SUBMISSION
Acid Sulfate Soils Centre (ASSC)

Submission to the Productivity Commission

Submission to the National Water Reform 2024 consultation on Integrated management of water for environmental and other public benefit outcomes

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ASSC thanks the Productivity Commission for the opportunity to respond to the National Water Reform 2024 consultation. For further information, please contact Professor Rob Fitzpatrick:

The Acid Sulfate Soils Centre (ASSC) brings together scientists in the University of Adelaide, CSIRO and other agencies in Australia and overseas for basic and applied research to increase the understanding of processes in acid sulfate soils in the fields of environmental science, mineral exploration, acid mine drainage, infrastructure damage and landscape rehabilitation.
The Acid Sulfate Soils Centre, which commenced in January 2012, is based at the University of Adelaide: (https://set.adelaide.edu.au/acid-sulfate-soils-centre/) with Prof Rob Fitzpatrick as the founding Director (2012-2023). The current Director is A/Prof Luke Mosley with Prof Rob Fitzpatrick as Deputy Director.

Goals

- Promote better understanding and management of acid sulfate soils to mitigate negative impacts on the environment by developing effective amelioration strategies.
- Maintain a high quality research program on acid sulfate soils using state-of-the-art methodology.
- Promote better understanding of the importance of acid sulfate soils to mineral exploration and minesite rehabilitation.

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Top photograph of a typical inland Acid Sulfate Soil of the subtype “Sulfuric cracking clay soil” in the dry river bed of Goolwa Channel - Currency Creek area, near north Goolwa during the Millennium Drought in November 2008, looking west towards to the Adelaide Hills, South Australia.
This “Sulfuric cracking clay soil” has trans-horizon polygonal cracks with acidic (pH < 4) surface coatings of the reddish-brown mineral, schwertmannite and pale yellow mottles of natrojarosite at depth (10 - 30 cm). This soil formed as a result of desiccation and dewatering of a former submerged pyrite-rich soil (Hypersulfidic subaqueous clayey soil) during drying cycles due to extreme drought conditions, between 2005 and 2009.

Bottom photograph taken at same location in December 2009 after reflooding due to winter rainfall runoff from adjacent catchments and pumping from Lake Alexandrina following installation of the temporary flow regulator across the Goolwa Channel at Clayton Bay.
This submerged soil, under 80 cm of water, has remained largely acidic for a period of six months and classifies as “Sulfuric subaqueous clay soil”.

As members of the Acid Sulfate Soils Centre (ASSC) we have prepared this submission to the National Water Reform 2024 with focus on *Integrated management of water for environmental and other public benefit outcomes*, which includes four (4) case studies across Australia that addresses the Productivity Commission's request for case studies with key data and supporting references.

The Acid Sulfate Soils Centre has published a series of publications across Australia covering the impact and management of degraded soil-landscapes **on water quality** from extreme:

1) Soil drying caused by prolonged drought conditions (and impacts of increasing bushfires),

2) Wetting caused by reflooding.

3) Excavation of drains and dams.

These environmental and excavation processes have resulted in a wide range of soil-landscape degradation issues, namely: acidification, salinisation, soil erosion clay dispersion/sodicity, waterlogging, soil compaction, production of noxious gases, monosulfide accumulation and disturbance in the following 4 regions:

- Coorong, Lower Lakes and Murray Mouth Region (Case Study #1),
- Lower Murray Reclaimed Irrigation Area (Case Study #2),
- Norfolk Island (Case Study #3) and
- South-west of Western Australia (Case Study #4).

As outlined in these 4 case studies, we believe that implementing an adaptive soil-landscape management approach is a minimum requirement in managing the long-term health and sustainability environmental water resources in the large and complex systems across Australia with major soil-landscape degradation issues. As the case studies show these issues are being increasing created by climate change (i.e. reduced rainfall and increased evaporation) and poor water management. As such, monitoring and the analysis and evaluation of the data collected are central to adaptive management and should be viewed as such, rather than as an optional enabler to this process.

Recommendation 1: Monitoring and evaluation findings will enable decision-makers to use adaptive management.

For example, the Millennium drought from 2007-2010 in the Murray-Darling Basin, which resulted in unprecedented low water levels in many wetlands and the Lower Lakes, caused oxidation of large areas of submerged acid sulfate soil (i.e. subaqueous soils containing iron sulfide minerals). One of the most severely impacted locations was in both the Lower Lakes of South Australia (a Ramsar site) (Case study #1) and Lower Murray Reclaimed Irrigation Area, South Australia (Case study # 2) with soil and water acidification occurring over large areas and costly management interventions (e.g. regulators, limestone dosing) undertaken.

Although the high river flows during 2010-2011 partially restored surface water quality in this region, a legacy of the highly acidified lake soil and pore water remained, and the long-term ecological impacts of this are unclear. An intensive research program was undertaken to inform the management of the acid sulfate soils in these 2 regions. This program demonstrated that the risk of localised water quality impacts (acidification events) is reduced if water levels are maintained above 0 mAHD.

The oxidation of pyrite to form sulfuric acid and sulfuric soils due to climate change, excessive water extraction, and extreme drought conditions in water catchments across Australia has been shown to offer the first visible warning against much larger imminent environmental water problems (e.g. water pollution and ecosystem impacts). Hence, acid sulfate soil materials can be compared with the well-known 'canary in the mine shaft', because external drivers can render the various acid sulfate soil materials either relatively stable (i.e. wetting, reflooding or reducing), or susceptible to rapid change (i.e. under drying or oxidising conditions). Like canaries in coal mines, the various types of acid sulfate soils can provide critical information about deteriorating environmental situations.

These submerged or subaqueous soils and groundwater are often "***out of sight, out of mind***" because they occur under rivers, wetlands and lakes and as such are "***hidden beneath our feet***" (Simmons, 2018). The four case studies below highlight the complex cumulative adverse impacts to reduced water supply and declining water quality in regions across Australia linked to exposure of these hidden hazards:

1. The environmental health of many of Australia's natural water systems is already seriously degraded and is continuing to degrade from successive droughts, bushfires and reflooding. (*Case study 1*: Lower Lakes, South Australia).
2. Some catchments are so degraded by excess extractions for human use and drought that action is urgently required (*Case study 2*: Irrigation Systems, South Australia).
3. The impacts of climate change are further reducing the amount and quality of water that can sustainably be extracted for human use. (*Case study 3*: Norfolk Island).
4. The impacts of clearing of native vegetation, drought and excavation of drains has resulted in extremely degraded wetlands and poor water quality in rivers, drains and lakes in the south-west of Western Australia (*Case study 4*: in south-west of Western Australia).

Recommendations

We recommend a nationally led, locally implemented, contemporary National Water Initiative (NWI), which addresses management strategies required to prevent the impact of degraded soil-landscapes on water quality, particularly from: (i) soil drying caused by prolonged drought conditions (climate change), (ii) wetting caused by reflooding events and (iii) excavation of wetlands (drains and dams), through the following actions:

1. Continuously assess and monitor all major catchments for improved adaptive management and governance.
2. Urgently assess and monitor major current and imminent threats such as acid sulfate soils and soil salinity as it is no longer sufficient to manage only water quantity issues in Australia's water resource systems; soil-landscape management is also essential. Vulnerable catchments should be reviewed to mitigate imminent threats.
3. Adequate environmental protection of water catchments including wetlands and lakes is a first prerequisite for sustainability. Environmental sustainability over generations is a first prerequisite for a National Water Initiative.
4. Adaptive management of human use of water, based on a thorough understanding of natural resources with a priority on soil-landscapes and the best available economic alternatives is a second prerequisite for sustainability.
5. Adaptive management is not possible without adequate modelling of Australia's water resource systems and their interconnections such as assessment and monitoring of soil-landscape systems and water quality.
6. Adequate investment is required in research and development and modelling to inform adaptive management.
7. Australia lacks a co-ordinated national strategic plan for water research. We believe this can be achieved by Recommendation 3 proposed by ATSE (2024) namely to: Re-establish and evolve the National Water Commission (NWC) to drive the reform process.

