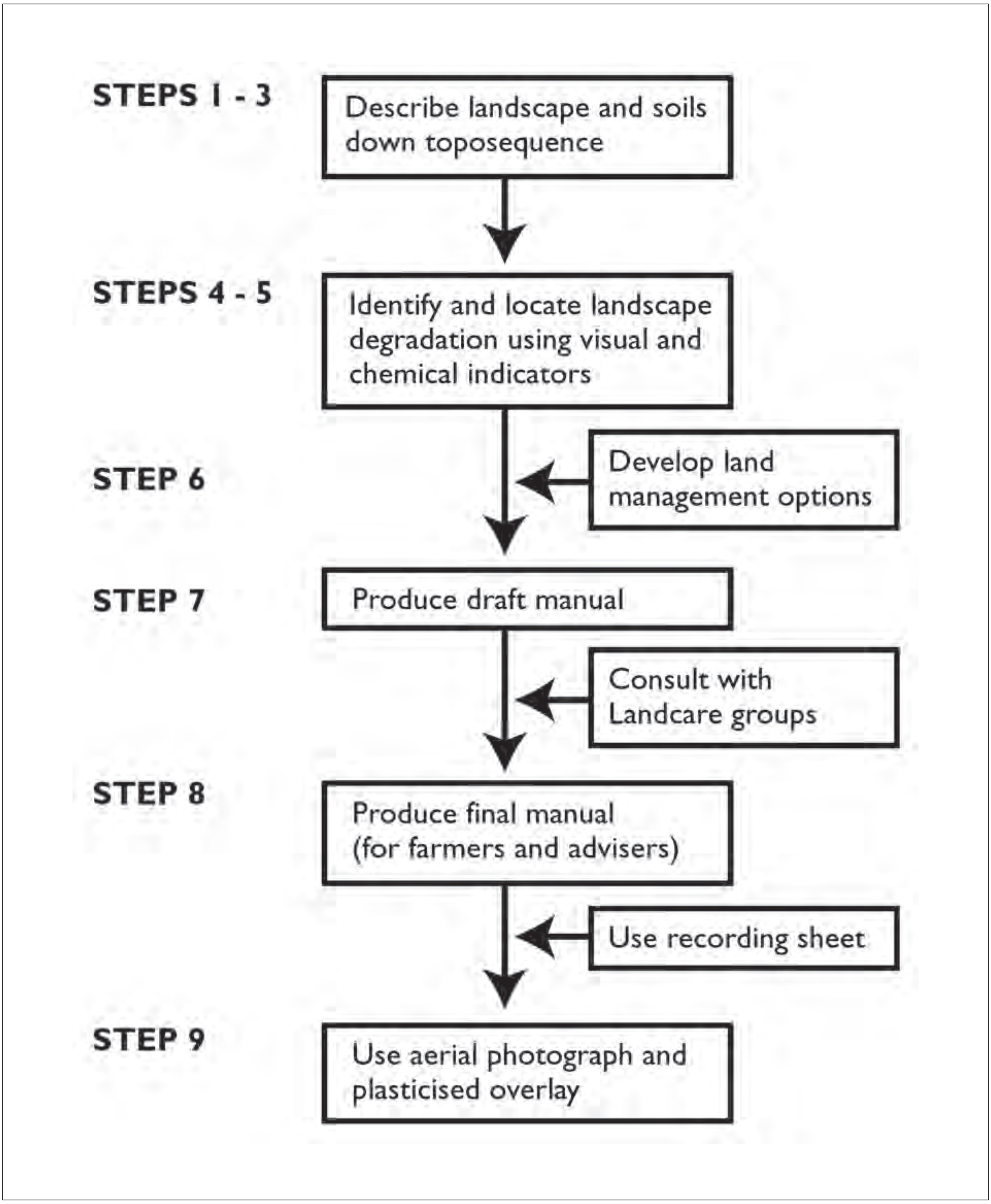


Figure A5-1. Flow diagram showing steps involved in developing manuals and handbooks for land management.

Source: Fitzpatrick et al. 2003.

- allowed rapid recovery of wetland vegetation
- prevented physical erosion of the A horizon
- allowed a return to neutral pH (pH = 6.5 to 7).

Approach to developing soil interpretation data for soils

The concepts and principles used to develop the various kinds of soil indicators, interpretations or groupings of soils are briefly summarised below.

In this handbook, soil interpretations have been developed at many levels of generalisation or abstraction and have been expressed in the form of descriptive classes of information (for example, high, moderate or low). These soil interpretations have been largely developed for national application. Consequently, they may often be too general for applications at the local or site level. However, these criteria are the basis from which to narrow limits or add further criteria for the local situation.

The process of developing the soil interpretations to predict and assess soils in the LMRIA is based on using standard soil methods (for example, Schoeneberger et al. 2012; Fitzpatrick 2012a).

Preparation of soil interpretations involved the following steps:

1. assembling information about the particular soil property and the landscapes in which they occur (for example, gilgai micro topographic landscape features)
2. modelling other necessary characteristics from the soil data (for example, climate and vegetation criteria)
3. deriving inferences, rules and guides for predicting the soil behaviour for specific conditions (for example, acid sulfate soil soils to predict poor water quality in adjacent drains)
4. integrating the soil predictions into generalisations for the map unit.

Finally, soil interpretations are most often developed in response to various farmer land use needs (for example, irrigation); thus the development process has included input from various farmers and professionals from different disciplines. User feedback has been crucial in the iterative process of refining specific interpretations.

Appendix 6

Understanding how drought changes in the LMRIA soil-water landscape has led to severe and widespread acidification during and after the Millennium Drought

It is useful to explore in detail the major changes that occurred in the Millennium Drought, particularly those relating to acid sulfate soils. To highlight the changes and spatial heterogeneity of acid sulfate soil properties and river-ground/-irrigation water interactions in the LMRIA before, during and after the Millennium Drought, a series of three schematic cross-section diagrams displaying the sequence of soil-water features, soil types and water flow paths have been created in Figures A6-1, A6-2 and A6-3. These are in the form of conceptual soil-regolith hydro-toposequence models (modified from Fitzpatrick et al. 2012a,b; 2017b) and help visualise the results from the studies conducted in the LMRIA. In these soil-regolith model examples, the spatial variation of all ASS materials identified is displayed in detail using a standard set of graphic symbols such as for sulfuric, hypersulfidic, hyposulfidic and monosulfidic materials. The examples also display other related features formed as a consequence of the formation ASS, such as soil cracks and salt efflorescences caused as a consequence of receding water levels due to extreme drought conditions. The thin vertical lines and brackets on the figures identify the spatial distribution of the various ASS subtypes (for example, sulfuric clayey soils), which is based on observations from the cores and auger samples collected.

Finally, these soil-regolith hydro-toposequence models have also been used as a framework or basis to explain some of the key intrinsic features and external drivers that render acid sulfate soils relatively stable or susceptible to rapid change (Fitzpatrick et al. 2012a; 2017b). Extrinsic and Intrinsic pedogenic thresholds (Muhs 1984) are defined rather loosely as a circumstance by which a 'relatively modest change' in an environmental driver such as droughts or flooding can cause a major change in soil subtype alteration (i.e. soil evolution) and soil properties (Fitzpatrick et al. 2012a; 2017b). Two predictive soil-regolith hydro-toposequence models were constructed by Fitzpatrick et al. (2017b) to describe and compare the major changes in acid sulfate soil subtypes, soil properties, key intrinsic features and external drivers occurring over time during 5 major periods of drying and wetting/reflooding cycles in irrigated pastures and natural wetlands.

Pre-drought: Pre-2007

Since the 1920s, water levels in the River Murray and adjacent wetlands have been artificially managed using locks, barrages and levee banks along the river channel; and this continues to the present, with seawater exclusion being their main function. The construction of locks, barrages and levee banks has allowed

1. artificially stable water conditions in the Lower Murray regions for over 80 years with a normal pool level of approximately +0.75 m AHD
2. considerable build-up of sulfidic, hypersulfidic and monosulfidic material in the lower lakes and adjacent wetlands.

These ASS materials accumulate because of

1. the evaporative concentration of sulfate from river nutrient/salt loads during the period of stable pool level and from groundwater sources
2. the lack of natural scouring and seasonal flooding during the time prior to major pre-European development (5000 BC to 1920s)
3. the plentiful supply of organic matter from Phragmites reed beds and dairy farming activities.

