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# Queensland Acid Sulfate Soil Technical Manual

## *Soil Management Guidelines Version 5.1*

Queensland Government

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*Front cover photo credit: Steve Wilbraham (DESI)*

# Acknowledgements

The *Queensland Acid Sulfate Soil Technical Manual, Soil Management Guidelines* (version 5.1) is an update of previous versions of the guideline (released in 2002, 2014 and 2023). Some material in this document (including earlier versions) builds on information from guidelines and policy developed by the WA Department of Water and Environmental Regulation, the 2018 National ASS Guidance material and the *NSW Acid Sulfate Soil Manual* (Stone *et al*. 1998). The principal authors of the Queensland *Soil Management Guidelines* are:

| | |
|---|---|
| Col Ahern | Retired, Principal Soil Chemist |
| Sue-Ellen Dear | Queensland Department of Resources (Chair of Editorial Committee) |
| Steve Dobos | Dobos and Associates |
| Angus McElnea | Queensland Department of Environment, Science and Innovation, Science Division |
| Nikki Moore | Queensland Department of Agriculture and Fisheries |
| Lauren O'Brien | New Zealand Landcare Research, formerly Queensland Government |
| Kristie Williams | Queensland Department of Resources |

Version 5.1 was released after consultation with the *2021–2023 Soil Management Guidelines Industry Reference Group*:

| | |
|---|---|
| Kathleen Ahern | Queensland Department of Environment, Science and Innovation, Environment Division |
| Steve Appleyard | Western Australia Department of Water and Environmental Regulation |
| Peter Armstrong | Sunshine Coast Regional Council |
| Dave Calland | Queensland Department of Resources |
| Del Fanning | Emeritus Professor, University of Maryland USA |
| Laurence Fox | Fox Environmental Consulting |
| Gunnar Haid | Canopy Enterprises Pty Ltd / 4 Pillars Environmental Consulting |
| Fenn Hinchcliffe | Canopy Enterprises Pty Ltd |
| Navjot Kaur | Aurecon |
| Graham Lancaster | Southern Cross University, Environmental Analysis Laboratory |
| Steve Lawrence | GHD Pty Ltd |
| Emily Leyden | University of Adelaide |
| Don Malcolm | Queensland Department of Resources |
| Jeremy Manders | Queensland Department of Environment, Science and Innovation, Science Division |

| | |
|---|---|
| Michelle Martens | Queensland Department of Environment, Science and Innovation, Science Division |
| Dane Moulton | Queensland Department of Environment, Science and Innovation, Environment Division |
| Josh Mitchell | Core Consultants |
| Phil Mulvey | Carbon Count |
| Shane Pointon | ASS Consultant |
| Colee Quayle | GHD Pty Ltd |
| Silvana Santomartino | PSK Environmental Pty Ltd |
| Paul Scells | Golder Associates |
| Dylan Stone | South Australia Department of Environment and Water |
| Leigh Sullivan | Emeritus Professor, University of Canberra |
| Nadia Toppler | Southern Cross University Environmental Analysis Laboratory |
| Kenny Walker | Queensland Department of Environment, Science and Innovation, Environment Division |
| Jon Walton | Queensland Department of Resources |
| Nick Ward | Southern Cross University, Environmental Analysis Laboratory |

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# Foreword

The Queensland Acid Sulfate Soil Technical Manual encompasses four individual guidelines: (this) *Soil Management Guidelines, Queensland ASS Sampling Guidelines, Laboratory Methods Guidelines 2004;* and a *Legislation and Policy Guide*.

Version 3.8 (Dear *et al. 2002)* and version 4 of the *Soil Management Guidelines* (Dear *et al.* 2014) were released following extensive consultation with a wide range of stakeholders and acid sulfate soil (ASS) professionals. Version 5 (released in December 2023) was formulated to ensure greater consistency with the 2018 National ASS Guidance material, and to provide further clarification where there were inconsistencies. Again, there was extensive consultation with stakeholders and ASS professionals. The review included updates in several sections including neutralisation strategies, verification testing, acidic soils and self-neutralising soils. The review also included additional sections on remediation, unconfined dewatering, components of ASS environmental management plans, water quality parameters, and a poem on sulfidisation. Version 5.1 was released in May 2024 to provide further clarity on requirements for trenching, acidic non-sulfidic soils and small volume disturbances.

Refer to the Queensland Government ASS website for information about the relationship between the 2018 National ASS Guidance material and chapters of the Queensland ASS Technical Manual—in particular, the *Queensland ASS Sampling Guidelines*.

This guideline applies to Queensland sites and is frequently adopted by other Australian jurisdictions. It has been developed based on experience in managing and researching ASS in Queensland, the exchange of national and international management experience, and on published research.

If you have any comments or questions, please contact soil.enquiry@resources.qld.gov.au. Constructive criticism and/or suggestions for additional content are welcome.

May 2024

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# 1. Introduction

The *Queensland Acid Sulfate Soil Technical Manual, Soil Management Guidelines (Version 5.1)* documents the risk to the environment when implementing various strategies to manage acid sulfate soils (ASS). Fundamental to the application of these guidelines are the **nine management principles** outlined in Section 2. Environmental management strategies employed for all ASS disturbances must be consistent with the intent of these principles, and in particular the primary objective of avoiding the disturbance of ASS wherever possible. An outcome of preventing harm to the environment must be achieved, regardless. This guideline should be used in conjunction with other National and Queensland guidance material.

The guidelines provide general information to support decision makers. They may not be suitable for every site, nor will they offer management solutions for all situations. Regulatory decision makers should have regard to this when they apply the guidelines. There may be cases where management strategies can deviate from those outlined, particularly due to advances in technology—alternative management strategies will need to be scientifically justified and must be consistent with the nine management principles (see Section 2).

The guidelines have been written with a multidisciplinary approach in mind, to make sure that relevant issues are covered. Although care has been taken to minimise overly technical language, expertise in a variety of disciplines may be needed to achieve *best practice environmental management*[1].

These guidelines focus on the management of coastal ASS rather than inland ASS. However all pyritic or sulfidic materials have the potential to produce acidity, sulfate and metals in a chemically similar manner. This may include pyrite-rich shales, mudstones and other rocks (Ballivy *et al*. 2002), some coal seams and mineral ore bodies (Johnson and Hallberg 2005) and some of the materials produced by disturbing these (quarry products, mine wastes etc). Acidity problems related to pyritic rock disturbance are commonly referred to as acid mine drainage (AMD), acid and metalliferous drainage or acid rock drainage (ARD). Methods of managing AMD/ARD have some commonality with methods discussed in these guidelines but are not covered here. For more information on AMD/ARD, refer to the *International Network for Acid Prevention*, *Amira ARD test handbook* and the *CRC for Transitions in Mine Economies*.

Further information on ASS chemistry, physical behaviour, and spatial distribution can be found at the Queensland Government ASS website, Queensland Department of Environment, Science and Innovation Library catalogue, Queensland Publications Portal, Water Quality Australia, Queensland Globe, Western Australia Government ASS website, University of Adelaide Website and in the sources cited in this guideline's reference section.

## 1.1 Purpose

The *Soil Management Guidelines* offer technical and procedural advice to minimise potential environmental harm and to assist in achieving *best practice environmental management* of ASS. The guidelines have been designed to aid decision-making and provide greater certainty to the construction, extractive and agricultural industries, state and local governments and the community in planning and operating activities that may disturb ASS.

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[1] *Best practice environmental management* is discussed further in the *Queensland ASS Technical Manual* Legislation and Policy Guide and in the *Environmental Protection Act 1994.* The *Legislation and Policy Guide* has not been updated since 2004, and much of the legislation has been repealed or updated. The guide does contain useful ancillary information but does not reflect current legislative status. The most relevant current pieces of Queensland legislation of relevance to ASS include: the *Planning Act 2016* and accompanying *State Planning Policy, State Development and Public Works Organisation Act 1971* and the *Environmental Protection Act 1994.*

## 1.2 Defining acid sulfate soils

Coastal acid sulfate soils (ASS) are coastal and near-coastal soils, sediments or other materials containing iron sulfides. They are environmentally benign when left undisturbed in an aqueous, anoxic environment, but when exposed to oxygen the iron sulfides oxidise, releasing sulfuric acid and soluble iron. Both substances have considerable ability to degrade the natural and built environment, and the acid may additionally mobilise chemical species (e.g. aluminium and/or heavy metals) which can be toxic or poisonous at low concentrations. Other hazards have also been recognised including the deoxygenation of surface waters, contaminant metal and metalloid release, malodours, nutrient release (Shand *et al*. 2018), and direct loss of vegetation and habitat.