Acknowledgments: The first author (RW Fitzpatrick) would like to acknowledge the inspiration and encouragement received from Professor Rob Lewis during the preparation of the following report for ATSE, which was used to assist in the preparation of two open consultations concerning the Murray-Darling Basin Plan and this Submission: Lewis RK and Fitzpatrick RW (2023) "Murray Darling Basin: An Incremental Catastrophe". RWF also acknowledges Dr John Radcliffe and other members the ATSE South Australia and Northern Territory Division for providing guidance and report review comments on Case Studies over the past 5 years.

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Simmons C.T. (2018). There's a problem with our water: our water is precious, so why aren't we paying more attention to its conservation and management? Encounter. 20 – 21.

Examples of best practice: Four case studies illustrating Environmental Problems

Case study 1. Successive droughts, bush fires and reflooding have led to seriously degraded natural water systems, which are continuing to degrade: Lower Lakes region, South Australia

The Millennium Drought period had its biggest impact in the Lower Murray from 2006 to 2010 where there were unprecedented low freshwater inflows from the River Murray to the Lower Lakes. As a consequence, the impacts that attracted most attention by Federal and State agencies (e.g. Murray-Darling Basin Authority, Federal Government, State Governments, especially in South Australia) and the media included acidification of the lakes and adjacent wetlands at the end of Murray River due to low river inflows and the large scale floodplain wetland vegetation mortality due to the lack of flood events (e.g. Leblanc et al., 2012). One of the most severely impacted locations was in the Lower Lakes of South Australia (a Ramsar site) with soil and water acidification occurring over large areas and costly adaptive management interventions (e.g. regulators, limestone dosing) undertaken (Fitzpatrick et al. 2018). Although the high river flows during 2010-2011 have partially restored surface water quality in this region, a legacy of the highly acidified lake soil and pore water remained in 2020 with obvious long term cumulative ecological impacts especially following successive drought and reflooding events.

Assessment and mapping: Around 2007 – 2010, at the end of Australia's Millennium Drought, previously submerged lake beds in the large Ramsar-listed wetlands of Lake Alexandrina and Lake Albert in the lower Murray–Darling Basin in South Australia became exposed. Over 20,000ha of fertile, irrigated farmland and ecologically diverse wetlands quickly turned into dried-out wastelands of cracked soil and mud. Much of the subaqueous soil in this area contained iron sulfide minerals, i.e. acid sulfate soil materials. Submerged this "sulfidic mud" or "hypersulfidic material" is harmless, but the drought exposed the lakebed soil to the air for the first time in more than 100 years. This allowed the sulfide in the soil to react with oxygen in the air to form sulfuric acid resulting in the formation of acid sulfate soils with sulfuric material (pH < 4) and extremely acidic (pH <2) sulfate-rich salt efflorescences in some areas – almost as strong as battery acid as shown Figure 1 (Fitzpatrick et al. 2008a,b;2009).

Figure 1: Photographs taken during Australia's Millennium drought of extremely acidic (pH <2.5) and saline (i.e. sulfate-rich salt efflorescences comprising sideronatrite) salts that have accumulated on surfaces of acid sulfate soils with sulfuric material - described as the 'nastiest soils in the world'.

Following the break of the drought in 2010, floodwaters inundated the oxidised and severely acidified acid sulfate soils. The rewetting of these sulfuric soils via rainfall and tributary inflow resulted in widespread surface water acidification (pH 2-5), especially in tributary areas and shallow embayments around the lake margins in 2009-2010. Significant quantities of contaminants (metals, metalloids) were also released from the sediment matrix by extreme acidification (e.g. pH <2) during the drought, at concentrations toxic to terrestrial and aquatic ecosystems. In some areas, prolonged inundation encouraged sulfate reduction and caused the return of subaqueous soil conditions to the whole lower lake region. However, the apparent pristine water surface was found to hide a problem that hasn't gone away. In several areas, beneath the surface at the soil-water interface lie acid sulfate soils with sulfuric material (Baker et al. 2013). But now, these soils have no or little buffering capacity – in other words, little ability to keep the pH level stable. Before the "Millennium Drought" these subaqueous soils had some buffering capacity to acidification, because they contained calcium carbonate minerals. Now, these minerals have been destroyed by the acidity, and are not able reform quickly.