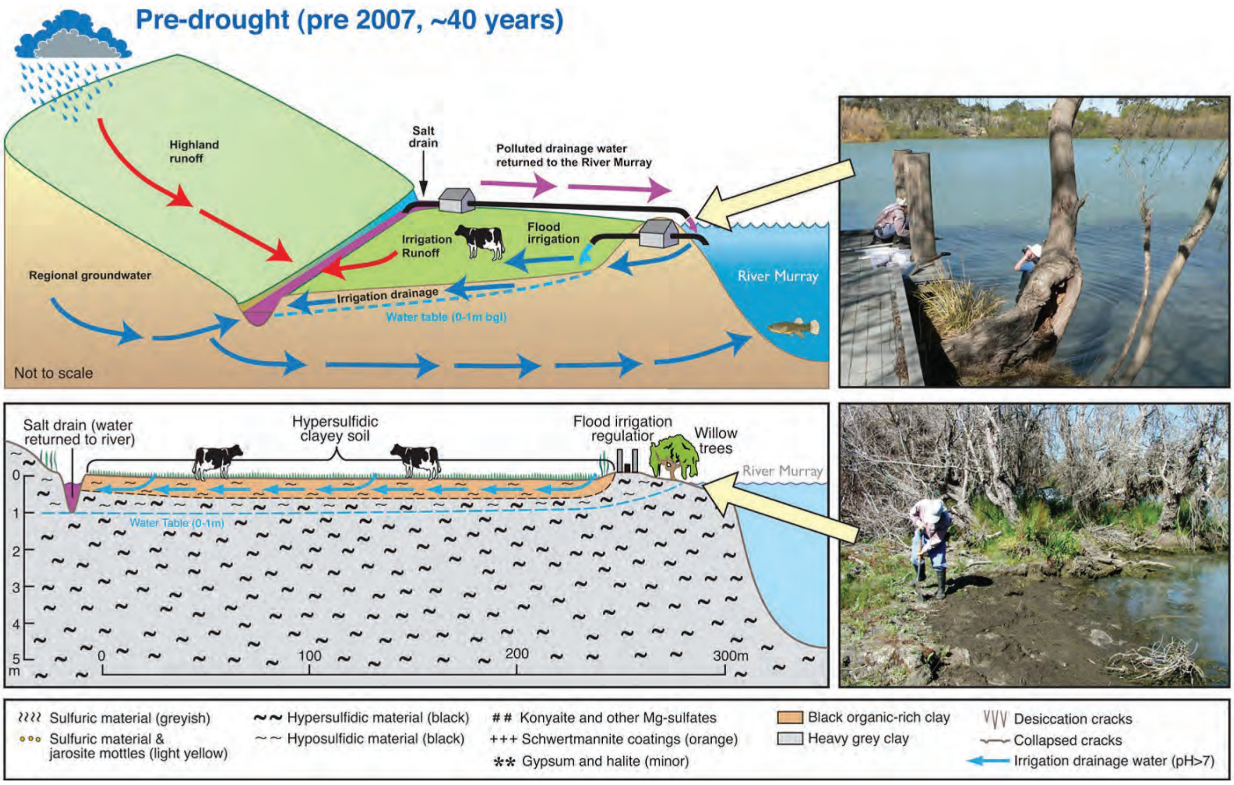


Figure A6-1. Generalised soil-regolith hydro-toposequence model during pre-drought conditions (pre-2007) illustrating the spatial distribution of

(i) hyposulfidic materials near the soil surface

(ii) hypersulfidic materials extending to depths >5 m

(iii) surface water levels, groundwater table levels and river flow, which were maintained for irrigation.

Source: modified from Fitzpatrick et al. 2012b; 2017b.

Prior to the drought, the most extreme period commencing in 2007, the LMRIA was separated into 27 irrigation areas, 24 of which were actively being farmed, mainly as dairy enterprises (Leyden et al. 2012). The conceptual 3D diagram in Figure A6-1 illustrates a typical flood irrigation area in the LMRIA showing pastures/swamps, which are at a lower elevation than the River Murray with sluices, siphons and pumps in the levee banks that are used to flood irrigate the pastures in each irrigation bay. The runoff and subsurface drainage then collects in the lateral side drains and the back channel, known as the 'salt drain'. The polluted/salty water from the salt drain is subsequently pumped back into the River Murray. The salt drains also receive regional and local irrigation groundwater inputs and occasional stormwater runoff from adjacent highland areas, including townships in some locations.

The pasture-productive non-acid sulfate soil layer at the surface (0-15 cm) occurs above hyposulfidic material (15-50 cm) and deeper hypersulfidic material (>50 cm) (Figure A6-1).

During the extensive pre-drought period (>80 years), surface water tables were maintained from irrigation, river and groundwater flows [high water table level of 0-1 m below ground level (bgl) is shown in Figure A6-1].

The build-up of hypersulfidic material, which is capable of severe acidification in the saturated soil profiles at depth (>50 cm), is due to stable water level conditions and the availability of sufficient iron, sulfate and organic material. Under these pre-drought saturated conditions, hypersulfidic material did not pose an immediate threat of acidification and metal release.

The top metre or root zone of these organic-rich hypersulfidic clayey soils shown in Figure A6-1 is largely unaffected by high acidity because the formation of significant amounts of sulfuric material is prevented, which is likely due to little previous pyrite content in this surface layer. Pyrite was unable to form and accumulate due to continuous wetting and drying cycles associated with flood irrigation over the last ~80 years (i.e. since the construction of the barrages in the 1920s). This contributed to a build-up of ANC, especially in near soil surface (0-15 cm). Acidic surface layers (above 1 m) were not identified pre-drought in the LMRIA (EPA 2008; Fitzpatrick et al. 2009; Shand and Thomas 2008).

Drought: 2007 to early 2010

During the prolonged hydrological drought from 2006 to early 2010, many of the farming enterprises in the LMRIA ceased operation due to an inability to irrigate because of the low water levels (i.e. during April 2009, the water level in the Lower Murray fell to below -1 m AHD, the lowest river level since records began) and water allocation restrictions. These conditions meant that most of the LMRIA was not able to be irrigated for substantial periods of time (2005-06 = 100% allocation, 2006-07 = 60%, 2007-08 = 32%, 2008-09 = 18%), which led to a drop in the water table of up to 3 m from pre-drought levels (Mosley et al. 2009; Figure A6-2).

As a consequence, the heavy clay soils dried and cracked, causing major damage to the rehabilitated irrigation bays and associated infrastructures with major socio-economic impacts. A further consequence of the drought was the concomitant severe soil cracking to depths of up 3.5 m and oxidation of pyrite in the hypersulfidic material (Figure A6-2). The relatively slow but continuous exposure and drying of the hypersulfidic material layers over ~ 5 years (2006 to 2010) permitted almost perfect conditions (i.e. moist and aerated) for pyrite to oxidise/transform to sulfuric acid and jarosites, especially along exposed cracks and ped faces (Figure A6-2). This process enabled