While the primary source of inorganic acidity in ASS is pyrite ($FeS_2$), other crystalline or amorphous iron sulfides can also generate acidity. The term ASS is used throughout these guidelines as a general descriptor and refers to a spectrum of materials as described in Table 1.

**Table 1: Terms commonly used to describe the spectrum of ASS[2]**

| Descriptor of ASS | Australian Soil Classification terminology | Terminology from other schema |
|---|---|---|
| Unoxidised soils, sediments, peats and other material with significant amounts of iron sulfides | These soils have 'sulfidic' material within the upper 1.5 m of the soil profile and can be hypersulfidic and/or hyposulfidic | Commonly referred to as potential ASS (PASS) due to their potential to produce acid if disturbed |
| Completely oxidised soils, sediments and other material which have no remnant iron sulfides but contain measurable[3] Actual and/or Retained Acidity that has resulted from the oxidation of iron sulfides | These soils have 'sulfuric' material within the upper 1.5 m of the soil profile | Commonly referred to as actual ASS (AASS) as they are acidic (pH less than 4). |
| Partially oxidised soils, sediments and other material with variable amounts of Actual and/or Retained Acidity and unoxidised iron sulfides | These soils contain a mix of sulfuric and sulfidic material within the upper 1.5 m of the soil profile | A mixture of AASS and PASS horizons within the same soil profile. |

*Note: There are a range of sparingly soluble oxidised ferric hydroxy-sulfate minerals (e.g. jarosite) that can form in ASS[4]. These minerals can generate further acidity as they later dissolve or hydrolyse, and they can also stimulate other chemical reactions. Acidity bound up in these minerals is referred to as 'Retained Acidity'. See ASS Tip 4, ASS Tip 5 and ASS Tip 32 for further information.*

The Australian Soil Classification (Isbell & NCST 2021) includes references to ASS within the Hydrosol, Organosol, Podosol, Arenosol, Rudosol and Vertosol soil orders to accommodate the diverse range of seasonally or permanently waterlogged soils, sediments and materials that are formed almost entirely under anaerobic conditions. Three kinds of sulfidic material are described in the Australian Soil Classification: hypersulfidic material, hyposulfidic material and monosulfidic material—these are described in the Glossary.

*Note: The 2018 National ASS Guidance material frequently refers to ASS as having properties and behaviour that have either been affected by the oxidation of reduced inorganic sulfur; or the capacity*

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[2] See Glossary for definitions of terms used in this table.

[3] Exceeding the 'texture-based acid sulfate soil action criteria' (see Table 2).

[4] These minerals form upon the hydrolysis of ferric sulfate if the pH is between 3.5 and 4 when oxidising conditions allow $Fe^{3+}$ to be stable (Fanning 1993).

*to be affected considerably by the oxidation of their reduced inorganic sulfur constituents. For these guidelines, this is considered to have the same intent as the definition above.*

The texture, or particle size distribution of ASS is variable and largely dependent on the local depositional environment. There is only a general relationship between iron sulfide content and soil texture, with higher sulfide levels more common in clays. Surface ASS horizons can contain considerable organic matter, as can monosulfidic black oozes (MBOs) (see ASS Tip 1). Peats can also contain high sulfide levels (see Case Study 1).

**ASS Tip 1: Monosulfidic black oozes**

Monosulfidic black oozes (MBOs) are highly reactive materials with extremely high moisture contents. They contain ultra-fine grained reactive iron sulfides, for example, amorphous FeS, greigite $\approx Fe_3S_4$ and mackinawite $FeS_{1-x}$ (where x is 0 to 0.1), which are intermediate products in the formation of pyrite. Monosulfidic black oozes may also contain pyrite.

They can form as thick accumulations (e.g. >1 m deep) in drains and waterways in ASS landscapes and are easily mobilised or resuspended during runoff events (e.g. major storms). MBOs can oxidise rapidly once exposed to oxygen and can cause severe acidification and/or deoxygenation of floodwaters (Sullivan *et al*. 2002; Bush *et al*. 2004a; Bush *et al.* 2004b). The sampling, laboratory analysis and management of MBOs warrant special attention in any environmental management strategy as MBOs are highly reactive and can oxidise within minutes when disturbed. Monosulfidic materials as described in the Australian Soil Classification encompasses a wider array of soil textures and consistencies. For these guidelines, MBOs and monosulfidic material are combined. Refer to the *MBO National Guidance material* (Sullivan *et al*. 2018c) for further information.

The following generalised terms are used to describe the complex acidity associated with ASS:

**Actual Acidity**: soluble and exchangeable acidity readily available for reaction, including pore waters containing metal species capable of hydrolysis (e.g. $Fe^{2+}$, $Fe^{3+}$ or $Al^{3+}$ ions). The laboratory analyte for Actual Acidity is Titratable Actual Acidity (TAA).

**Retained Acidity**: acidity retained by sparingly soluble and insoluble oxidised sulfur compounds (derived from sulfide oxidation) that slowly produce acid (e.g. jarosite, natrojarosite and schwertmannite). Retained acidity is estimated using calculations from either the Net Acid Soluble Sulfur ($S_{NAS}$) or Residual Acid Soluble Sulfur ($S_{RAS}$) method. See ASS Tip 4 and ASS Tip 5 for the calculations.

**Potential Sulfidic Acidity**: acidity associated with the complete oxidation of sulfides (two moles of acidity are generated in the disulfide oxidation (i.e. $S_2^{2-}$ in pyrite), and two moles of acidity are released from the oxidation and hydrolysis of the iron in pyrite to ($Fe(OH)_3$). The laboratory analytes for Potential Sulfidic Acidity are Chromium Reducible Sulfur ($S_{CR}$) and Peroxide Oxidisable Sulfur ($S_{POS}$). For brevity, 'potential acidity' will be used in these guidelines.

**Net Acidity:** the quantitative measure of the acidity hazard of ASS materials. It is determined from an Acid Base Accounting (ABA) approach (see Section 3).

See the Queensland Acid Sulfate Soils website for more information on laboratory methods.

The forms of acidity described above are defined using laboratory tests and cannot be numerically compared until the test results are converted into common units. Two such common units are used throughout this guideline: mol $H^+$/t and %S. The first, mol $H^+$/t, is an 'equivalent acidity unit', describing forms of acidity in terms of the number of moles of $H^+$ produced per tonne of dry soil material.  The second %S, is an ‘equivalent sulfur unit’, describing forms of acidity in terms of the equivalent percentage of reduced inorganic sulfur that if oxidised, would generate this amount of acid.  Choosing a common unit to use when conceptualising ASS acidity is a matter of personal preference, but care must be taken to convert test results accurately into the same units.

*Note: Under the 2018 National ASS Guidance material, Net Acidity and its components are presented in acidity units only due to its obvious links to acidity.*

Acid sulfate soils often contain a mixture of the above forms of acidity, and their relative proportions may change during periods of wetting, drying and aeration.  This can occur as a natural process related to climatic cycles.  Extended periods of drought can lead to a drop in the watertable, allowing near-surface PASS to oxidise.  The return of rainfall and the subsequent rise of the watertable allows acid and iron generated during the dry period to be exported into ground- and surface-waters.  In natural environments, this situation is generally not problematic, as the oxidation period is short, temporary and relatively small volumes of ASS are affected.  In addition, the structure of the natural coastal plains environment, with its winding network of stream channels, may allow for more buffering of acidity within the system (see ASS Tip 15 for information on buffering capacity).  An exception to this rule is areas with sandy soils and offshore sand islands (such as K’gari, Moreton Island (Mulgumpin) and Stradbroke Island (Minjerribah)).