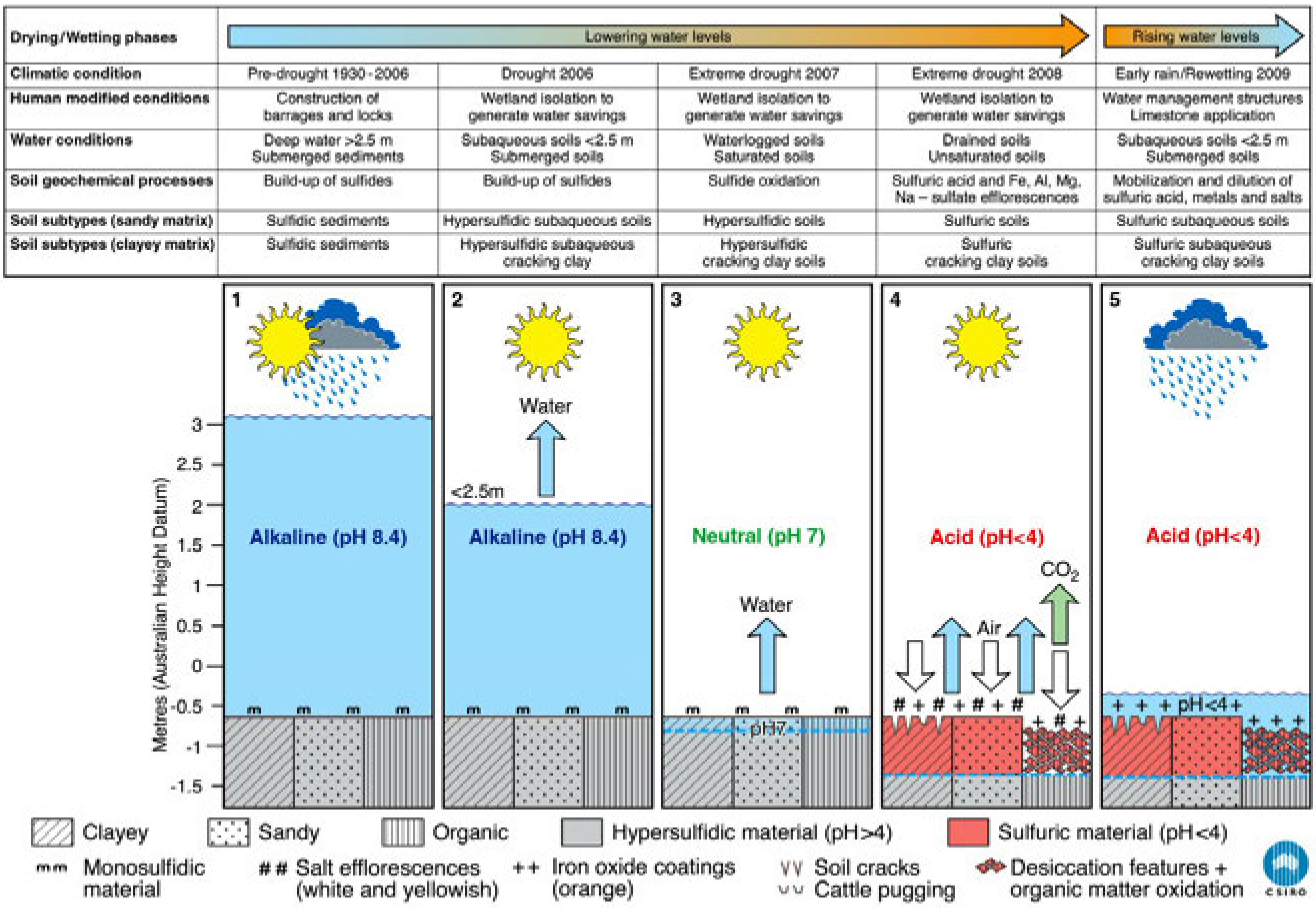

Figure 2: Generalised predictive soil-regolith model illustrating the role of climate variability (drought triggered and early winter rains), environmental conditions imposed by humans (i.e. modifications from barrages, isolating wetlands and weirs) and water conditions (subaqueous, waterlogged, dried and rewetted), which play a vital role in the alteration of soil geochemical processes and sequential transformation of various sandy, clayey and organic acid sulfate soil subtypes. (From Modified from Fitzpatrick et al. 2018; Fitzpatrick et al. 2008b, 2009b, 2011d).

The generalised predictive soil-regolith model shown in Figure 2 illustrates the Lower Lakes and River Murray region, which experienced lowering of water levels due to drought, followed by winter rainfall rewetting and flooding in 2010 (Fitzpatrick et al. 2008b, 2009, 2011). The soil-regolith model outlines sequential transformations progressively through five sediment/soil types from:

1. alkaline deeper water sediments →
2. alkaline subaqueous soils →
3. neutral waterlogged soils containing 'benign' hypersulfidic material →
4. acidic drained soils containing 'nasty' sulfuric material (pH <4) →
5. rewetted acidic subaqueous soils with sulfuric material and water.

From 2007 to 2009 the partial drying of wetland systems in the Lower Lakes and River Murray region caused the hypersulfidic subaqueous clays to transform to sulfuric clays. On rewetting, sulfuric subaqueous clays were formed in 2009 (Figure 2.5). Rewetting/reflooding caused widespread, gradual formation of acidic, sulfuric materials that persisted in subsoils, following restoration of the lake level (+0.7 m AHD) (Baker et al. 2013; Fitzpatrick et al. 2018). A similar sequence occurred in Lake Albert (Fitzpatrick et al. 2018). This is consistent with observations that, for several years post-drought, groundwater remained acidic under the previously (Millennium Drought) exposed lake beds (Leyden et al. 2016). This appears to be linked to a lack of available organic matter to drive sulfate and other reduction cycles, which increase alkalinity in the soil to neutralise acid present (Kölbl et al. 2018).

This means that when the next drought comes along, the newly exposed acid sulfate soils with sulfidic material will become even more rapidly acidic and to a greater depth. Hence when these soils are subsequently rewet by flooding, a greater volume of water would then become even more acidic. Hence, although the high river flows during 2010-2011 have partially restored surface water quality a legacy of the highly acidified lake soil and pore water remains with obvious long term cumulative ecological impacts, especially following successive drought and reflooding events.

Mapping and laboratory analyses showed that an extensive acid sulfate soil hazard is present in the Lower Lakes with about 82% (67,087 ha) of the total lake area (82,219 ha) has potential for developing sulfuric (pH<4) material in the soils/sediments if water levels decline.

In some areas, prolonged inundation encouraged sulfate reduction and caused the formation of hypersulfidic subaqueous clays in summer 2011 and hyposulfidic subaqueous clays in winter 2011 (Fitzpatrick et al. 2011d). It was also established that acidity has been flushed, from several areas which contained sulfuric materials, during the early winter of 2009 (Fitzpatrick et al. 2008a,b, 2009).

Another example of a long-term impact on soil and water resources in the lower Murray region is in Mussel Lagoon and Jury Swamp, which became so dry in the Millennium Drought that during ***a bushfire***, extreme temperatures melted and fused the soil into “brick-like” fragments. These soils are changed for forever in a completely irreversible process.

Management strategies: The outcomes of this work have demonstrated that the risk of localised water quality impacts (acidification events) is reduced if water levels are maintained above 0 mAHD. The risk of broad-scale lake acidification was reduced if water levels were stabilised at or above minus 1.5 m AHD in Lake Alexandrina and minus 0.5 m AHD in Lake Albert. Hence, for these and other reasons, there is need for improved environmental flows to the Lower Lakes to prevent water levels falling below 0 m AHD during severe droughts. Implementing Sustainable Diversion Limits and management strategies (e.g. water recovery) under the Murray-Darling Basin Plan is required to prevent water levels falling below this level, particularly during low flow drought periods. Local management strategies were developed to: (i) treat large areas of exposed acid sulfate soils with sulfuric (pH <4) materials and associated acid water bodies via aerial dosing of limestone (Fitzpatrick et al. 2018) and (ii) build temporary flow regulators across water channels to allow water levels to be raised so as to saturate exposed sulfuric and sulfidic soils to minimise further sulfide oxidation and to allow the early season flows (which would have mobilised acid and heavy metals) to be held back, allowing natural in situ bioremediation to proceed.

Effective monitoring strategies: Unless acid sulfate soil properties, associated groundwater levels/hydrogeochemistry and drain water quality are monitored and assessed, the need for, and efficacy of, acid sulfate soil and water management actions cannot be assessed or understood. For example, based on soil-and water-monitoring results, warning signs were erected to warn the public of the hazards present (Fitzpatrick et al. 2018; 2011). This would not have been possible without the monitoring information to inform the risk assessment.

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Case study 2. Excess water extractions for irrigation and drought have led to extremely degraded irrigation areas: Lower Murray Reclaimed Irrigation Area, South Australia

The legacy of land-use changes and irrigation on the poor health of the Murray-Darling Basin (MDB) has highlighted the environmental and economic costs of declining water quality due to soil and water salinisation and acidification. During droughts, reduced rainfall and limited irrigation water availability has resulted in falling water tables, which has led to major irreversible environmental impacts arising from exposure and oxidation of acid sulfate soils. Remediation and mitigation imposes ongoing financial burdens on the agricultural sector. The Lower Murray Reclaimed Irrigation Area, farmed for over 100 years, experienced widespread soil acidification during the Millennium Drought. Reduced rainfall and limited irrigation water availability led to the formation of acidic sulfuric clay soils (pH<4), which persist despite the return of flows.

As a result of the Millennium Drought and subsequent reflooding of the area in 2010 the deep sulfuric clayey soils (> 50 cm) and adjacent acid iron-rich precipitates in drains in the LMRIA poses an ongoing major reclamation 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 now remaining in the deep clays, (3) the low pH, complex biogeochemistry and hydrology of the acid drainage, and (4) the toxic iron-rich precipitates in drains, which sequester metals and acidify between reflooding, rainfall and irrigation events. These major ongoing modifications to the landscape have created new soil and water issues, which require careful management to both sustain agriculture and protect the broader River Murray environment. Considering that the sulfuric material generated during the Millennium Drought has persisted for a decade or longer in the LMRIA has highlighted the complex cumulative adverse impacts of successive drought and reflooding events, especially in irrigated areas.