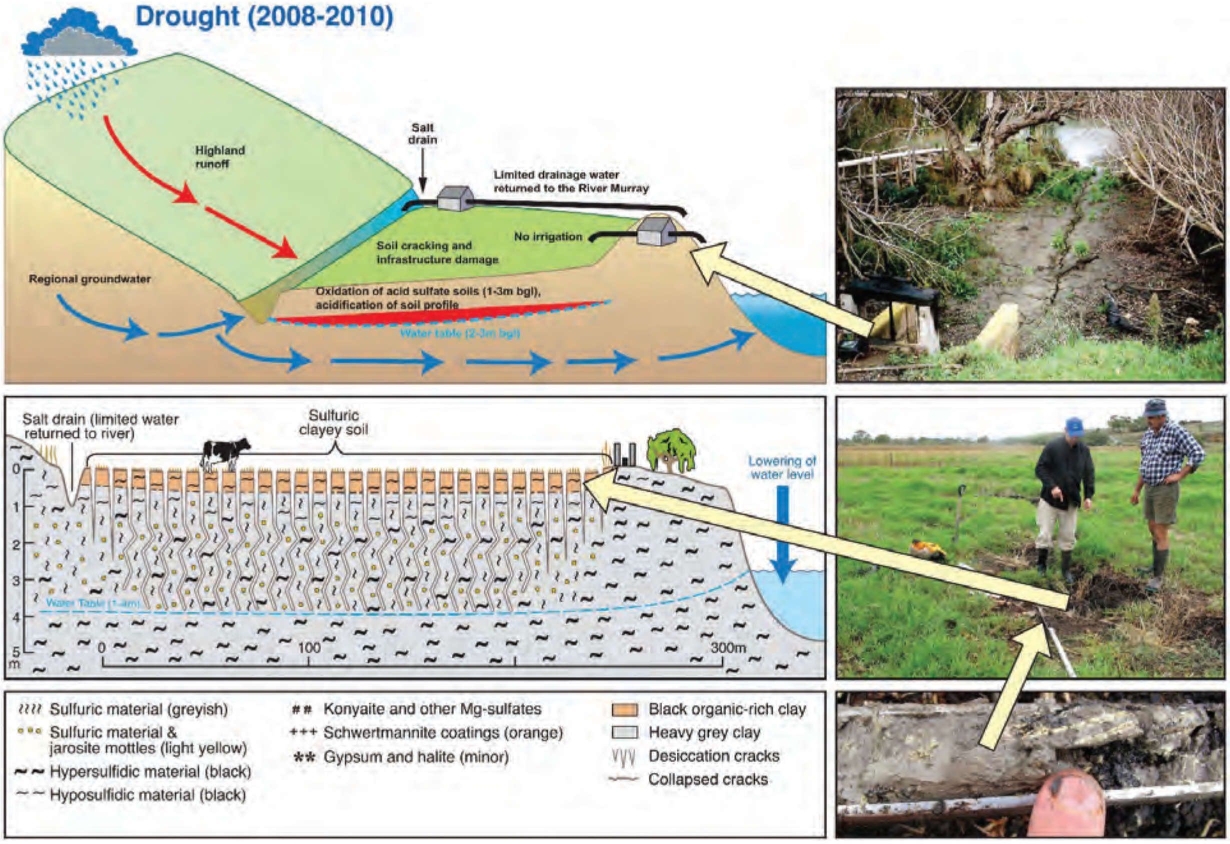


Figure A6-2. Generalised soil-regolith hydro-toposequence model during drought conditions (2008-early 2010), illustrating the spatial distribution of

(i) deep cracking patterns

(ii) sulfuric materials extending to a depth of 3.8 m along cracks with light yellow jarosite mottles [see inset photograpH of core in auger showing pale yellow (2.5Y 7/6) masses of jarosite along old root channels and faces of peds]

(iii) hyposulfidic materials near the soil surface

(iv) hypersulfidic materials below 3.8 m

(v) groundwater table levels and river flow.

Source: modified from Fitzpatrick et al. 2012b; 2017b.

hypersulfidic material to transform to sulfuric material with the consequent development of deep 'sulfuric clayey soils' in the LMRIA for the first time.

Inspection of several soil transects in former irrigation bays (where cattle are still grazing) identified widespread occurrences of deep sulfuric clayey soils (sulfuric material with prominent pale yellow (2.5Y 7/6) natrojarosite coatings, especially along old root channels and on planar vertical cracks and weaker horizontal planes/closed cracks (Figure A6-2).

In summary, this situation across the LMRIA between 2006 and 2010 had low water tables, which was caused mainly by increasing drought conditions, including low river and groundwater levels, and the inability of irrigators to access water for irrigation. The low water table level under the LMRIA floodplain during the drought has resulted in oxidation of previously undisturbed 'hypersulfidic clayey soils' (Figure A6-2) to progressively transform to deep (>3.0 m) sulfuric clayey soils (Figure A6-2) with sulfuric material. These processes and transformations of similar soil subtypes were previously identified in several natural/human-modified wetlands adjacent to LMRIA pastures/ swamps such as the Swanport wetland (for example, Fitzpatrick et al. 2008a,b; 2009; 2017b).

Under these low water conditions in the Murray River, the irrigation drains run mostly dry (Figure A6-2). This change of hydraulic condition creates a total change in the hydro-geochemical conditions. The hydraulic gradient in the direction towards the irrigation drains changes into a horizontal groundwater flow under the drain towards the river. Due to the lowering water level as shown in Figure A6-2, oxygen will likely diffuse into the aquifer, triggering sulfide oxidation at the outer margin of the reduction zone. Therefore, as an explanation, a combination of parallel processes is favoured: the oxidation of pyrite, and, subsequently, the precipitation of schwertmannite in drains as shown in the section below and in Figure A6-3.

Post-drought reflooding and irrigation: 2011 to 2012

The substantial increase in rainfall from March 2010 to early 2011 within the Murray Darling Basin catchment resulted in river flooding and water levels throughout the LMRIA and adjacent wetlands to increase from approximately ~ -1 m AHD to 0.7 m AHD. Post-drought reflooding and irrigation between 2011 and 2012 caused extensive mobilisation of soil acidity (H+), metals and metalloids, which were produced in the sulfuric clayey soils as a result of the oxidation process, and were then mixed with the shallow groundwater as water levels rose in the Lower Murray in late 2010 (Figure A6-3). This resulted in acid water and precipitation of the bright reddish-orange plumes of fine iron-rich precipitates comprising mainly schwertmannite, which was also found coating vegetation and the base of drains (Figure A6-3). The drainage water is pumped back into the River Murray, a practice which is necessary to keep the saline water tables low enough to maintain agricultural practices in this region (Leyden et al. 2012).

A further consequence of the rewetting/reflooding is the formation of isolated pockets of 'sulfuric subaqueous clayey soils' and the continued widespread presence/perseverance of sulfuric clayey soils (Figure A6-3). The drains in these irrigation areas also receive regional groundwater inputs and require drainage (via pumping back to river) to avoid back-flooding of pastures.

Our findings highlight that maintaining water tables on agricultural soils via irrigation and drainage can promote the formation of deep (>3.5 m) sulfuric material with extensive retained acidity (jarosites), which can persist for decades or longer (Fitzpatrick et al. 2017b).

The LMRIA, like other areas of the Murray Basin, contains sulfur derived from cyclic salt accumulation and pyritic sediments. Sulfur is mobilised in the form of dissolved sulfate in surface and groundwaters as shown in Figure A6-3, with increasing concentration downstream. The increases in water table heights caused by reflooding have increased the amount of dissolved sulfate, particularly in the lower reaches of the LMRIA. The increases in water tables have also increased groundwater discharge, concentrating sulfur at the lands surface. The disposal of saline waters in the drain and disposal/evaporation basins has also contributed to the development of a number of sulfate-rich hyper-saline wetlands, as shown by the occurrences of isolated pockets of sulfuric subaqueous clayey soils (Figure A6-3).