Human disturbance of ASS imposes a different pattern: disturbance volumes are significantly larger (particularly in the case of broadscale floodplain alterations) and disturbance is usually permanent, semi-permanent or ongoing (e.g. urban development, agriculture).  Acid and iron production becomes continuous rather than intermittent, and solutes may be easily transported through artificial drainage networks.  It can thus overwhelm the environment's ability to buffer the acidity produced.  The result is a significant pollution problem which may affect many stakeholders (Appleyard *et al*. 2004; Simpson *et al*. 2010).

## 1.3 Occurrence of acid sulfate soils

Acid sulfate soils occur naturally over extensive areas of low-lying coastal land, predominantly below 5 m Australian Height Datum (AHD)[5].  These soils may be found close to the natural ground surface but may also be buried at depth in the soil profile.  All disturbances to soils, groundwater hydrology or surface drainage patterns in coastal areas below 5 m AHD should be investigated, and an assessment of ASS risk be undertaken to allow the adoption of appropriate design and management to avoid potential adverse effects from ASS on the natural and built environment (including infrastructure) and human health.  This includes disturbance of soil or sediments below 5 m AHD where the natural ground level of the land is above 5 m AHD.  Any areas of filling and or reclamation will also need to be considered along with ASS areas that have previously been disturbed and/or where the hydrology/hydrogeology has been modified.

Although most coastal ASS in Australia are found below 5 m AHD, in some locations they may be encountered above this elevation, for example in Tasmania (Tasmanian Government 2010).  Parts of central Queensland also contain ASS at elevations over 5 m AHD (e.g. from Port Clinton to St Lawrence, and around Yeppoon).  ASS can be found or can form in any anoxic, aqueous environment where sulfate-reducing bacteria are provided with organic matter (their energy source) and available sulfate and iron (see ASS Tip 2).  Examples include bottom sediments in drains and bore drains, dams, constructed and natural waterways, swamps and billabongs, periodically stagnant creeks and places with perched watertables.  These environments are not restricted to coastal areas.  They can occur anywhere throughout Australia where the above conditions for sulfate reducing bacteria can be met.  Acid sulfate soils in non-coastal areas are commonly referred to as ‘inland ASS’, ‘upland ASS’

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[5] Note that not all soils in the low-lying parts of coastal floodplains below 5 m AHD are ASS; but in Queensland, ASS are predominantly located below 5 m AHD.

or ‘non-coastal ASS’ (Hall *et al*. 2006; Fitzpatrick and Shand 2008b; Biggs and Watling 2008; EPH and NRM Ministerial Council 2011; Fitzpatrick *et al.* 2018a). While most coastal ASS are geologically young (<10 000 years old), inland ASS can be found in much older sediments. These inland occurrences are not limited by stratigraphy or age.

**ASS Tip 2: Sulfate-reducing bacteria**

These bacteria can occur anywhere where four conditions exist together: aqueous environment, anoxic waters, available organic matter (bacterial food) and soluble sulfate ions. The bacteria prefer pH between 6–8, however, can withstand low pH values (pH <5) (Koschorreck 2008). The bacteria metabolise the organic matter, using the sulfate ions as the terminal electron acceptors, and they produce hydrogen sulfide (rotten egg gas, $H_2S$) as a waste. The $H_2S$ reacts with soluble iron, first precipitating amorphous FeS (iron monosulfide). With continued bacterial production of $H_2S$, FeS is converted to $FeS_2$ (iron disulfide; pyrite or marcasite).

*Note: Although an ‘oily’ film on the water surface is a good visual indicator of ASS disturbance, this film is due to iron oxidising bacteria that are converting dissolved* $Fe^{2+}$ *into Fe(III) oxides. Sulfate-reducing bacteria occur in the benthic sediments and keep away from oxygen.*

**Case Study 1: Peat with pyrite, Stirling, Western Australia**

In 2001, concerns were raised about groundwater quality in the City of Stirling, WA. Use of small groundwater bores or ‘spears’ for irrigating gardens was common in the area, but gardens fed by such water were starting to die. Investigation revealed acidic (pH <5.5), metal-rich (Fe, Al, Pb) groundwater as deep as 10−12 m below the surface, with high arsenic levels a feature of many of the bores tested (commonly up to 800 µg/L, over 100 times the Australian Drinking Water Guideline value of 7 µg/L). The source of the acidification was found to be new nearby residential developments, where lakes and water features had been excavated in pyrite-rich peats. These surface water bodies were found to have pH values as low as 2. Several aspects of the development were held responsible for generating the acidity—a six-metre lowering of the local watertable during the construction phase, the surface stockpiling of excavated peat, and the structure of the artificial lakes and wetlands themselves. In addition, the local climate and a fire in the stockpiled peat likely exacerbated acidity and metal export during the investigation period. Extensive rehabilitation works were required in the area, and the incident prompted development of comprehensive ASS management policy in WA (Western Australian Government 2002).

Sulfidic peats (or soils containing some sulfidic, organic-rich layers) occur in coastal Queensland, and have recorded laboratory results of up to 2806 mol $H^+$/t (equivalent to 4.5%S). Disturbance of these peats can cause substantial problems that can be extremely difficult to remediate.

# 2. Management principles

The *Soil Management Guidelines* are to be applied by following the nine management principles:

### The nine management principles

1. The disturbance of ASS should be avoided wherever possible.
2. Where disturbance of ASS is unavoidable, preferred management strategies are:
   - minimisation of disturbance
   - neutralisation
   - hydraulic separation of sulfides either on its own or in conjunction with dredging
   - strategic reburial (reinterment) of potential ASS.

   Other management measures may be considered but must not pose unacceptably high risks.
3. Works should aim to achieve *best practice environmental management*, when it has been shown that the potential impacts of works involving ASS are manageable, to make sure that the potential short- and long-term environmental impacts are minimised.
4. The material being disturbed (including the *in situ* ASS, surface water and groundwater), and any potentially contaminated waters associated with ASS disturbance, must be considered in developing a management plan for ASS and/or in complying with the *general environmental duty*.
5. Receiving marine, estuarine, brackish or fresh waters (including groundwaters) are not to be used as a primary means of diluting and/or neutralising ASS or associated contaminated waters.
6. Management of disturbed ASS is to occur if the ASS action criteria listed in Table 2 of this guideline are reached or exceeded.
7. Wherever possible, ASS below the watertable should not be disturbed by changes in elevation and/or physiochemical properties of the watertable to ensure that these minerals are not exposed to oxidising conditions. Permanent unconfined groundwater dewatering is unacceptable.
8. Placement of untreated ASS above the seasonally lowest watertable elevation, with or without containment, is not an acceptable long-term management strategy. For example, soils that are to be stockpiled, disposed of to landfill, used as fill, placed as temporary or permanent cover on land or in waterways, sold or exported off the treatment site or used in earth bunds, that exceed the ASS action criteria in Table 2 should be treated/managed.
9. The following issues should be considered when formulating ASS environmental management strategies:
   - sensitivity and environmental values of the receiving environment. This includes the conservation, protected or other relevant status of the receiving environment (e.g. Declared Fish Habitat Area, Marine Park, Coastal Management District, Wetland Protection Area, Erosion Prone Area and protected wildlife)
   - whether groundwaters and/or surface waters are likely to be directly or indirectly affected
   - heterogeneity, geochemical and textural properties of soils on site
   - the project’s life cycle
   - management and planning strategies of local and/or state government, including statutory planning instruments.

Moving beyond the first management principle of avoiding disturbance needs to be justifiable. Short and long-term environmental and economic costs must be considered. Regulatory decision makers will **expect scientific justification** as part of a development application involving ASS disturbance.