Assessment and mapping: Prior to draining the natural wetlands for agriculture on the historic floodplain of the River Murray between Mannum and Wellington, this region cycled between wetting and flushing, and partial drying conditions in response to seasonal and climatic cycles causing the excessive build-up of sulfidic material to be kept in check by oxidation of pyrite during dry periods/droughts and removal during scouring floods. As the LMRIA became managed for irrigation and river navigation by constructing barrages and locks, acid sulfate soils with sulfidic materials began to build-up.

The LMRIA was a successfully farmed irrigation area for well over 100 years (1880's to 2007). During this time the level of the river determines whether gravity-fed flood irrigation can be used, which is the normal method of irrigation (Figure 1). However, 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. This extreme lowering of the water table during the Millennium Drought resulted in deep oxidation of sulfides in anaerobic hypersulfidic material to depths greater than 3.5 m in the previously saturated irrigated pastures and within 50 cm of the soil surface in the natural wetlands (Fitzpatrick et al. 2017a,b,c). A conceptual model of these processes is shown in Figure 1 below and more details see Fitzpatrick et al. (2017a).

Oxidation and acidification between 0.5 and 3.5 m of sulfidic clayey soils was enhanced by the formation of very large cracks up to 3.5 m deep (Figure 1). The severe Millennium Drought left an area of over 5000 ha in the Lower Murray River (South Australia) dried, cracked and acidified as river and groundwater levels fell nearly 2 m.

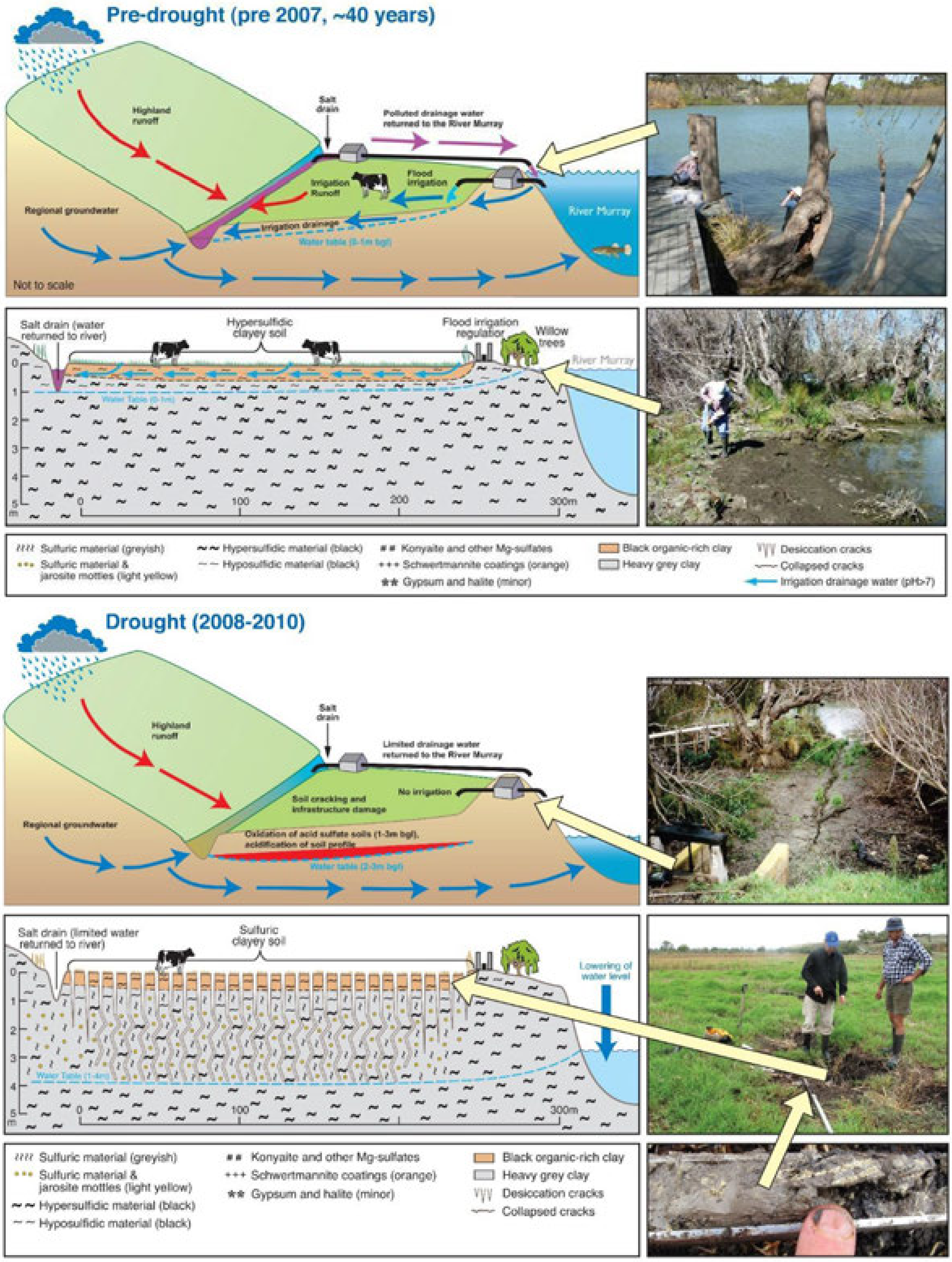

Figure 1. Explanatory soil-regolith hydro-toposequence model during (top) pre-drought and (bottom) drought conditions (2008-early 2010). The drought conditions illustrating the spatial distribution of: (i) deep cracking patterns, (ii) sulfuric materials extending to a depth of 3.8 m along cracks with light yellow jarosite mottles [see inset photograph of core in auger showing pale yellow 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 (adapted from Fitzpatrick et al. (2017a).

Rewetting and flooding after the drought caused mobilization of sulfuric acid, soluble sulfates, ferrous iron, nutrients and metals with transport into the River Murray. The reflooding and irrigation during 2011caused collapsed cracking patterns, sulfuric materials extending to a depth of 3.8 m along cracks with light yellow jarosite mottles and sulfuric materials extending to the soil surface with reddish-yellow surface coatings of iron-rich precipitates containing schwertmannite as shown in Figure 2.