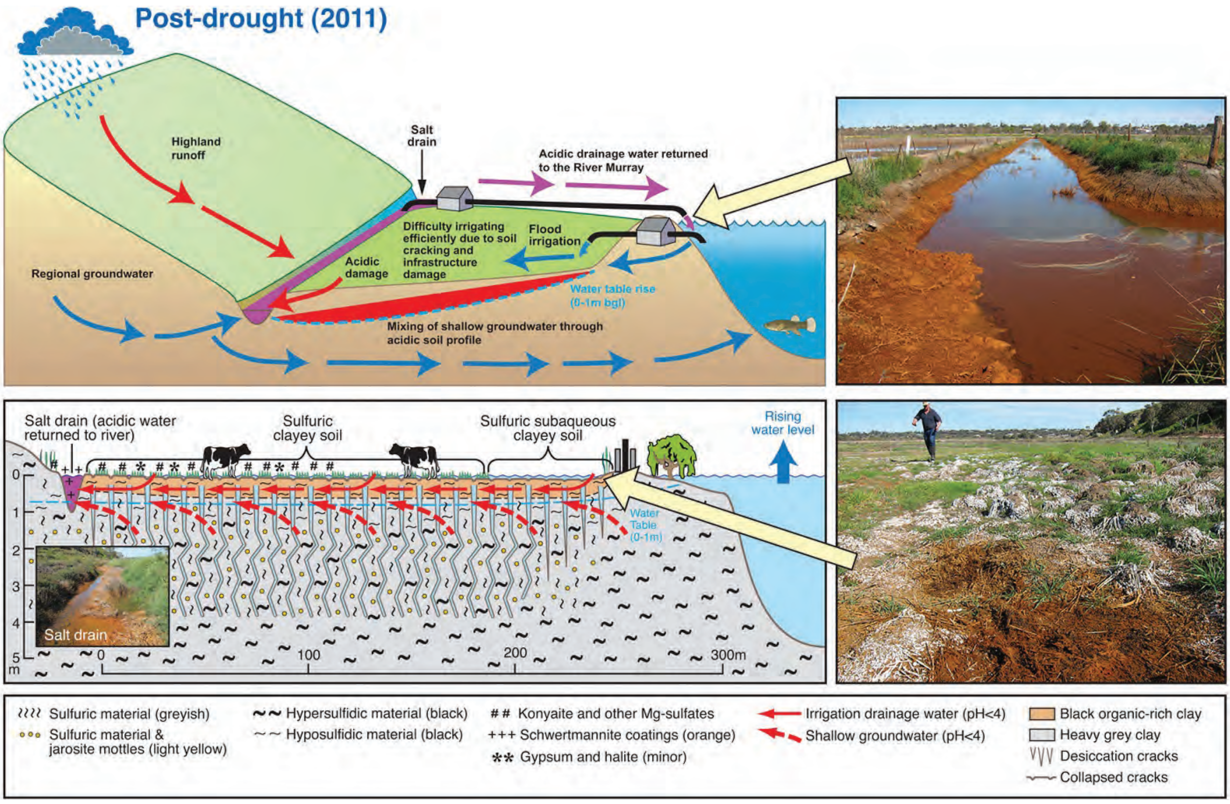


Figure A6-3. Generalised soil-regolith hydro-toposequence model during post-drought reflooding and irrigation during 2011, illustrating the spatial distribution of

(i) deep collapsed cracking patterns

(ii) sulfuric materials extending to a depth of 3.8 m along cracks with light yellow jarosite mottles

(iii) sulfuric materials extending to the soil surface with reddish-yellow surface coatings of iron-rich precipitates containing schwertmannite (see inset photograpH of soil surface with reddish-yellow coatings of iron-rich precipitates and white salt efflorescences)

(iv) hyposulfidic materials near the soil surface

(v) hypersulfidic materials below 3.8 m

(vi) surface water levels, groundwater table levels and river flow.

Source: modified from Fitzpatrick et al. 2012b; 2017b.

Appendix 7

A. Drain operations and water quality

Drainage is essential in the LMRIA to keep the rising saline regional groundwater table out of the pasture root zone and to remove salt from the landscape. Drainage water is typically returned to the River Murray via a network of drains and large pumps. This can create water quality impacts in the River Murray (Mosley and Fleming 2010), so drainage volume should be minimised via efficient irrigation and recycling of water where practical, and drain water quality maximised via employing best management practices on farms to minimise pollutant inputs to drains (for example, preventing surface runoff directly into drains). Drains can also indicate what is happening on the farm, in particular their level and colouration.

Drain water composition and historical perspective

The LMRIA drainage water returned to the River Murray historically contained high levels of nutrients and bacteria that impacted river water quality (EPA 2008; Mosley and Fleming 2010). These contaminants largely arose from surface runoff and subsurface drainage from widespread dairy farm operations. Between 2003 and 2008 the Commonwealth and South Australian state governments funded ($22 million) and facilitated a major rehabilitation and restructuring program in the Lower Murray Reclaimed Irrigation Area (LMRIA) in partnership with irrigators to reduce irrigation water use and pollutant loads returned to the River Murray. Unfortunately the lack of irrigation, along with the soil cracking and slumping during the drought, resulted in large-scale loss of the infrastructure improvements that were made during rehabilitation, and many dairy farms ceased production. Post-drought acid sulfate soil exposure and oxidation and rising water tables resulted in mobilisation of acidity and metals to the drainage channels and back to the River Murray (Figure A7-1). This issue has persisted to the present across the LMRIA (Mosley et al. 2014a,b).

Link between drainage operations and agricultural production

Drainage pumps in the LMRIA need to be operated regularly to maintain the saline (and acidic post-drought in many areas) groundwater table below about 0.5 to 1 m from the surface of the paddock. Failure to do so will result in the excellent productive agricultural topsoil becoming contaminated by the high concentration of salt, and (in many regions after the Millennium Drought) acidity and metals present in the groundwater. This contamination can lead to impacts on, or a complete loss of, agricultural production. Drainage volumes are on average higher in the spring-summer irrigation season months, and periodically after moderate to large rainfall events.

Figure A7-1. Drainage channel (left) before and (right) after drought. The presence of the strong-brown iron oxyhydroxy mineral schwertmannite is seen in the drain after the drought and subsequent flooding, indicating that acid sulfate soil exposure and oxidation has occurred. Bottom: a drain pump out to the River Murray after the drought, showing influence of iron precipitates and discoloured foam.

Source: Authors.

Reducing drainage volumes and recycling of drainage water

Efficient irrigation infrastructure and careful irrigation application (i.e. to prevent water running off the end of the irrigation bay) result in lower drainage water volumes and reduce potential impacts on the river. This also saves money via reduced pumping costs.

Recycling of drainage water can help retain nutrients and organic matter on-farm, enhancing soil fertility. However, care must be taken with the salinity of the water recycled on-farm. This can be managed by 'shandying' (part dilution with fresh river water) and/or irrigation with pure river water in between more saline recycled water applications.

Infrastructure impacts from acid drainage

Maintaining water quality is not just an issue relating to the River Murray. Figure A7-2 shows drainage pump infrastructure severely damaged (i.e. needing to be replaced) due to acid corrosion. Where possible, pump units and metal pipes and other products should be kept out of drainage waters to minimise corrosion. Low-corrosion pump and pipe materials should be used where practical.

Figure A7-2. Drainage pump damaged by acid. Orange-brown (iron-rich) precipitates are also observed, which are characteristic of acid drainage impacts.

Source: Authors.

B. Irrigation assessment

Importance of irrigation

Irrigation in the LMRIA is **mandatory** in order to prevent land salinisation, soil cracking and acidification (during drought). Irrigation can also restore currently salinised land to an improved state.

To highlight this, our recent field research trial clearly demonstrated the benefits of irrigation and drainage in reducing soil salinity and sodicity of surface soils in the LMRIA. Drainage-only did not achieve satisfactory results and the soil deteriorated markedly (i.e. there was a doubling of EC and Exchangeable Sodium Percentage) compared to irrigated treatments over the relatively short two-month period of the trial (Figure A7-3).