# 3. Risk assessment

Proponents disturbing ASS assess the risk of disturbance by considering both on- and offsite impacts. The construction, operational and maintenance risks will also need to be evaluated.  Queensland Government ASS mapping is available for many coastal areas and should be viewed prior to any decisions being made to disturb ASS (see ASS Tip 3).  An assessment of risk should be a precursor to proposals with the potential to disturb ASS.  The risk assessment describes the footprint of all potential impacts (including offsite impacts) and the values and risks within the footprint.  Values should at least include biodiversity values (flora and fauna, connectivity, etc), environmental values and water quality objectives under the *Environmental Protection (Water and Wetland Biodiversity) Policy 2019* (surface and groundwater).  Risks could include the potential for causing unlawful, serious, or material environmental harm or an environmental nuisance (as defined within the *Environmental Protection Act 1994*).

Determining whether ASS are present at a site and managing disturbed ASS appropriately can involve major costs.  When considering projects in areas likely to contain ASS, proponents should take these costs into account as early as possible.  These costs may compromise a project’s design or economic viability.

A thorough ASS investigation (in compliance with the latest *Queensland ASS Sampling Guidelines*), soil analyses (according to the latest *Queensland* and *National* *Laboratory Methods Guidelines* or AS4969 (Standards Australia)) and a groundwater investigation (in compliance with the *Guidance for the dewatering of acid sulfate soils in shallow groundwater environments* (Shand *et al*. 2018)) are essential components of a broader risk assessment before making any land use decisions.  The development of a conceptual site model (CSM) as a primary planning and decision-making tool can assist with evaluating design and management options along with identifying and managing site uncertainty (i.e. data gaps) and risk.  The CSM is a written and/or illustrative representation of the physical, chemical and biological processes that may control the ASS source, receptors (i.e. human, built environment and/or ecological), and exposure pathways (soil, groundwater, surface water and/or sediments) between the sources and receptors.  The CSM should support scientific and technical decisions for the site and can be refined as the project progresses and allow re-evaluation of environmental risk related to adoption of various management strategies (see Section 6.1 and Appendix A6-1 and A6-2 for examples of CSMs).  For further information about CSMs, refer to NEPM (2013).

Check lists for an ASS investigation report and an ASS environmental management plan (EM plan) have been compiled by Soil Science Australia as part of the Registered Soil Practitioner Acid Sulfate Soil (RSP-ASS) training and accreditation program (see ASS Tip 6).  These checklists (see Appendix 1 and Appendix 2) should be used as a guide for consultants and assessing authorities when compiling or reviewing ASS investigation reports and ASS EM plans.

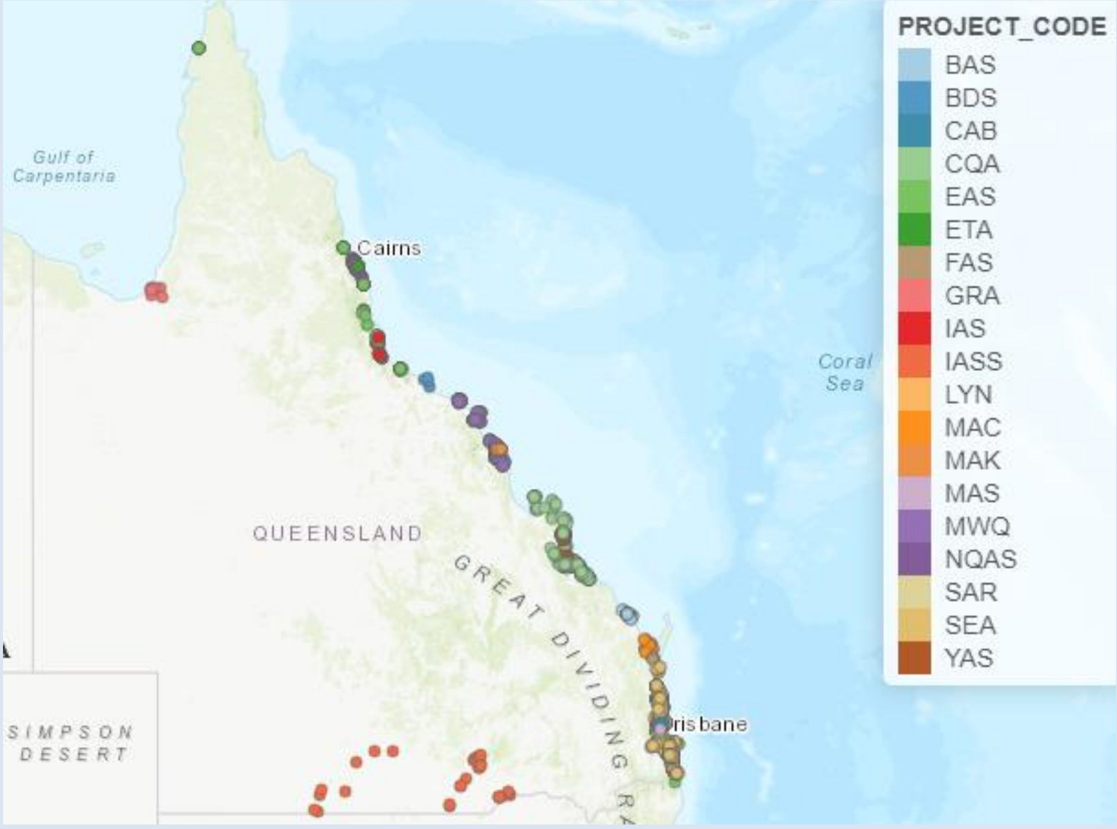
The risk assessment must consider the nine ASS management principles (see Section 2), particularly the first and lowest-risk principle of avoidance, and must include a discussion of the treatment category (per Section 3.3) and liming rates (if relevant).

*Note: The National ASS Identification and Laboratory Methods Manual (Sullivan et al. 2018b) describes laboratory methods which can be used to conclusively identify the presence or absence of ASS, to quantitatively assess the associated hazards, and includes a section on interpretation of laboratory results.  The 2004 Queensland Laboratory Methods Guidelines and Australian Standard AS4969 also include the option of analysing soil using the Suspension Peroxide Oxidation Combined Acidity and Sulfur (SPOCAS) method, which can provide additional information to aid with interpretation of results. If choosing SPOCAS analysis, the methods to calculate Net Acidity and liming rates must be consistent with the definitions contained within the 2018 National ASS Guidance Material.*

**ASS Tip 3: Existing ASS Information**

The Queensland Government has completed ASS mapping for many coastal areas of Queensland with scales ranging from 1:25 000 to 1:100 000. Whilst these mapping scales are not suitable for property scale ASS investigations, the information can be used to supplement applicant collected data. This data can also be used by assessing officers to validate the results of ASS investigations.

The reports and publications are available from the Queensland Department of Environment, Science and Innovation Library catalogue and the Publications Portal. The Spatial data (mapping and site data) can be viewed from the Queensland Globe and downloaded from the spatial catalogue at QSPATIAL. The National ASS mapping can also be viewed from the Queensland Globe. More than 5700 ASS soil profile descriptions are publicly available on the Queensland Globe, the majority of which also have laboratory data. Refer to Queensland soils website for a step-by-step guide to accessing soil information from the Globe. The figure below shows the spatial distribution of ASS sites in Queensland.



Further information is available at the Queensland Government ASS website.

The ASS and groundwater investigations are required to provide information on the environmental setting, location of and depth to ASS, the Net Acidity present in the soil, and groundwater characteristics. The latest *Queensland ASS Sampling Guideline* contains further information on ASS investigations. Successful ASS management depends on the results of the investigation—and results from the investigation help to determine the most appropriate management strategy for a site.

If the groundwater or the surface drainage patterns are to be disturbed (See Table A3-2), and ASS are present, there is potential for acidification and release of contaminants (e.g. metals, metalloids and nutrients) into the soil and groundwater resources. An assessment of the hazards and risks associated with any groundwater disturbance that also takes into consideration potential offsite impacts is required.  The investigation will need to characterise the groundwater, evaluate alternatives to dewatering, minimise the impacted area, and monitor before and after any dewatering.  Refer to the *Guidance for the dewatering of acid sulfate soils in shallow groundwater environments* (Shand *et al*. 2018) for information on risk assessments and management strategies for groundwater dewatering.