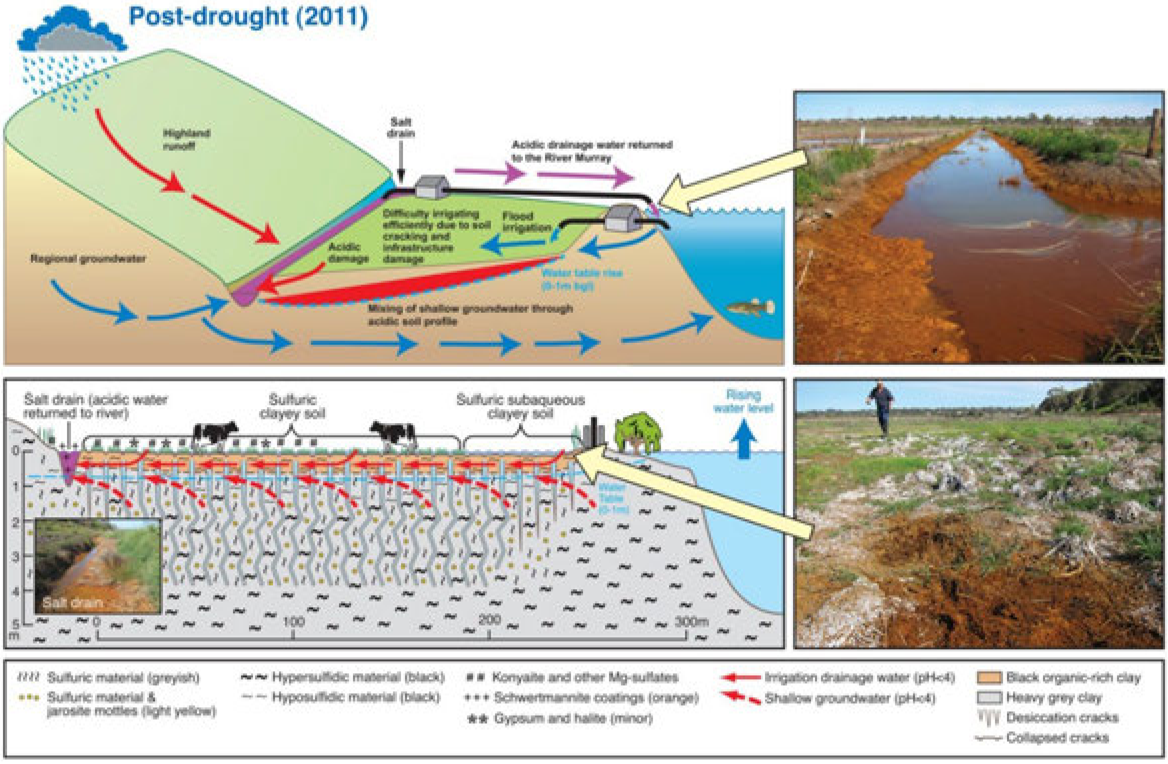

Figure 2. Explanatory soil-regolith hydro-toposequence model during post-drought reflooding and irrigation during 2011, illustrating the spatial distribution of: (i) deep collapsed cracking patterns, (ii) sulfuric materials extending to a depth of 3.8 m along cracks with light yellow jarosite mottles, (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 and (v) surface water levels, groundwater table levels and river flow (from Fitzpatrick et al., 2017a)

As expected with the low pH conditions, high concentrations of soluble metals (in particular Al, Fe, Mn, Ni, Zn) were also found in the drainage water which greatly exceed the ANZECC guidelines for protection of aquatic ecosystems and Australian Drinking Water aesthetic and health guidelines. The drainage water is discharged via large pumps into the River Murray, a practice which is necessary to maintain the viability of the agriculture of the LMRIA due to rising saline (and now acidic) water tables on the floodplain.

Monitoring within the River Murray has found that the acid and metalliferous discharge is being diluted quickly within a localised mixing zone and ecological and water quality effects are confined within this region (Mosley et al. 2014a.b).

The iron-rich precipitates also contained high concentrations of metals (Al> Cu> As> Zn> Pb> Co) and nutrients (e.g. P) due to co-precipitation/scavenging of these elements during the formation of schwertmannite (Fitzpatrick et al. 2017b).

Severe acidification is still present over 12 years post drought, there has been little change in pH in the deeper soil profile (Mosley et al. 2017; Fitzpatrick et al. 2017a; Kölbl et al. 2017).

Management strategies: This information has led the development of a handbook, which describes a set of specific data requirements/soil indicators that provide instruction to conduct soil-landscape investigations for the assessment and management of acid sulfate soils, salt-affected soils and all other soils in the LMRIA to provide sustainable management of water resources and hence future food security (Fitzpatrick et al. 2017c). Irrigation in the LMRIA is mandatory in order to prevent land salinisation, soil cracking and formation of acid sulfate soils (i.e. acidification during drought). As such, management strategies are required to prevent river water levels falling below 0 m AHD, particularly during low flow drought periods. 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 paddocks. Failure to do so will result in the productive agricultural topsoil becoming contaminated by the high concentration of salt, acidity and metals present in the groundwater. This contamination can lead to impacts on, or a complete loss of, agricultural production.

The formation and occurrence of acid sulfate soils in the LMRIA was used as justification to establish and legislate a Water Allocation Plan (the Plan) for the River Murray Prescribed Watercourse (PWC) (2023). The Plan is a statutory instrument and is written according to the legal requirements of the Landscape South Australia Act 2019 (Landscape Act). To manage the effects of acid sulfate soils, high saline groundwater levels and cracking on irrigated and non-irrigated land within the LMRIA, this Plan establishes a consumptive pool for Environmental Land Management Allocations (ELMA) – the All Purpose Consumptive Pool (Class 8). ELMA is also supported under Schedule E of the Agreement, which provides South Australia with the right to divert 22.2 GL for environmental land management purposes in the LMRIA. One of the key objectives of the Water Allocation Plan (PWC, 2023) is to: "Contribute to the prevention of increased soil salinity and acid sulfate soils, and associated land management issues. water can also reduce risks associated with acid sulfate soils". Hence it is critically important, particularly during droughts, that ELMA is protected.

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Case study 3. Climate change and drought has resulted in extremely degraded wetlands and poor water quality in rivers and dams on Norfolk Island

The cumulative adverse impacts from climate change and the recent drought have resulted in water levels of wetlands, streams and dams to drop across Norfolk Island. In some wetlands where major soil disturbance had occurred from extensive excavation from drainage, erosion or cattle pugging water levels in soils have also declined. These low water levels have exposed wetlands that have been permanently submerged and/or saturated with hypersulfidic peaty soils (pyrite rich; pH >4) for thousands of years. These processes have resulted in the formation and exposure of sulfuric peaty soils (i.e. pH < 4) in most wetlands across Norfolk Island that have dried.

If detected and managed appropriately, peaty hypersulfidic soils do not pose any major risk. However, if disturbed or drained and left unmanaged the sulfuric peaty soils have been shown to pose considerable risks to acidifying water in dams, drains and streams, which has impacted on humans, stock and the environment.

It is important that landholders and advisors can easily recognise the different dominant types of acid sulfate soils on Norfolk Island and know what management action to take if they identify these soils on their property. An example of the different types of acid sulfate soils in a dam along the Headstone Creek during different successive drying and reflooding periods in 2020, *2021 and 2022 is provided from Fitzpatrick et al. (2023).*

Assessment: Soil survey investigations on Norfolk Island in 1953 (Stephens and Hutton, 1954; Hutton and Stephens, 1956) did not identify and map the occurrence of acid sulfate soils (ASS). The reason for this omission was because the global existence of ASS was only recognised in 1973 by Pons (1973). However, a wide range of ASS have been identified across the Island in drainage lines with peaty wetlands based on successive field and laboratory investigations in four representative areas during: (i) 2020 following a dry period caused by drought conditions (Petheram et al. 2020), (ii) 2021 following a wet period of "just below" average rainfall and (iii) 2022 following 12 months of wet periods with above average rainfall (Fitzpatrick et al. 2023).

Since the mid-1970s there has been a notable reduction in rainfall across Norfolk Island. This has been most obvious during spring, where 23 of the last 25 years have seen rainfall below the long-term mean. Climate models project that Norfolk Island's winter and spring will continue to become drier in the future (Director of National Parks, 2011; Mimura et al. 2007, Petheram et al. 2020). Norfolk Island has experienced the worst drought on record between 2019 and early 2020.

Prior to the recent drought, wetlands on Norfolk Island would have gone through short periodic wetting and drying cycles. As a result, these wetlands have been inundated and/or saturated for many thousands of years and organic matter has continued to accumulate. Under those conditions these organic-rich (peaty) soils with high amounts pyrite remained covered by water, (i.e. Subaqueous hypersulfidic soils) or saturated (i.e. Saturated hypersulfidic soils) preventing them being exposed to oxygen.