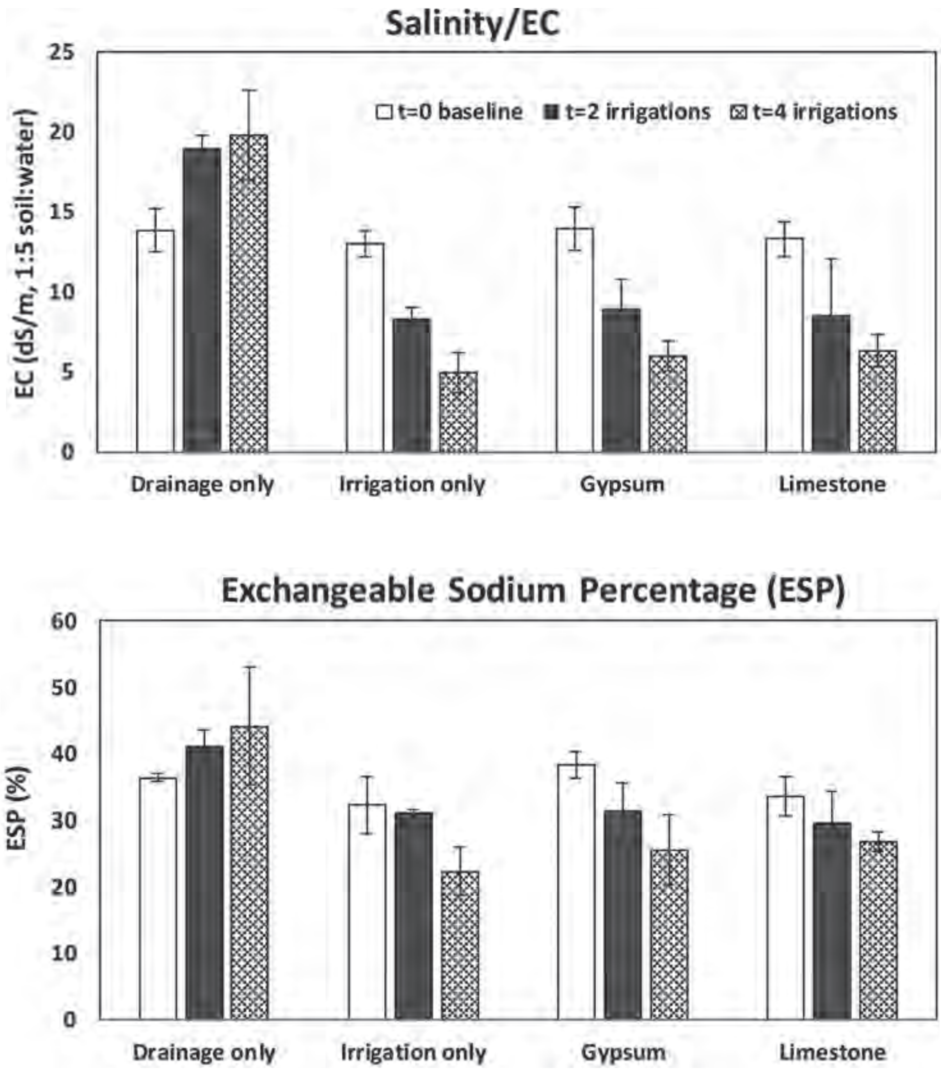


Figure A7-3. Electrical conductivity (EC) and Exchangeable Sodium Percentage (ESP) at t = 0 baseline, and after 2 and 4 irrigations on the different treatment plots (0-0.1 m layer) at Mobilong irrigation area. Error bars show the standard deviation (n = 3). Note: the drainage-only treatment did not receive any irrigation but samples were taken at the same time as the other treatments.

Source: See Mosley et al. 2017 for more details.

This is predominantly due to the low rainfall and high evaporation over summer (when trial was conducted) resulting in salt concentrating at the soil surface. There is also upward saline (10 to 30 dS/m) regional groundwater pressure in this region (Barnett et al. 2003) that, coupled with capillary rise through the heavy clay soil, likely assists in transporting salt to the surface soils.

The lack of irrigation during the Millennium Drought also highlighted that deep cracks can develop if irrigation water is not applied, leading to severe soil acidification as discussed above and further below.

Irrigation efficiency and frequency

Efficient irrigation in the LMRIA is on the order of 0.5 to 1.0 ML/ha/watering, with an average of around 0.7 ML/ha/watering (Mosley and Fleming 2009; and recent unpublished data). Generally, irrigation bays which are short and/or have a steeper gradient will have a higher efficiency than bays which are longer and have a lower gradient. The length of irrigation bays varies within and between different irrigation areas. When irrigation is inefficient, large amounts of water are lost to ponding and drainage, just to get the irrigation front down the bay. Hence less irrigation events are possible within a given water allocation.

In 1990, flood irrigations were undertaken typically 14-21 times per year (Philcox and Douglas 1990), although the frequency of irrigation has reduced towards the lower end of this scale on most commercially irrigated properties now (Philcox and Scown 2012). Towards the end of the inter-irrigation period, the pasture may obtain up to 40% of its water from the water table.

Impact of the Millennium Drought on irrigation efficiency

Following the severe 2007-10 drought, the irrigation water efficiencies in the LMRIA were severely reduced. During the drought, river and groundwater levels fell to their lowest in over 100 years from 2007-10. Coupled with restricted irrigation water allocations, there was very little irrigation water applied. This led to severe soil cracking to depths greater than 2 m. Remaining irrigators have observed large water losses during irrigation due to flow through the cracks and increased lateral movement to adjacent irrigation bays. Irrigation has now become much more 'patchy' across the region with less commercial irrigation and dairy land use. Philcox and Scown (2012) surveyed farms across the LMRIA region and estimated total post-drought area and volume of irrigation. Philcox and Scown (2012) found only 7 of 21 (33%) dairy farms surveyed had water use near to pre-drought levels (1-2 ML/ha/irrigation). The rest were extremely variable with amounts from 4-5 up to 7.4 ML/ha/irrigation. The water use efficiency post-drought at Long Flat Irrigation Area is shown in Figure A7-4. The average immediate post-drought (2011-12) efficiency was 4.6 ML/ha/watering. The federally funded On Farm Infrastructure program (laser levelling and channel upgrades) administered by the SAMDB NRM Board has provided funding for over 500 ha of land scheduled to have laser levelling and other infrastructure upgrades (funding provided in return for surrendering part of water allocations). The OFEIP infrastructure upgrades (principally laser levelling) have halved water use per irrigation in 2015-16 at Long Flat to an average of approximately 0.7 ML/ha/watering compared to the unlasered paddock average of 1.5 ML/ha/watering (Figure A7-4). This is now comparable to the pre-drought average efficiencies on laser levelling infrastructure in the LMRIA (Mosley and Fleming 2009). It is noted that the unlasered paddock efficiency in 2015-16 still showed a large efficiency improvement from the immediately post-drought irrigation efficiency (Figure A7-4), likely due to soil cracks closing over time.

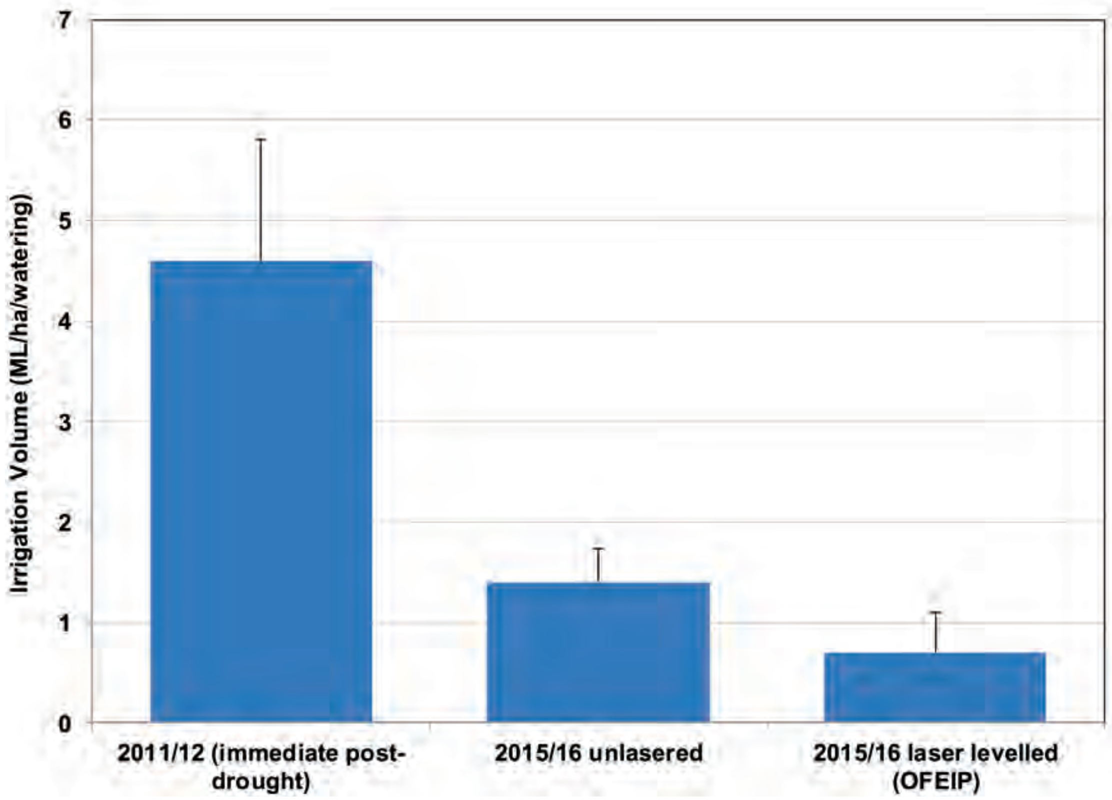


Figure A7-4. Water use per irrigation immediately post-drought (2011-12) and after laser levelling (2015-16) of some bays.
Source: Authors.

Similar results were achieved at Mobilong where following laser levelling (Figure A7-5) water use was approximately ¼ that before laser levelling and the whole length of bay was able to be irrigated.