Small disturbances in sensitive areas can still have considerable impacts if not managed appropriately.  Impacts can also be cumulative where several smaller disturbances occur in a catchment.  Proponents and regulators should seek to avoid or minimise situations where multiple small ASS disturbances could create complex management issues involving many stakeholders.  For more information on small disturbances, refer to Section 3.4.1 and Section 7.5.

Soil texture or sediment particle size distribution also affects the disturbance risk.  Coarse-textured sands containing ASS (e.g. hypersulfidic sands) and sulfidic peats are particularly vulnerable to rapid oxidation due to their relatively higher permeability and often negligible (or slowly acting) acid buffering capacity.  Water also moves through coarse material quickly, which may promote the migration of ASS reaction products from their source and also create large volumes of contaminated leachate.  Peaty or organic soils may have high acidity, part of which may be non-sulfidic.  They are commonly low-pH soils and hence do not have effective acid buffering capacity but may provide a natural flora and fauna specific environment that needs to be maintained.

Fine-textured soils, such as medium to heavy clays or silty clays tend to oxidise at a slower rate than sandy soils.  The clays may also provide a higher buffering capacity (see ASS Tip 15) against pH change, but clay soils often have much higher sulfide levels than sandy soils.

## 3.1 Action criteria, Net Acidity and ASS management

Action criteria, in conjunction with the volumes of disturbance involved (Table 2) define the acidity levels beyond which ASS require management.  Action criteria are based on the soil's 'Net Acidity'.  Soils with Net Acidity below the action criteria may still be ASS but may not require management.

Net Acidity is calculated as the sum of Potential Sulfidic Acidity plus Actual Acidity plus Retained Acidity[6], that is:

***Net Acidity = Potential Sulfidic Acidity + Actual Acidity + Retained Acidity***

Acid Neutralising Capacity (ANC) is only included in the quantification of Net Acidity when the effectiveness of a soil material's measured ANC has been corroborated by other data that demonstrates the soil material does not experience acidification during complete oxidation under field conditions[7].  The ANC of ASS that are partially or completely self-neutralising soils due to naturally occurring calcium carbonate require corroboration to assess the effectiveness of any neutralising capacity (see ASS Tip 19).

When ANC has been corroborated appropriately, Net Acidity is calculated as:

***Net Acidity = Potential Sulfidic Acidity + Actual Acidity + Retained Acidity – Acid Neutralising Capacity***

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[6] Net Acidity was previously defined as the sum of Existing Acidity (Actual + Retained) plus Potential Acidity minus Acid Neutralising Capacity (ANC).  With the release of the 2018 National ASS Guidance material, there is now a national definition.

[7] Kinetic tests to corroborate ANC are described in the *National Acid Sulfate Soils Identification and Laboratory Methods Manual* (Sullivan *et al*. 2018b).

The action criteria are calculated in equivalent acidity units (mol $H^+$/t) or equivalent sulfur units (%S)[8].

As clay content tends to influence the soil's natural buffering capacity, the action criteria for smaller disturbances (≤1000 t) are grouped into three broad texture categories—coarse, medium and fine. The action criteria for projects disturbing more than 1000 t of ASS are set at the lowest Net Acidity value, irrespective of texture. *Note: the weight of the material being disturbed is based on the wet weight, not oven dry weight.*

The **highest laboratory result(s)** identified during the ASS investigation should always be used to decide if the relevant action criterion level has been met or exceeded. Using the average or mean of a set of results is not appropriate or acceptable. However, all of the laboratory results should be considered to determine the liming rates and appropriate management based on its risk categorisation (see Section 7.3.6 and Table 3)[9].

**Table 2: Texture based acid sulfate soil action criteria**

| **Type of material** | | **Net Acidity** | | | |
|---|---|---|---|---|---|
| | | **1–1000 t material disturbed** | | **>1000 t material disturbed** | |
| *Texture range (NCST 2009)* | *Approx. clay content (%)* | *Equivalent Acidity (mol $H^+$/t)* | *Equivalent Sulfur (%S)* | *Equivalent Acidity (mol $H^+$/t)* | *Equivalent Sulfur (%S)* |
| *Coarse: sands to loamy sands and peats* | <5 | 18 | 0.03 | 18 | 0.03 |
| *Medium: clayey sands to light clays* | 5–40 | 36 | 0.06 | | |
| *Fine: light medium to heavy clays and silty clays* | >40 | 62 | 0.10 | | |

*Note: All Net Acidity results are on an oven-dry basis.*

When calculating the total amount of material to be disturbed, the calculations must include the ASS material exposed by groundwater drawdown if any large-scale dewatering and/or drainage works are proposed. This is the mass of ASS materials contained within the groundwater cone of depression (refer to Section 10.1 and Shand *et al.* 2018).

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[8] In previous guidelines, a combination of symbols and abbreviations has been used to define whether an analytical result is a direct measurement of acid or sulfur content, or a derived measure (expressed in 'equivalent units' for convenience of calculation). For example, $S_{CR}$ (%S) is a direct measure of reduced inorganic sulfur, which theoretically should produce acid on oxidation. If $S_{CR}$ (%S) is converted into equivalent acid units, this conversion is indicated by the prefix 'a-' resulting in a-$S_{CR}$ (mol $H^+$/t). Conversely, if TAA (mol $H^+$/t), which is a direct measure of acidity, is converted into equivalent sulfur units, this conversion is indicated by the prefix 's-' resulting in s-TAA (%S). Further examples are defined in the *Laboratory Methods Guidelines*, Section F, Codes. *Note: The 2018 National ASS Guidance material presents laboratory results in acidity units with no references to the prefixes. This approach has been followed for these guidelines.*

[9] See Section 7.6 for information on non-sulfidic acidic soils and the action criteria.

**ASS Tip 4: Retained acidity calculations**

There are two methods used to determine Retained Acidity—$S_{NAS}$ and $S_{RAS}$. The results from these methods need to be converted into equivalent units before using them in Net Acidity calculations. When calculating Retained Acidity (SRA) one of the following equations should be used:

SRA (mol $H^+$/t) = $S_{NAS}$ (%) x 623.7 x 0.75 or

= $S_{RAS}$ (%) x 623.7 x 0.75

SRA (%S) = $S_{NAS}$ (%) x 0.75 or

= $S_{RAS}$ (%) x 0.75

**ASS Tip 5: Calculation of $S_{NAS}$ and $S_{RAS}$**

At the time of publication of the *Soil Management Guidelines V5.1,* there is a misprint in the correction factor for Net Acid Soluble Sulfur ($S_{NAS}$) calculations as documented in the *2018 National ASS Guidance material*. $S_{NAS}$ calculations should adhere to the following:

$S_{NAS}$ (%) = ($S_{HCl}$ – $S_{KCl}$) x 2.0

*Note: The correction factor of 2.0 should also be applied to $S_{RAS}$ when being used in Net Acidity calculations.*

It is acknowledged that this method for Retained Acidity determination is likely to produce conservative estimates for some materials (e.g. for highly organic soils), although this is less likely to be the case for $S_{RAS}$. However this approach should be followed until further refinements to the methodology are approved.

## 3.2 Suitably skilled and experienced person in ASS science

For ASS disturbances greater than 1000 tonnes and/or for disturbances affecting groundwater, a suitably skilled and experienced person in ASS science must conduct the ASS investigation, risk assessment and develop the EM plan. This person will:

- possess an appropriate tertiary degree that includes specialisation in soil science, hydrology, geochemistry and/or environmental engineering.
- understand the geochemistry of local ASS landscapes for the purpose of mapping, describing, sampling and managing the impacts from disturbing ASS; and
- be competent in the description of soils in accordance with the latest version of the *Australian Soil and Land Resource Survey Field Handbook* and/or AS1726:2017.

Such a person would be a Certified Professional Soil Scientist (CPSS), a Registered Soils Practitioner in ASS (RSP-ASS), or an accredited environmental scientist/engineer/or equivalent with 10 years of experience in ASS. Advice from other specialists may also be necessary, for example, hydrogeologists for groundwater disturbances and geotechnical engineers for filling disturbances.