However, the recent unprecedented drought conditions have led to a considerable drop in water table levels, exposing these soils with hypersulfidic material along sections of wetlands and streambanks. We provide illustrations in Figure 1 of the following 4 sequential acid sulfate soil transformation processes caused by environmental (rainfall) and anthropogenic (drainage and dam building) factors:

1. Formation of Hypersulfidic organic soils (pH >4) during prolonged wet pre-drought periods (i.e. remained inundated and saturated for many thousands of years with continued accumulation of organic matter).

2. Transformation of Hypersulfidic organic soils to Sulfuric organic soils (pH<4) during prolonged dry periods. As water tables progressively receded between 1970 and 2020 the formation of Sulfuric organic soils followed the sequence:

Subaqueous hypersulfidic organic soils (inundated) → Hypersulfidic organic soils (moist to mostly waterlogged) → Sulfuric organic soils (drying) (Figure 1a). These soils have accumulations of: (i) pale-yellow Ammoniojarosite and Hydronium jarosite and (ii) brownish-yellow precipitates of schwertmannite on dry dam surfaces and on dead reeds along sides of dams.

3. Transformation of Sulfuric organic soils to Monosulfidic and/or Hypersulfidic organic soils during reflooding periods caused by high rainfall conditions (Figure 1b). Reflooding caused the reformation of Fe-monosulfides and pyrite and the formation of Subaqueous Monosulfidic organic soils (Figure 1c) and Hypersulfidic organic soils. Monosulfidic material with gel-like consistency is common in shallow dams and contains monosulfides (FeS), which can rapidly deoxygenate water if disturbed (Figure 1c).

4.Irreversible or permanent transformation of Hypersulfidic organic soils to Sulfuric organic soils following deep excavation (>2m) and draining of wetlands (drying).

If drought conditions continue, the Sulfuric peaty soils will become thicker and more common in wetlands and along streambanks as water levels drop further and expose larger areas of wetlands and streambanks. Sulfuric organic soils also develop in similarly drying areas where major soil disturbance had occurred from extensive excavation from drainage, erosion or cattle pugging such as in dry dams if continued stream flows drop considerably (Fitzpatrick 2020) as shown in Figure 1(c).

Sulfuric organic soils on Norfolk Island can become extremely acidic (i.e. pH 1.7 to 2.5) that few aquatic animals and plants can survive as shown in Figure 1a. Sulfuric acid lowers pH levels, which makes several soil nutrients less available to plants. The presence of Sulfuric organic soils can reduce farm productivity and animal productivity because the acid discourages good quality pasture. Grazing animals may take in too much aluminium and iron by feeding on acid-tolerant plant species and by drinking acid water. Sulfuric organic soils may also make farmland more prone to salinity and waterlogging. If sulfuric acid is washed into waterways it can kill fish and aquatic plant species.

(a)	(b)	(c)

Figure 1.Photographs of Headstone Creek dam with Sulfuric organic soils in: (a) 2020 during the drought/dry period showing overlying sulfuric material with pale yellow and brownish-yellow iron precipitates (pH 1.7) on the dry dam surface and on dead reeds along the side of dam overlying black monosulfidic material at depth and (b) 2021 & (c) 2022 during wet/waterlogged periods showing suspended brown coloured iron-rich precipitates in the water filled dam with Subaqueous Monosulfidic material overlying sulfuric material (from Fitzpatrick et al. 2023).

Sulfuric organic soils have damaged infrastructures on Norfolk Island by corrosion and dissolution of cement mortar, calcarenite building bricks in bridges (Fitzpatrick et al. 2023; Petheram et al. 2020).

The Sulfuric organic soils, especially with acid iron-rich precipitates pose a major remediation challenge because of:

- the large volume and distribution of pyritic and acidic material
- the lack of neutralising minerals due to the dominance of organic matter (peats)
- the low pH (i.e. ranging from 1.7 to 3.5) with complex biogeochemistry and hydrology
- iron-rich precipitates (dominantly as schwertmannite and jarosites) that buffers acidity and scavenges metals between drying, rainfall and reflooding events.

Management strategies: When acid sulfate soil types on Norfolk Island are identified they can be effectively managed or treated (e.g. Fitzpatrick 2020) to avoid potentially negative environmental impacts such as poor water quality and damage to infrastructures.

The oxidation of pyrite to form sulfuric acid and the mineral jarosite in Sulfuric organic soils, due to extreme drought conditions across Norfolk Island, offer the first visible warning against much larger imminent environmental problems such as: (i) surface and ground water pollution, (ii) damage to heritage structures within the Kingston and Arthur's Vale Historic Area (KAVHA) by corrosion and dissolution of cement mortar, calcarenite building bricks used to construct the Watermill dam and bridges and (iii) strong odours from Sulfuric monosulfidic soils.

Hence, we liken acid sulfate soils on Norfolk Island to the canary-in-the-coalmine, being the first to suffer when the environment is under stress such as impact from climate change because external drivers can render the various types of ASS either relatively stable (i.e. wetting, reflooding or reducing to form Hypersulfidic organic soils), or susceptible to rapid change (i.e. under drying or oxidising to form Sulfuric organic soils) conditions. Like canaries-in coalmines, the types of ASS across Norfolk Island can provide critical information about deteriorating environmental situations. A detailed understanding of ASS change processes during wetting-drying cycles has assisted advisors and landholders to easily recognise the different dominant types of ASS and to know what management actions to take if they identify these soils on their property.

Effective monitoring strategies: Understanding how the various types of peaty acid sulfate soils in wetlands across Norfolk Island may respond to changing climatic and current drought conditions and designing long term research and monitoring programs will inform management responses.

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Case study 4. clearing of native vegetation, drought and excavation of drains has resulted in extremely degraded wetlands and poor water quality in rivers, drains and lakes in south-west of Western Australia

Rising water-tables due to clearing of native vegetation in the south-west of Western Australia have been recognised as causing secondary salinisation of landscapes with impacts mostly considered to be due to increased salt accumulation and waterlogging. Much of the shallow saline groundwater rising to the surface has recently been recognised as being acidic (pH<4.5) posing an additional threat. More than 9000 km of deep drains (>2 m depth) are estimated to exist in the Wheatbelt and there is a need to fully characterise the scale of threat posed by the natural hazard posed by acidic groundwaters and how this might be modified by practices such as groundwater drainage.

The discharge of acidic groundwater via water-table rise or deep drains to lakes and floodplains has led to the formation of sediments that have remarkably similar chemistry to those of inland Acid Sulfate Soils with sulfuric material rather than acidity having been generated within the profiles.

It is vital for all landholders, community groups, drainage contractors and local governments in catchments across south-west of Western Australia to be aware of the many impacts that result from: occurrence of sulfuric materials and disturbance of sulfidic materials as these have important consequences for environmental, engineering, economic, and quality of life perspectives. Disturbance and oxidation of hypersulfidic material can to destroy wetlands, acidify and deoxygenate waterways and increase the incidence of fish kills and disease, contaminate valuable groundwater resources and public park space, facilitate the mobility and accumulation of heavy metals, corrode, attack and destabilise roads, concrete and steel infrastructure, stimulate blooms of marine blue-green algae, decrease the agricultural productivity of land, increase odour problems and increase mosquito and arbovirus incidence.

Assessment: According to Degens (2009a,b,c) there has been increasing farmer interest (particularly in the eastern Wheatbelt) in using deep open drains to manage shallow saline watertables in broad valley floors because of mixed confidence in alternative options. More than 90 000 kilometres of salinity earthworks have been constructed in parts of the Wheatbelt, of which at least 4000 km are deep (at least 2 m) open groundwater drains (Degens 2009a,b,c; Shand & Degens 2008; Degens et al. 2008).