Environmental Land Management Allocation (ELMA)

Depending on individual swamp location, the Environmental Land Management Allocation (ELMA) water entitlement for the LMRIA varies between 2.3 ML/ha/year (South End of LMRIA) to 6.5 ML/ha/year (North End of LMRIA). With non-laser-levelled and drought-affected infrastructure and soils, ELMA only enables 1-3 irrigations across a swamp, and in some areas with poor infrastructure water cannot be applied. By upgrading the flood-irrigation inlet infrastructure and laser levelling, about 0.7-1 ML/ha or less efficiency can be achieved, which potentially enables up to about 5-7 ELMA irrigations per annum. Soil-water (HYDRUS computer program) modelling and soil-water measurements in this project suggests that 3-7 irrigations per year is sufficient to keep land from salinising and soil from cracking. This compares well to the number of ELMA irrigations achievable on improved infrastructure (but is insufficient, however, to achieve full agricultural pasture production). Given the rising saline groundwater tables in this region, and regional groundwater discharge (with no salt interception schemes), the current ELMA allocation if applied correctly is considered a minimum, particularly in the southern end of the LMRIA.

Figure A7-5. (Top) Irrigation bay at Mobilong being laser levelled, and (bottom) laser levelled paddock with new crop sown and monitoring piezometer in foreground.

Source: Authors.

Alternative irrigation strategies during drought and in difficult application areas

The back swamp areas where water is difficult to apply via flood irrigation could be setup for ELMA irrigation using a travelling irrigator (Figure A7-6) with a flooded suction installed from the river to a fixed pump and distribution system. The travelling irrigator used at Monteith in the drought and a recent trial at Mobilong had a 100 mm (4") pipe system which is a much smaller pipe diameter than that required for flood irrigation (400-500 mm). The recent trial applied water from the travelling irrigator at a rate of 0.5 ML/ha/watering (i.e. 50 mm irrigation depth). With this efficiency, up to 10 ELMA irrigations could be undertaken within an ELMA allocation. During severe drought, a travelling irrigator could be very useful in protecting LMRIA soils from cracking, as water could be sourced directly from the river, even if water levels are lower than those that enable flood irrigation. The use of a travelling irrigator is, however, more labour- and energy-intensive than gravity-fed irrigation.

Using irrigation to recovery salinised and sodic soils

Land that is currently salinised and sodic in back swamp areas can be remediated. Our recent research trial showed that with four irrigations and active drainage the soil salinity was reduced to about a

Figure A7-6. Travelling irrigator in operation at Mobilong irrigation area.
Source: Authors.

third of its initial value, with sodicity also reduced (Figure A7-3). In contrast, in the soil that was not irrigated, salinity increased over the two-month trial period. Gypsum and limestone are not necessarily required to remediate the soils we conducted the trials in; irrigation-only proved just as effective in reducing exchangeable sodium levels and increasing exchangeable calcium levels (i.e. reducing soil sodicity). This may differ depending on the nature of the soil and particular salinity-sodicity issue characteristics. It has been previously noted that very high levels of gypsum are required on the LMRIA heavy clay soils (up to 10-20 tonnes/ha[1]). Hence if applied it is usually targeted to specific problem areas (for example, back swamp areas with poor drainage and soil salinity/sodicity issues) rather than broadscale application.

Drainage following irrigation to export salt from irrigation areas

Drainage following irrigation is critical in the LMRIA to leach salt from the root zone of plants and export salt that accumulates from regional saline groundwater inputs and evaporation. Drainage pumps and channels need to be maintained in good condition and operated immediately after irrigation to reduce the risk of waterlogging and land salinisation (see above).

Co-ordinated irrigation on irrigation bays and within irrigation areas

Co-ordinated irrigation can be beneficial to improve water efficiency due to lateral losses from previous irrigations on adjacent bays providing 'bonus' subsurface water that means less irrigation water needs to be applied. It is beneficial to irrigate adjacent bays or areas in sequence (within 1-2 days timescale) where possible to receive maximum efficiency benefits in this manner.

Climate change

Climate change is predicted to significantly increase (by approximately 15%) the number of irrigations required by 2030 or 2050, and drought frequency is likely to increase. Improved infrastructure in the LMRIA and more frequent irrigation and drainage will enable improved soil, vegetation and water quality outcomes into the future. Irrigators will need to achieve ongoing efficiency improvements to meet the demands of a changing climate.

1 http://www.dairysa.com.au/f.ashx/ProjectPublications/DairySA-factsheet-gypsum-for-the-lower-murray.pdf.

Appendix 8

ELMA Discussion Paper

The Environmental Land Management Allocations (ELMA) and the Water Allocation Plan for the River Murray River Prescribed Watercourse can be found in the following four page fact sheet, which can also be downloaded via the following website link: http://www.naturalresources.sa.gov.au/files/sharedassets/sa_murray-darling_basin/water/allocation_plans/river_murray_2017/rm-wap-adoption-elma-fact.pdf.

Water Allocation Plan

River Murray Prescribed Watercourse

Environmental Land Management Allocations

Environmental Land Management Allocations (ELMA) apply to the Lower Murray Reclaimed Irrigation Area (LMRIA) (see figure 1).

Applying water to soil on irrigated and non-irrigated land in the LMRIA is a management approach to address salinity and acid sulphate soil issues. ELMA helps to maintain the LMRIA as a productive irrigation area, and also contributes to managing water quality issues, which can impact on SA Water offtakes. A volume of 22.2 GL is set aside in the Murray-Darling Basin Agreement for ELMA.

The Water Allocation Plan for the River Murray Prescribed Watercourse (the Plan) includes ELMA in a separate class within a consumptive pool. Up to 22.2 GL of water access entitlements has been allowed for granting to landholders for application within the LMRIA to manage the issues in the area. The Plan sets out requirements for how this volume should be used, for example through application rates to best manage the issues. ELMA is important to the long-term management and productive capacity of the LMRIA.

What has changed in the Plan?

ELMA has been maintained in the Plan with minor updates. The existing policy mandates that ELMA cannot be transferred because it is important that the full water allocation is used each year to address land management issues. For this same reason, ELMA is not eligible for private carryover.

ELMA expires upon the sale of land and reverts back to the Minister. The new owner can then apply for ELMA.

High level objectives have been added to highlight the importance of ELMA. These objectives focus on the benefit that ELMA has to land assets in the LMRIA, and also the importance of keeping the water levels in the Lower Lakes above 0.4 metres Australian Height Datum (AHD) to ensure access to water and prevent riverbank collapse.

Government of South Australia

Natural Resources
SA Murray-Darling Basin

What are the issues in the Lower Murray Reclaimed Irrigation Area?

The LMRIA is affected by highly saline groundwater due to its low lying landscape and the construction of infrastructure to manage the river at constant levels. Before locks, barrages and levee banks were constructed, groundwater would have discharged to the River Murray at the lowest point in the landscape. The construction of levee banks has resulted in the river level being held higher, making the LMRIA the lowest lying point and therefore a discharge point for the saline groundwater.

While infrastructure works have secured access to water for agriculture in the region and provided the ability to gravity feed water for irrigation, this also means that management of the saline groundwater is required. Drainage channels and irrigation of the land have allowed the saline groundwater to be kept to a suitable depth below the surface.

During the drought, low river levels and low water allocations resulted in no irrigation occurring on a number of properties. Groundwater levels also dropped. This caused the acid sulfate soils to dry out, leading to severe cracking and the formation of subsurface sulfuric acid (see figure 2). When water did return, acid in the soil was at risk of being mobilised and entering the River Murray channel through drainage channels. This resulted in a risk to water quality in the River Murray, potentially affecting SA Water offtakes, and causing other environmental impacts.

For the LMRIA to continue to be a productive area, and to mitigate water quality risks, it is important that salinity and acid sulfate soil issues continue to be managed in the future.

Why is ELMA important?

Without application of ELMA water or other irrigation, the risk of soils drying and cracking is high, and salinity and acid sulfate soil issues could reoccur. It is important to keep the soil profile wet to avoid these issues and the resultant risks to water quality and the river environment.

For more information on the issues in the LMRIA, please refer to the EPA website – www.epa.sa.gov.au (search LMRIA)

How do I know if I need ELMA?

ELMA is available if you own property in the LMRIA (see figure 1) as the water is specifically to manage issues in this region. If you own a property in the LMRIA you are encouraged to apply for ELMA; details of how to apply are below.

I own a property in the Lower Murray Reclaimed Irrigation Area (LMRIA) but I don't irrigate. Do I need ELMA?

ELMA is important to all land in the LMRIA and should be applied to land even if it isn't irrigated. The application of water keeps the soil profile wet and prevents drying, cracking, and exposing soils to air, which can cause acid and water quality issues.

How do I apply for ELMA?