**ASS Tip 6: Registered Soil Practitioner – Acid Sulfate Soil**

In 2023, Soil Science Australia introduced the Registered Soil Practitioner – Acid Sulfate Soil accreditation program. This accreditation is for soil practitioners that have demonstrated a high level of technical competence in the assessment and management of ASS (with a minimum of five years substantial workforce experience in this field). To maintain accreditation there is a commitment to ongoing professional development to ensure that the most relevant and up-to-date soil science knowledge is applied and evolves with the best available science. There are two pathways to RSP-ASS accreditation; one for soil professionals that prepare ASS investigation reports and ASS management plans, and one for those that assess these reports and plans.

**ASS Tip 7: Independent third-party review**

Regulatory decision makers have the option of requiring independent review of all management proposals (similar to the auditing provisions used in Contaminated Land assessments) to confirm that risks to the environment have been eliminated. A statement of uses or activities for which the site is suitable should be included.

As part of Quality Assurance (QA) a principal contractor and/or project manager may require a contractor to provide Quality Control (QC) or validation reports as a means of verifying that ASS have been appropriately managed, including integrating monitoring and reporting within EM plans.

This can be required as a condition of development approval or can be submitted when the development application is lodged. Independent third-party review could also be a component of the closure reporting for the site.

Within the contractual arrangements, there should be a mechanism for facilitating remediation measures and immediate reporting of any potential or actual environmental harm.

## 3.3 Risk categorisation to guide management planning

Table 3 can be used to quickly evaluate the environmental risk posed by a planned disturbance. The table contains pre-calculated treatment amounts, based on the use of pure agricultural lime (i.e. $CaCO_3$) for disturbances of a given tonnage and laboratory-determined Net Acidity.

*Note: ANC is not taken into consideration in the calculations of this table.*

The table has been divided into five risk-based treatment categories (low, medium, high, very high and extra high—explained in detail in Sections 3.4.1 to 3.4.5). Note that environmental risk increases in line with the level of treatment needed. Other factors will also influence the level of treatment required, such as:

- the nature of the works to be undertaken
- the staging and duration of construction
- the soil characteristics (e.g. variability of sulfide concentrations, soil bulk density, physical characteristics such as texture, acid neutralising capacity)
- surface and subsurface hydrology
- sensitivity of the surrounding environment, and
- the history of the site.

Disturbance volumes may need to include any ASS surrounding an excavation that may be exposed to air during site works but must be converted to tonnage by multiplying by the bulk density before referring to Table 3.

The tonnes of pure fine $CaCO_3$ required to treat the total disturbance can be read from Table 3 at the intersection of the mass of soil (in tonnes) [rows] and the Net Acidity [column]. Where the exact weight or soil analysis figure does not appear in the heading of the row or column, interpolate between the stated values.

*Note that Table 3 assumes use of a material with 100% neutralising value (NV), but commercially available products including aglime have lower neutralising values.*

Before final treatment levels are determined, the figures in Table 3 will need to be adjusted to account for the neutralising value of the treatment material available (whether it is aglime or some other neutralising material).

**ASS Tip 8: Use of the term 'lime'**

Some caution is advised when reading literature related to ASS management. 'Lime' can refer to several substances, including calcium oxide (Burkart *et al.*1999), calcium hydroxide (Harris *et al.* 2004), and calcium carbonate. In Queensland, the Agricultural Standards Regulation 1997 sets a broad definition of the term, calling it '*a substance consisting mainly of calcium or magnesium carbonate, oxide or hydroxide, or a combination of calcium or magnesium carbonate, oxide or hydroxide, for decreasing the acidity of soil'*. In this document, use of the term 'lime' is avoided due to its loose definition. 'Aglime' is defined more stringently in this document, and always refers to a substance that is ≥98% calcium carbonate by weight, with a particle size <0.5 mm. 'Hydrated lime' or 'slaked lime' is calcium hydroxide. Calcium oxide is sometimes referred to as 'burnt lime' or 'quicklime'.

Always confirm the chemical makeup of the exact substance under discussion before interpreting the literature. It is also prudent to test any neutralising materials purchased to confirm their composition and purity (including presence of metal contaminants) as well as their particle size.

Instructions for calculating lime application rates are contained in ASS Tip 18. For information about appropriate laboratory methods to measure acidity, refer to the *National acid sulfate soils identification and laboratory methods manual*, Australian Standard AS4969 and/or the *2004 Queensland Laboratory Methods Guideline*.

Management options besides neutralisation can be used to treat ASS. For example, material may be hydraulically separated or strategically reburied[10]. The pure $CaCO_3$ requirement is used as a surrogate measure of risk because:

- it allows the treatment category to be easily selected by reading from Table 3
- it ensures that the proponent has a level of awareness of the potential cost of neutralising agent that may be required if other management practices are not effective
- it enhances the awareness of the proponent about the 'reality' of the extent and risk of the disturbance that they are planning (e.g. it is easier for most people to visualise the management needed to mix 25 t of $CaCO_3$ through 900 t of soil than it is to conceptualise the potential harm that may result from the acid that may be generated by 900 t of soil containing 0.6 %S).

See Section 7.3.4 for further information on calculating liming rates.

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[10] See Sections 8 and 9 for more detail on hydraulic separation and strategic reburial.

**Table 3: Estimating treatment categories and pure $CaCO_3$ required to treat the total weight of disturbed ASS, based on Net Acidity of soils**

| **Disturbed ASS (t)$^2$** | **Net Acidity, expressed in %S and mol $H^+$/t units$^1$** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **0.03**<br>*18* | **0.06**<br>*36* | **0.1**<br>*62* | **0.2**<br>*125* | **0.4**<br>*250* | **0.6**<br>*375* | **0.8**<br>*500* | **1**<br>*625* | **1.5**<br>*940* | **2**<br>*1250* | **2.5**<br>*1560* | **3**<br>*1870* | **4**<br>*2500* | **5**<br>*3120* |
| **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 |
| **10** | 0 | 0 | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.7 | 0.9 | 1.2 | 1.4 | 1.9 | 2.3 |
| **50** | 0.1 | 0.1 | 0.2 | 0.5 | 0.9 | 1.4 | 1.9 | 2.3 | 3.5 | 4.7 | 5.9 | 7.0 | 9.4 | 12 |
| **100** | 0.1 | 0.3 | 0.5 | 0.9 | 1.9 | 2.8 | 3.7 | 4.7 | 7.0 | 9.4 | 12 | 14 | 19 | 23 |
| **250** | 0.4 | 0.7 | 1.2 | 2.3 | 4.7 | 7.0 | 9.4 | 12 | 18 | 23 | 29 | 35 | 47 | 59 |
| **500** | 0.7 | 1.4 | 2.3 | 4.7 | 9.4 | 14 | 19 | 23 | 35 | 47 | 59 | 70 | 94 | 117 |
| **1000** | 1.4 | 2.8 | 4.7 | 9.4 | 19 | 28 | 37 | 47 | 70 | 94 | 117 | 140 | 187 | 234 |
| **2000** | 2.8 | 5.6 | 9.4 | 19 | 37 | 56 | 75 | 94 | 140 | 187 | 234 | 281 | 374 | 468 |
| **5000** | 7.0 | 14 | 23 | 47 | 94 | 140 | 187 | 234 | 351 | 468 | 585 | 702 | 936 | 1170 |
| **10 000** | 14 | 28 | 47 | 94 | 187 | 281 | 374 | 468 | 702 | 936 | 1170 | 1404 | 1872 | 2340 |
| **50 000** | 70 | 140 | 234 | 468 | 936 | 1404 | 1872 | 2340 | 3510 | 4680 | 5850 | 7020 | 9361 | 11701 |
| **100 000** | 140 | 281 | 468 | 936 | 1872 | 2808 | 3744 | 4680 | 7020 | 9361 | 11701 | 14041 | 18721 | 23401 |

| | |
|---|---|
| **L** | Low treatment (<0.1 t $CaCO_3$)$^3$ |
| **M** | Medium treatment (0.1 to 1 t $CaCO_3$) |
| **H** | High treatment (1 to 5 t $CaCO_3$) |
| **VH** | Very High treatment (5 to 25 t $CaCO_3$) |
| **XH** | Extra High Treatment (>25 t $CaCO_3$) |