Deep drains used to manage shallow watertables in the eastern Wheatbelt can intercept and convey acidic saline waters, thereby creating conditions for the development of inland ASS processes in drains and acidified receiving environments. The hydrochemistry of the waters from deep open drains reflect that of regional groundwaters, which in many areas are acidic in the absence of drainage. The main materials and key processes in the drains are discussed in the following sections from Fitzpatrick et al. (2008):

Drain water salinity and acidity: Most drains were typically very saline at the time of sampling (January) with specific electrical conductance (SEC) in the range 60-100 dS/m. Low pH is widespread, with more than half of the drains sampled in October 2004 being less than pH 3. Drain pH decreases during summer, probably due to oxidation of ferrous iron in groundwaters, iron minerals in sediments and/or evaporation. The pH was lowest east of a line from Dalwallinu to Dumbleyung (pH less than 3.5) and highest (pH greater than 6) in the western and central part of the Basin. Only a few sporadic high pH (alkaline) samples were taken from drains in the eastern areas. Most eastern drains with a low pH (less than 4.5) had elevated concentrations of iron, aluminium, cobalt, copper, zinc, lead, uranium and a range of other trace elements and rare earth elements.

Drain mineral environments: Several materials were generally evident within the drains and were used to indicate different geochemical process zones. These materials broadly consisted of (from the original excavated base of the drain): unconsolidated saturated sediments including hypersulfidic material, monosulfidic material (black oozes), sulfuric material, saturated gels and precipitates, salt crusts overlying saturated sediments and salt crusts in the capillary zone above the drain waters. Not all materials were present within all drains. For example, in recent constructed drains (<3 years age) or drains with little sedimentation, there was little sedimentation and therefore minimal sediment profile development, gels and precipitates. The main materials and key processes that these indicate are discussed in the following sections.

Hypersulfidic material: occurred in most drain sediments (Figure 1b & 1c) as a thin horizon/layer (5 to 10 cm thick) representing a pool of stored acidity, that could contribute to drain water acidity seasonally or in aged drains. The Hypersulfidic material mostly consists of accumulations of iron sulfide minerals, one of the end products of the process of sulfate reduction (i.e. the use of SO_4^{2-} instead of O_2 during microbial respiration). Sulfate reduction is a natural process that occurs in virtually all the drains. However, the quantities or thickness of hypersulfidic material that accumulate in the drains is a function of many factors. The key requirements for high rates of sulfate reduction and sulfide accumulation are: (i) a high concentration of sulfate in surface or groundwater, (ii) saturated iron rich soils and sediments for periods long enough to favour anaerobic conditions, and (iii) the availability of labile carbon to fuel microbial activity. Saline groundwaters in the wheatbelt generally contain quite large concentrations of sulfate and ferrous iron.

Thus, drains that intercept saline groundwater should be expected to accumulate sulfide minerals in their bottom sediments over time, especially if they are permanently flowing or waterlogged. If flushed out of the drain as floodwaters scour drain channels, hypersulfidic material will oxidise and may become acidic. However, in some drains the ubiquitous presence of carbonates of calcium, magnesium and sodium in drain sediments and banks may neutralise drainage acidity. The extent to which this occurs, however, is dependent on whether the carbonates remain in contact with the acidic waters and are not armoured with precipitates or buried.

Layers of hypersulfidic material also occur in receiving lakes (Figure 2 - in this case the hypersulfidic material has oxidised / transformed to sulfuric material).

Monosulfidic material (Monosulfidic Black Ooze or MBO): is readily observed in the surface sediments of most drains (Figures 1b & 1c) and in receiving lakes (e.g. Figure 2). The high nutrient environment, especially at the edges of drains and the activity of algae and micro-organisms cause reducing conditions to develop and the formation of black, smelly iron monosulfides and other sulfides. Erosion of organic rich topsoils and influx of saline groundwater, with low redox potentials (reducing), into the drains are also likely to contribute to MBO formation. MBO is very reactive if exposed to oxygen, but provided that the materials remain anoxic and undisturbed they are relatively non-reactive.

Sulfuric materials – including gels and precipitates: Subaqueous soil horizons and sediments in some drains and receiving environments are highly acidic (pH <3.5) and by definition classify as “sulfuric material’. Acidity can form through several mechanisms:

(i) primarily by iron hydrolysis reactions or ferrolysis (Brinkman 1979) when anoxic ground water containing dissolved ferrous ions is exposed to air and ferrous ions are oxidised to the ferric ions, which reacts with water to form orange -brown precipitates, gels or crusts of ferric oxyhydroxides, releasing free hydrogen ions in the process.
(ii) When sulfidic materials are drained and exposed to air, they oxidise and produce sulfuric acid. If the amount of acidity produced exceeds the buffering capacity of water and sediments, acidification occurs. Prior to draining, materials that can cause acidification by sulfide oxidation are called hypersulfidic material. Once the hypersulfidic material is drained, it will transform to sulfuric material.

Mineral precipitates and gels present in the drains were indicative of specific geochemical conditions occurring (or having occurred). The occurrence of bright yellow natrojarosite mottles in some of the clay-rich sulfuric horizons are indicative of acid conditions in the pH range 3.5-4. Similarly, the occurrence of orange coloured mottles, gels and crusts (Figure 1a) are indicative of schwertmannite and akaganéite, which forms from the oxidation of ferrous iron in acid conditions in the range pH 4-5. Many of these minerals occurred in drains above the ground-water level, indicating that there is a store of acidity in soil profiles that could contribute to future, if not current drainage acidity. The minerals also present a reactive surface that can alter the solubility of trace metals in the drainage waters.

Saline and subaqueous soils with sulfuric material may occur in receiving lakes (Figure 2).