If this applies to you, you are encouraged to apply for ELMA. You will need a water licence, a site use approval and a water resource works approval. Application forms can be found at http://www.environment.sa.gov.au/licences-and-permits/water-licence-and-permit-forms

To find out more about how to apply, please contact DEWNR Berri Office on (08) 8595 2053.

How should ELMA be applied to land?

For irrigated land, guidelines are in place to assist landholders to apply water, including ELMA, in line with best practice methods to manage land issues effectively. The guidelines are available on the Natural Resources SA Murray-Darling Basin website – www.naturalresources.sa.gov.au/samurraydarlingbasin. Follow the links in the Water menu.

Maximum application rates are also detailed in Chapter 6.3.3 of the Plan. These rates are in place to reflect the appropriate application of water for managing the effects of rising groundwater on the land. The volumes differ based on where the property is located.

Where land is not irrigated, ELMA must be applied at a rate that is appropriate for managing the effects of rising saline groundwater and remnant acid sulfate soil issues.

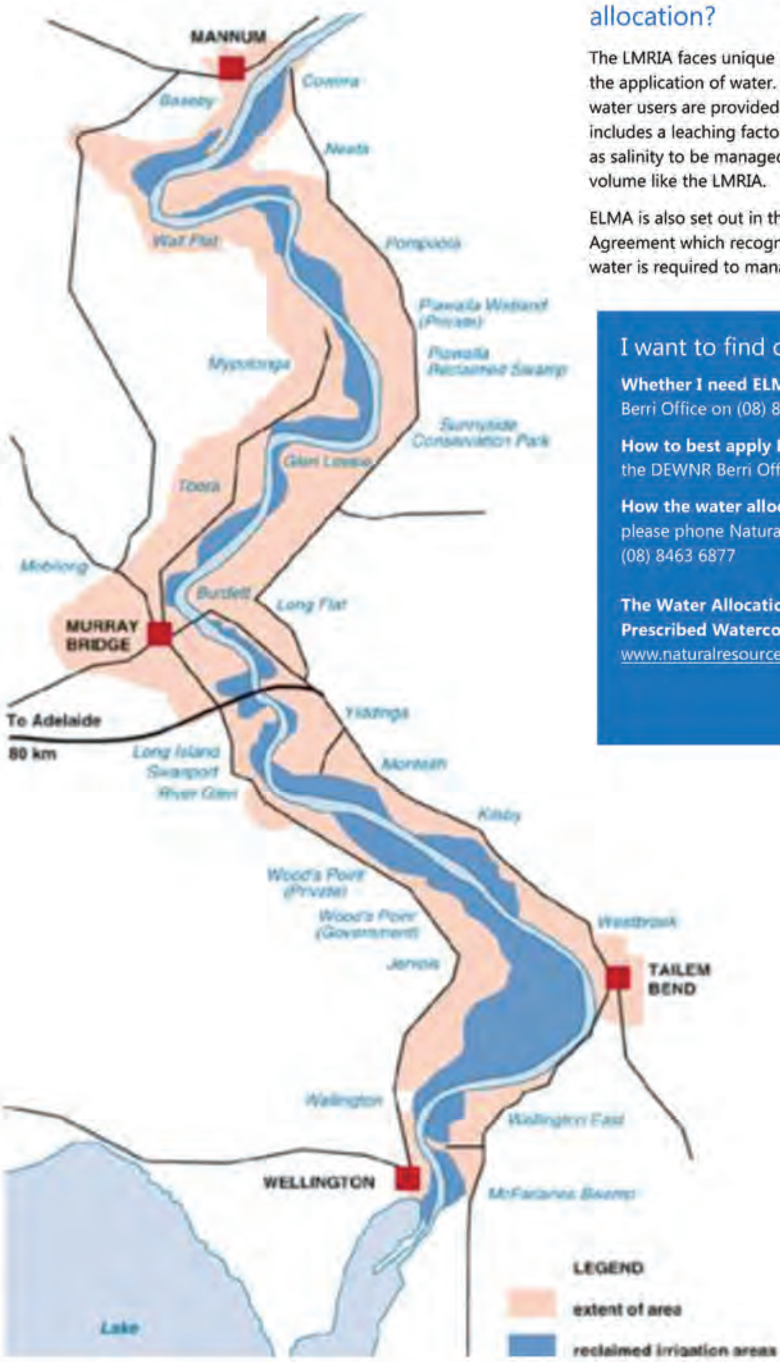
Can ELMA be traded?

No. ELMA cannot be traded as it is allocated specifically to manage issues in the LMRIA and is therefore applicable to these land parcels only and must be applied evenly across the land. When a property is sold, ELMA reverts back to the Minister, and can then be allocated to the new owner upon application.

Government of South Australia

Natural Resources
SA Murray-Darling Basin

Figure 1 - The Lower Murray Reclaimed Irrigation Areas



Why don't other areas have an environmental land management allocation?

The LMRIA faces unique issues that are best managed by the application of water. In other areas along the river, water users are provided a volumetric approval that includes a leaching factor. This volume allows issues such as salinity to be managed, without requiring a separate volume like the LMRIA.

ELMA is also set out in the Murray-Darling Basin Agreement which recognises that a specific volume of water is required to manage the unique issues in the area.

I want to find out more about...

Whether I need ELMA, please phone the DEWNR Berri Office on (08) 8595 2053

How to best apply ELMA to my land, please phone the DEWNR Berri Office on 08) 8595 2053

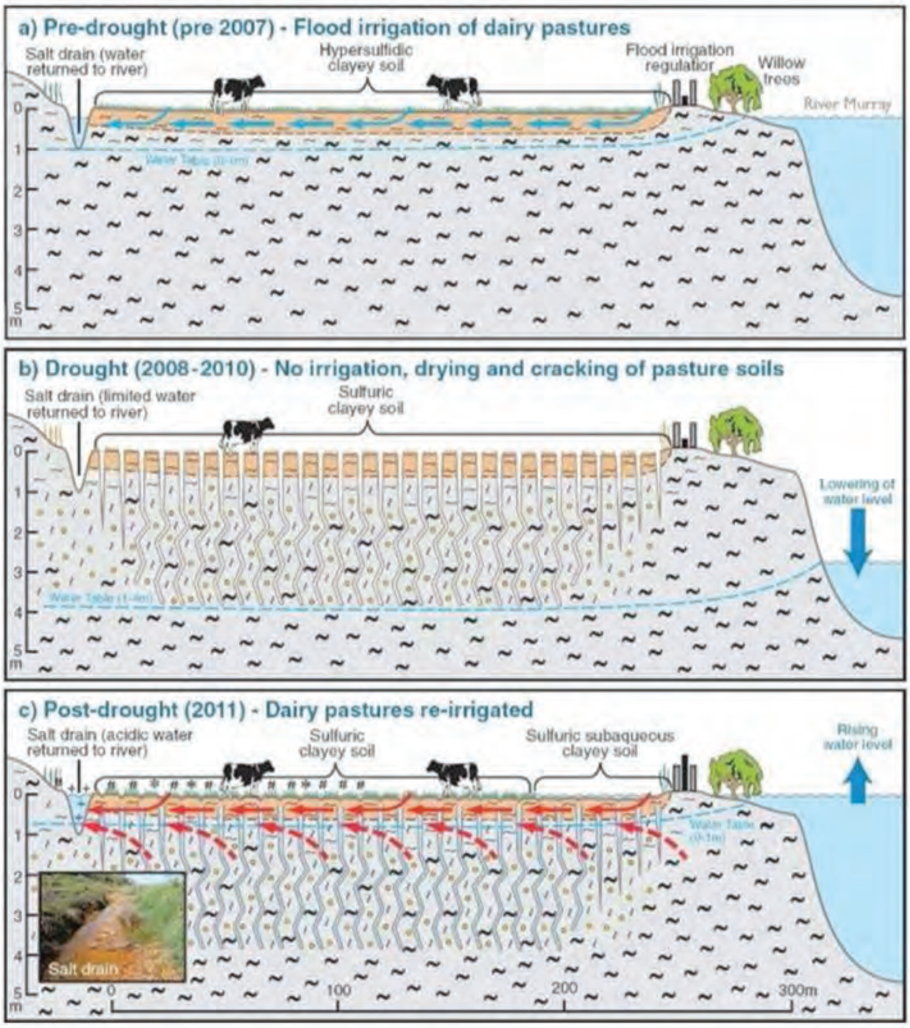
How the water allocation plan manages ELMA, please phone Natural Resources SAMDB on (08) 8463 6877