**TABLE NOTES**

1. Net Acidity is the sum of the Potential Acidity plus Actual Acidity plus Retained Acidity. Potential Acidity is measured using Chromium Reducible Sulfur ($S_{CR}$) or Peroxide Oxidisable Sulfur ($S_{POS}$). For samples with pH <6.5, the Actual Acidity must also be measured using Titratable Actual Acidity (TAA). The Retained Acidity of soils with pH<4.5 and/or if jarosite or other insoluble sulfate minerals must be estimated using calculations based on Net Acid Soluble Sulfur ($S_{NAS}$) or Residual Acid Soluble Sulfur ($S_{RAS}$). If the ANC of the soil is corroborated by appropriate testing (e.g. via slab incubation tests), the ANC can be used in Net Acidity calculations.
2. An approximate soil weight (tonnes) can be obtained by multiplying the volume of soil (in cubic metres, $m^3$) by bulk density (BD, t/$m^3$). Dense fine sandy soils may have a BD up to 1.8, and hence 100 $m^3$ of such soil may weigh up to 180 t. If soil BD is unknown, use 1.7 t/$m^3$ or refer to Table 5.1 in Sullivan *et al*. (2018b). In these calculations, figures should be converted to dry soil mass, since laboratory results are reported on a dry weight basis.
3. Application amounts are for pure fine $CaCO_3$, assuming a neutralising value (NV) of 100% and using a safety factor of 1.5. A factor that accounts for Effective Neutralising Value must be used for commercial grade aglime. See ASS Tip 18.

## 3.4 Treatment categories

The treatment categories in this section are based on the weight of soil to be disturbed and its Net Acidity. The categories relate to managing risk by neutralisation of ASS so that there is no adverse impact on the receiving environment.

*Note: If the disturbance involves groundwater dewatering*[11] *or if the site is close to an environmentally sensitive area/acidophilic ecosystem (even if <5 t of* $CaCO_3$ *treatment is required), then the disturbance will need to be treated as per Section 3.4.5, and an EM plan will be required.*

*Note: See Section 7.5 for more information on small volume disturbances of <100* $m^3$.

### 3.4.1 Low level of treatment – Category L

For disturbances of ASS requiring treatment with less than 0.1 t of fine $CaCO_3$ as per Table 3, the management should ensure that:

- soils are treated with an amount of neutralising agent that will counter their Net Acidity (up to the equivalent of 0.1 t of fine $CaCO_3$, e.g. five x 20-kilogram bags of fine aglime, available from hardware or agricultural supply stores). Thorough mixing of the aglime is not required.
- site run-on, runoff and infiltration of water and leachate that is percolating through the soil is managed (any bunding must be made from non-ASS materials)
- document the ASS management strategies that were implemented on site and include photographic records. These may need to be provided to the regulatory decision maker upon request.

### 3.4.2 Medium level of treatment – Category M

For disturbances of ASS requiring treatment with 0.1 t to 1 t of fine $CaCO_3$ as per Table 3 (where the seasonally lowest watertable elevation will not be altered), the management should ensure that:

- soils are treated with an amount of neutralising agent that will counter Net Acidity (up to the equivalent of 1 t of fine $CaCO_3$)
- the neutralising agent is thoroughly mixed with the soil, but verification testing is not required.
- site run-on, runoff and infiltration of water and leachate that is percolating through the soil is managed (any bunding must be made from non-ASS materials)
- document the ASS management strategies that were implemented on site and include photographic records. These may need to be provided to the regulatory decision maker upon request.

### 3.4.3 High level of treatment – Category H

For disturbances of ASS requiring treatment with >1 t to 5 t of $CaCO_3$ as per Table 3 (where the seasonally lowest watertable elevation will not be altered) management should ensure that:

- more detailed plans of disturbance and detailed ASS investigation reports are provided to the regulatory decision makers
- soils are treated with an amount of neutralising agent that will counter their Net Acidity (up to the equivalent of 5 t of fine $CaCO_3$)

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[11] Groundwater dewatering is defined in the Glossary.

- the neutralising agent is thoroughly mixed with the soil
- laboratory tests to verify that the ASS have been properly treated and that neutralising material has been thoroughly mixed with the soil
- the site is bunded using non-ASS material to divert run-on and collect all site runoff during earthworks
- pH of any pools of water collected within a bund or sump (particularly after rain) is monitored and treated appropriately before release or reuse to keep pH in the range 6.5 to 8.5 (or as per site-specific conditions)
- a guard layer of neutralising material is applied to treatment pad surfaces to help intercept and neutralise leachate from ASS
- all leachate from treatment pads and/or discharge water from excavations should be contained in a sump, and must meet acceptable standards of pH, oxygen, metal content (particularly iron and aluminium), and turbidity prior to release
- document the ASS management strategies that were implemented on site and include photographic records. These may need to be provided to the regulatory decision maker upon request.

### 3.4.4 Very high level of treatment – Category VH

For ASS disturbances requiring treatment with >5 t to 25 t of fine $CaCO_3$ as per Table 3, (and no alteration of the seasonally lowest watertable elevation is involved) then the proposed management should include, but not be limited to:

- more detailed plans of disturbance and ASS investigation report (using a higher laboratory analysis intensity if minimal laboratory analysis was undertaken)
- treating soils according to their Net Acidity with the appropriate amount of neutralising agent (up to the equivalent of 25 t of fine $CaCO_3$)
- laboratory tests to verify that the ASS have been properly treated and that neutralising material has been thoroughly mixed with the soil
- substantial bunding of the site using non-ASS material to divert site run-on and collect all site runoff during earthworks
- monitoring the pH of any pools of water collected within the bund (particularly after rain). Water must be treated to keep pH in the range 6.5 to 8.5 (or as per site-specific conditions)
- treatment pads are designed as per Section 7.4
- preventing infiltration of water and/or leachate from passing through ASS to groundwater using impermeable materials. Otherwise, apply extra layer of neutralising material to intercept and neutralise leachate from ASS
- all leachate from treatment pads and/or discharge water from excavations should be contained in a sump, and must meet acceptable standards of pH, oxygen, metal content (particularly iron and aluminium), and turbidity prior to release
- providing a simple but thorough EM Plan that meets the requirements of the regulatory decision makers
- on completion of works, provide documentation of ASS management strategies to the regulatory decision makers in the form of a simple closure report (see Section 12), including information on the final placement/use of disturbed soil.

### 3.4.5 Extra high level of treatment – Category XH

For ASS disturbances requiring treatment with more than 25 t of $CaCO_3$ as per Table 3, a comprehensive EM Plan must be formulated, and a risk assessment undertaken. The EM plan must consider groundwater dewatering if the seasonally lowest watertable level will be altered (see Table A3-2 and A3-3 for required management levels and monitoring aspects). Detailed closure reporting will be required as part of this process (see Section 12). All EM plans must be completed by a suitably skilled and experienced person in ASS science (Section 3.2). See Appendix 2 for information on minimum requirements for EM plans.

# 4. Management strategies

As outlined in the management principles 1 and 2 (see Section 2), the preferred strategy to deal with ASS is avoidance (see Section 5). **Avoiding the disturbance of ASS should be considered at all sites.** This may necessitate a review of the construction design or layout. There will be situations where disturbance is unavoidable. For these situations, the next management strategy to be considered is minimisation of disturbance (Section 6). Once methods of minimising disturbance have been fully explored, the following risk-based management strategies are preferred for dealing with any unavoidable disturbances:

- neutralisation of ASS (Section 7)
- hydraulic separation on its own or in conjunction with dredging (Section 8)
- strategic reburial of PASS at least one metre deeper than the seasonally lowest watertable elevation, or several metres below permanent standing water (Section 9). This method alone is not suitable for soils with significant Actual and/or Retained Acidity.