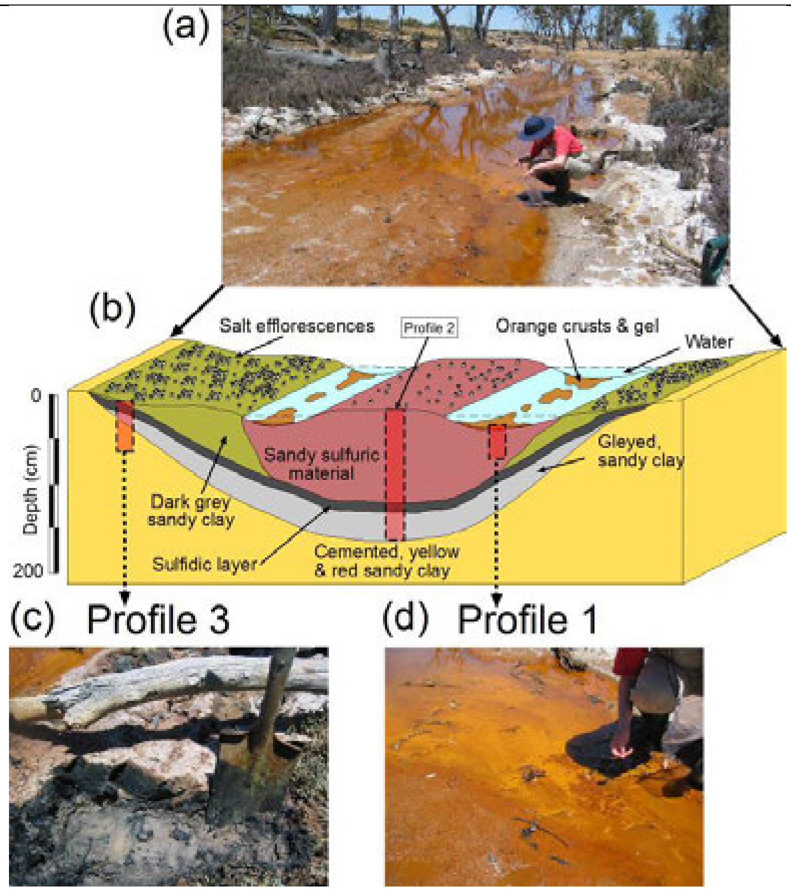

Figure 1. Schematic cross-section or hydro-toposequence (b) through a drain showing acid sulfate soils with orange crusts and gels (a and d) comprising mostly of Fe-oxyhydroxides (akaganéite: β-FeOOH) and Fe-oxyhydroxysulfates (schwertmannite) in surface waters overlying soil horizons consisting of: (i) reddish sulfuric material (pH <3.5), soft and sandy in Profiles 1 and 2, (ii) black hypersulfidic material (pH >4) friable and sandy clay in profiles 1, 2 and 3, (iii) greyish gleyed sandy clay and (iv) yellow matrix with red mottles, hard, sandy clay. White salt efflorescences occur on the sides of the drain in profile 3 overlying a mixture of uniform black, sulfidic material and monosulfidic black ooze, which in turn overlies mottles of black, sulfidic material in a yellowish-greenish-grey to olive mottled clay. (From Fitzpatrick et al. 2008).

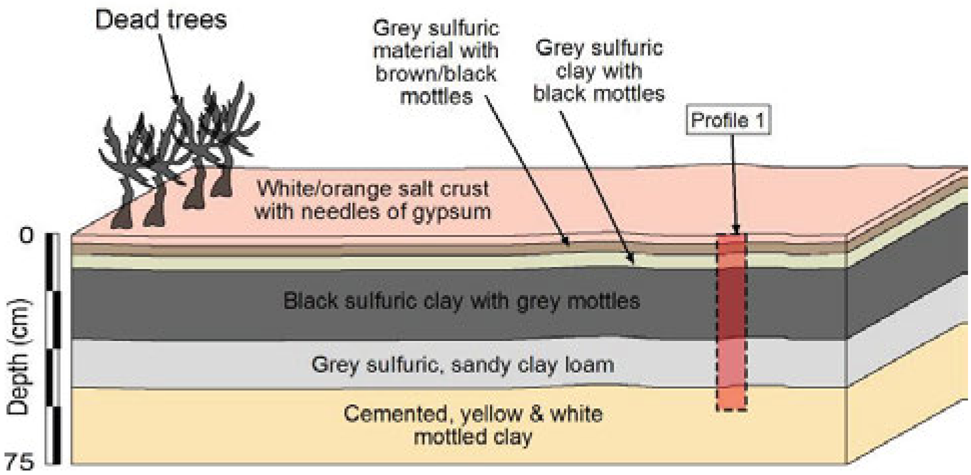

Figure 2. Schematic cross-section or hydro-toposequence through receiving lake D17 (Cunderdin Rd, Elachbutting) showing white salt efflorescence crust with needles of gypsum overlying layers of black and grey sulfuric material (profile 1) (From Fitzpatrick et al. 2008).

In the WA wheatbelt drains, the dominant source of acidity appears to be the acidic, oxidised, iron rich shallow ground-water discharging to the drains (where the water is acidic prior to drainage), though formation of secondary minerals in the drain sediments provides additional pathways of acid storage and release.

Salt crusts - Sulfate-containing salt efflorescences and oxyhydroxysulfate minerals: Soluble sulfate/chloride-containing minerals in efflorescences are produced by evaporation of ground and capillary waters. These evaporite minerals reflect the geochemical reactions resulting from the combination of groundwater, drainage water and drained soils in regions. For example, zones under:

- alkaline conditions (e.g. surface soil horizons in the drain batters) where Na/Ca ratio >4, eugsterite, gypsum and thenardite (i.e. Na-Ca-sulfate salts) form.
- acid conditions (e.g. interface of groundwater and drain batter in the base of drains) where Na/Ca ratio <4; bloedite and pentahydrite (i.e. Na-Mg-sulfate salts) form.

A predominance of sulfate-containing evaporite minerals occur in the drains because of the specific chemical composition and pH of inflowing drainage waters containing Na, Ca, Mg, Cl, Ba and SO_4. This composition probably arises from saline groundwaters enriched in sulfate (with other elements sourced from mineralised zones) seeping through soils. Declines in pH of the waters (due to oxidation of ferrous iron) on exposure to air or mixing with oxygenated waters can cause additional mineral dissolution and contribute to precipitation of a range of sulfate-containing minerals, each reflecting different geochemical conditions in the drains. These minerals include:

- pentahydrite, starkeyite, bischofite, bassanite, carnallite, rozenite, barite, halite and gypsum in sandy sulfuric horizons with pH <3.0;
- natrojarosite and jarosite in clay-rich sulfuric horizons with pH 3.5-4,
- eugsterite, bloedite, glauberite, gypsum, thenardite, mirabilite, schwertmannite, lepidocrocite, akaganéite and colloidal poorly crystalline, pseudoboehmite-like (white) precipitates in sulfidic materials with pH >5.

Management strategies: There is a need to manage not only the impacts of rising saline groundwaters in the broad palaeodrainage systems of inland south-western WA but also the impacts of geochemical processes coupled with the discharge. Acid waters discharging from drains will need to be managed to contain potential risks of discharging these to lakes and waterways. This management may involve treatment of waters or drain design to minimise export of acidic waters while maximising hydrological effectiveness (e.g. shallower, more frequently spaced drains). A step-by-step process is provided by Degens (2009a,b) to assist with designing treatment systems for acidic saline water discharging from deep drains. According to Degens (2009) the following treatment options that may be suitable for use in acidic saline drains include lime-sand beds, subsoil carbonate beds, in-drain composting beds and diversion wells. Lime-sand basins, composting wetlands, lime-sand reactors and hydrated lime dosing units are suited for treatment at drain ends. These options range in effectiveness from full treatment of a range of acidic waters to partial neutralisation, with costs for common drain water acidity levels varying from 10 cents per kL for some treatment options to more than 90 cents per kL, although all costs exclude managing sludges and/or decommissioning treatment systems. The following more specific management options have been proposed by Fitzpatrick et al. (2008):

- Drains need to be designed and managed to minimise turbulent flow velocities to minimise flushing of precipitates and gels (frequently containing trace metals) and disturbance of sulfidic sediments (being a store of acidity and trace metals). In particular, entry of surface waters from catchments to the drains should be avoided without measures to contain flow velocities.
- Drain design to maximise hydrological residence times and formation of precipitates will contribute to maximising retention of trace metals within the systems.
- Management of trace metal mobility and acid release will need to be considered when maintenance cleaning of sediments from drains is carried out. This might include mixing of sediments with alkaline drain spoils, placement within depressions on drain spoils (allowing drying and containment but contact with alkaline spoils) or collection and containment in a site without risk of off-site impacts (i.e. outside of a surface flow path).
- Accumulated vegetation in drains (e.g. roly poly residues) is best removed using an excavator particularly where large compact accumulations of materials occur in conjunction with iron precipitates. Burning of residues can result in the formation of a cemented iron plug that can significantly impede flows.

Acidic lakes that occur due to regional groundwater discharge (i.e. not drainage) may require management of geochemical risks including acidity and soluble trace metals to protect alkaline down-stream environments. Acidic groundwater discharge is best managed by containment and/or treatment in sites with minimal risk of down-stream transport which may be difficult to achieve which discharge to lakes in the central floodway.

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