The Water Allocation Plan for the River Murray Prescribed Watercourse, please visit: www.naturalresources.sa.gov.au/samurraydarlingbasin

Government of South Australia

Natural Resources SA Murray-Darling Basin

Figure 2 – process of acid sulphate soil oxidation in the LMRIA during the drought (CSIRO, 2013)



Appendix 9

Glossary of terms

Acidity	Acidity of soils is usually not a problem unless the pH drops below 4 or 5. Oxidised acid sulfate soils can have very low pH (2 or less) values and are potentially very corrosive.
Alkalinity	For the purposes of this investigation, 'alkalinity' describes soils which have an increasingly alkaline trend with depth such that the subsoil pH is greater than 8.5. Alkaline soils may have pH values in excess of 10 and these can be very corrosive.
Aggregate	Unit of soil (clod) that contains groups of micro aggregates.
Amelioration	To make or become better.
Calcareous soil materials	Carbonate segregations or fine earth (soil matrix) effervescence with 1M HCl. The list of calcareous materials generally increases in hardness and excavation difficulty from segregations or fine earth carbonate to carbonate gravels to 'calcrete' (hard and indurated)
Ironstone gravels	Ironstone gravel, massive nodular ironstone, ferricrete: The list of ironstone gravelly materials generally increases in hardness and excavation difficulty from pea size gravels to nodular ironstones and 'ferricrete'.
Clay	Soil particles smaller than 0.002 mm. Particles in this size fraction are involved in swelling and shrinking of soils and in holding exchangeable cations. This is the <0.002 mm material as the weight percent of the total <2 mm. The pipette method under 3A (Soil Survey Staff, 2011) is the standard. For soils that disperse with difficulty, the clay percentage commonly is evaluated from the 1500 kPa retention under 4B (Soil Survey Staff, 2011). Carbonate of clay size is included.

Colour-coded maps and the RAG traffic light system	Colour-coded maps have been frequently used by geologists to convey geological information to non-geologists and other specialists (for example, Donnelly and Harrison 2013). The Red-Amber-Green system, also known as the 'RAG' or 'traffic light' system, is a convenient method to facilitate the easy visualisation of complex information or data sets, in a manner that may be easily interpreted and executed for soil hazard. Red is frequently associated with highest risk or hazard, amber moderate risk and green the lowest risk. A red polygon designation on thematic maps signifies 'danger' or 'hazard'. Close liaison between soil scientists and farmers/planners ensures that research investigations are translated to practical outcomes.
Damage	In this context, damage refers to soil structure results from soil compaction, smearing, remoulding or pulverising.
Dispersion	Disintegration of micro aggregates into individual clay, silt and sand grains; the opposite of flocculation.
Duplex	Term applied to soil profiles which have relatively sandy A horizons, more or less sharply separated from underlying relatively clay rich B horizons.
Electrical Conductivity (EC)	Measured in deciSiemens/m (1 dS/m = 100 mS/m). It is a measure of the concentration of salts in solution. Low-salinity waters have values less than 0.25 dS/m and high-salinity irrigation waters have values greater than 0.75 dS/m. Water with an electrical conductivity of 0.01 dS/m contains about 0.1 me/litre anions or about 6.4 mg/litre dissolved salts. The salt tolerance of crops varies, some being adversely affected when the electrical conductivity of the 1:5 soil:water extract is in the region of 1 dS/m; a large number of crops are adversely affected when the figure is 1 dS/m or higher.
Gilgai	Regularly spaced humps and depressions found in the surfaces of some cracking clays. This micro relief is produced by swelling clays following prolonged expansion and contraction due to changes in moisture content; usually a succession of micro basins and micro mounds in nearly level areas, or of micro valleys and micro ridges parallel to the direction of the slope. There are two broad groupings of gilgai: low gilgai with a vertical interval <300 mm (i.e. crabhole, normal, linear and lattice gilgai types), and high gilgai with a vertical interval of >300 mm and commonly >800 mm (i.e. melon-hole and contour gilgai types).
Gypsum	Calcium sulfate ($CaSO_4$) used to reduce dispersion. A naturally mined substance or also formed as a by-product of fertiliser manufacture.
Impermeable	Not able to transmit water or air.

Lime	Calcium carbonate, often termed agricultural or calcitic lime to distinguish it from dolomitic lime.
Mottled	Having blotches of soil with a different colour.
Organic-rich	Organic materials are plant-derived organic accumulations that have 18% or more organic carbon if the material has 60% or more clay; 12% or more organic carbon if the material has no clay or a proportional content of organic carbon if clay content is between 12-18% clay (see figure in Isbell and National Committee on Soil and Terrain 2016).
Ped	An individual natural soil aggregate consisting of a cluster of primary particles and separated from adjoining particles by surfaces of weakness that are recognisable as being natural.
pH	A scale of measurement of acidity or alkalinity. The scale runs from 1 to 14 with 7 being neutral. Below 7 is acid and above is alkaline. Soil pH values can be up to 1.5 units lower when measured in a 0.01M $CaCl_2$ suspension than when measured in a water suspension. In the interests of standardisation it is recommended that a 0.01M $CaCl_2$ suspension (1 part soil:5 parts solution) is used. pH values below about 4 (very acidic) or above about 10 (very alkaline) may be corrosive of cable and infrastructure.
Salinity	An excess of water-soluble salts, usually sodium chloride, that restricts plant water uptake due to a process known as osmosis.
Self-mulching	Refers to cracking clay surfaces that develop a soft and crumbly condition after wetting and drying fracturing (of soil aggregates). Self-mulching refers to that condition of the surface soil, notably of clays, in which a high degree of pedality is exhibited with the peds falling apart naturally, as the soil dries to form a loose surface mulch. In cultivated soils, ploughing when wet may appear to destroy the surface mulch which, however, will reform upon drying.
Slickensides	Natural shiny surfaces found on soil aggregates formed by the parallel orientation of clay particles during swelling and shrinking cycles. Refers to polished or grooved surfaces within rocks or soils resulting from part of the mass sliding or moving against adjacent material along a plane which defines the extent of the slickensides. In soils, they occur only in clay-rich materials with a relatively high swelling clay content.
Smearing	Disruption of clay-rich aggregates under moist conditions to produce shiny, impenetrable surfaces.
Sodicity	An excess of sodium causing dispersion to occur.

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

Appendix 10

Factual key, salinity, size classes and sodicity

Factual Key	The Factual Key (Northcote 1979) is a soil type indication that uses a system of letters and numbers. It was used in the construction of the Atlas of Australian soils.			
	Profile Form		**Sub-div**	**Description**
	O	Peaty soils		Acid, neutral or alkaline
	U	Mineral soils, texturally uniform; subdivisions based on particle size and shrink/swell capacity	**Uc**	Coarse textured, sandy
			Um	Medium textured, loamy
			Uf	Fine textures, clayey
			Ug	Fine textured with periodic cracking in dry periods, unless irrigated
	G	Mineral soils, texturally gradational	**Gc**	Calcareous throughout (contains calcium carbonate)
			Gn	Not calcareous, but may be in subsoil
	D	Mineral soil, texturally duplex (coarse material overlies fine clayey material); colour sequence from red to grey indicates increasing wetness	**Dr**	Red-coloured subsoil clay; well drained
			Db	Brown-coloured subsoil clay
			Dy	Yellow-coloured subsoil clay
			Dd	Dark-coloured subsoil clay
			Dg	Grey-coloured subsoil clay (grey, greenish grey, bluish grey)
			These subsoil clays may be mottles with soil of different colour	
Salinity	Salinity is common in the more arid parts of Australia. It is usually associated with shallow water tables and is frequently responsible for damage to infrastructure.			

Size classes	Particle size classes are used to describe the mineral material that makes up soil.	
	Particle Name	**Australian system (mm)**
	Clay	<0.002
	Silt	0.002-0.02
	Sand	0.02-2
	Fine gravel	2-6
	Medium gravel	6-20
	Coarse gravel	20-60
	Cobbles	60-200
	Stones	200-600
	Boulders	600-2000
	Large boulders	>2000
Sodicity	Sodicity is a soil condition associated with present or past salinity, the legacy of which is to alter the properties of clays. Sodic clays are particularly susceptible to dispersion and erosion by fresh water even in arid areas where infrequent strong rainfall events can occur. Care is needed in restoring excavations in these soils. Gypsum application may help in some situations. Highly sodic soils also have alkalinity (high pH) and can be corrosive.	