Measures to minimise drainage and the extent of fluctuations beyond the seasonally lowest watertable elevation, and measures to ensure discharge waters are monitored and treated (when necessary) will be required where groundwater dewatering is proposed. Refer to Sections 7.1.2 and 10.1, and the *Guidance for the dewatering of acid sulfate soils in shallow groundwater environments* (Shand *et al*. 2018).

The management strategies are not ranked in any order of effectiveness or preference, as the best management for a particular project will be site-specific. Even though the above management strategies are preferred, they still carry environmental risks and may not be suitable for every site.

Sections 6, 7, 8 and 9 outline the significant environmental risks and management considerations associated with the strategies. Project managers will need to decide whether the issues raised in these sections apply to their sites. These sections are not intended to be comprehensive, and sometimes other environmental risk or management considerations may be relevant. Therefore, all projects should be subject to a risk assessment to determine the level of environmental risk for the site.

Higher-risk management strategies documented in Section 10 include groundwater dewatering and drainage, stockpiling ASS, basements below the watertable, strategic reburial of soils with Actual and/or Retained Acidity, vertical mixing and pre-excavation neutralisation. Strategies described as unacceptable in Section 11 include above ground capping, hastened oxidation, seawater and groundwater neutralisation, and unconfined groundwater dewatering.

Management strategies other than those listed as preferred may be considered, but risks are higher where there is limited information on their successful use. Innovative management strategies that are neither described in this guideline nor precluded are welcome but will need to be scientifically justified. A pilot trial may be required for undocumented treatment methods.

In a new disturbance, any Net Acidity should be fully treated. The definition of disturbance includes *in situ* soils subjected to changes in groundwater regime (e.g. by filling or draining). The receiving environment (e.g. seawater or groundwater) should not be relied upon as a primary means of treatment.

Developments in the ‘extra high’ treatment category (Section 3.4.5) may need to be staged to make sure that the disturbance is manageable. To reduce the level of risk further, a variety of management strategies may be used to provide the best management for the specific soil type or environmental setting. For example, hydraulic separation might be used to treat soils extracted from sandy areas; fine-textured soils with low sulfide content could be neutralised with a suitable agent; and areas with high levels of sulfides and heavy, hard-to-treat clays could be strategically reburied or their disturbance avoided in the planning and design of a proposal. Other strategies will also need to be developed to manage the impacts from smaller disturbances (such as infrastructure trenching and drain cleaning—see Sections 6.8 and 6.9).

In managing risk and selecting preferred management strategies in situations where all relevant approvals have been obtained, proponents are responsible for deciding that the project can be conducted in a way that will not result in environmental harm. In cases where some form of approval permitting a level of impact has been issued under the *Environmental Protection Act 1994*, the developer or operator will have to meet specific performance requirements and provide a greater level of assurance for the impact to be accepted by government.

Where managing the ASS has been poorly planned and executed, the risks to the environment are often high, and the costs and difficulty of remediation will be extreme. Appendix 6 includes three ASS remediation case studies that demonstrate the complexity and longevity of such projects.

**ASS Tip 9: ASS and climate change**

Researchers in South Australia have investigated changes in the biogeochemical cycling of iron, sulfur and carbon in coastal wetland soils, resulting from sea level rise induced seawater inundation. The results indicate that when soils are inundated for long periods of time (>1.5 years), a slowing of iron reduction is observed as reactive iron is progressively consumed by microbially driven reductive processes. However, where abundant sulfate is available, microbially mediated sulfate reduction continues, as long as sufficient available organic matter is present to drive the process. In the absence of free $Fe^{2+}$ from iron reduction processes, the sulfide produced from *in situ* sulfate reduction no longer has anything to bind with and thus can accumulate in porewater. Known as ‘sulfidisation’, this process can be toxic in some ecosystems. As sea level rise begins to impact coastal wetland soils, sulfidisation is likely to become more commonplace, especially in areas where total organic carbon is high and where reactive iron can be depleted over time (Leyden *et al.* 2023).

There is increasing evidence that changes to wetting-drying cycles and other associated climatic changes (such as increased drought and fire severity) are significantly changing the properties of ASS (e.g. the rates of redox processes/changes, acid-neutralising, buffering mechanisms and sulfide oxidation etc) (Fanning *et al.* 2017). Drought, climate variability and resource management can lower surface and groundwater levels and decrease soil moisture in coastal and inland landscapes, enabling the oxidation of ASS. Peat fires can burn below the surface for months/years and can release noxious levels of sulfur dioxide and particulates (Blake *et al.* 2009). The subsequent acidification of soils results in significant environmental issues. It is likely that management mechanisms will struggle to manage the complexity of these scenarios. See Appendix A6-2 for an example of the drought induced acidification event in the Lower Lakes of South Australia during the Millennium Drought of 1997–2010.

# 5. Avoidance strategies

The first principle of ASS management is to avoid the disturbance of ASS wherever possible. Avoiding the disturbance of ASS is always preferred over mitigation and active management. Avoidance carries the least environmental risk, as iron sulfides are unreactive while they remain in an anoxic, preferably anaerobic (reducing) environment. However, just because an ASS is under water does not necessarily mean that there is no risk, as water can contain and transport dissolved oxygen. Avoidance is also often the cheapest option. The risks and costs associated with long-term discharge of acid-, iron- or aluminium-containing leachate, the potential for degradation of aquatic ecosystems, remediation costs, delays associated with development approvals, and the potential long-term management and monitoring needs may outweigh the benefits of major earthworks.

To apply this principle sensibly, a thorough site-wide ASS investigation completed in accordance with the latest *Queensland ASS Sampling Guidelines* must be conducted before any development plans are considered. The results of the investigation can be used by a proponent to avoid disturbing higher-risk areas, rather than trying to employ higher-risk management strategies to address site constraints. This reduces overall environmental risk and is commonly more cost-effective.

In the past, it was not customary to avoid disturbing ASS, especially since few people accepted that ASS disturbance would cause environmental problems. Higher community expectations leading to increasingly stringent government policy now require adherence to this avoidance principle. Documented evidence should be presented, showing that avoiding ASS disturbance has been seriously considered as the primary management approach at all sites. A sound case must be made for choosing to disturb ASS, along with a low-risk management plan that is acceptable to regulators. The following section provides guidance on when it is best to avoid ASS.

This is not to say that if a site investigation uncovers areas with Actual and/or Retained Acidity (e.g. either through natural processes, or because of historical human disturbance) then treatment should be avoided. A treatment plan for such acidified areas will need to be developed and implemented.

## 5.1 Statutory planning mechanisms to avoid ASS

The principal goals of the *National Strategy for the Management of Coastal Acid Sulfate Soils* include ‘avoid disturbance of coastal ASS’ (National Working Party on Acid Sulfate Soils 2000).

In situations where there is a high probability of ASS occurrence, state and local government planning strategies should, as far as practicable, give preference to land uses that avoid disturbance of ASS. Where disturbance cannot be avoided by these means, planning instruments should require the involvement of planning and assessment staff at a local and/or state government level to oversee proposed development in areas considered high-risk for ASS.

When determining the risk and manageability of a land use or proposal, assessors should consider whether the following features will be involved:

- large and/or deep excavations
- creation of new land (reclamation)
- dredging or similar extractive works
- major change to groundwater systems via extraction, drainage, bunding, surface sealing or placement of heavy fill
- significant change to surface drainage patterns
- temporary or permanent disturbance.

Land uses such as extractive industries, golf courses, marinas, canal estates, agriculture requiring drainage, and land uses with basements, car parking, elevator shafts or other infrastructure below ground level—which are likely to result in significant amounts of excavation, filling, or dewatering—should be avoided in areas with a high probability of containing ASS. Local and regional plans should direct such projects away from high-risk ASS areas. Where ASS occurs at a significant depth, the above land uses may not be a problem if they are unlikely to result in the disturbance of ASS layers.

At the time of writing, Queensland legislation manages disturbance of ASS through three primary mechanisms:

a) First, the *Planning Act 2016* contains provisions that oversee the creation of statutory planning instruments. These instruments contain powers to direct high-risk development works away from areas likely to contain ASS. These powers may be exercised by setting required planning controls at the local government level, and/or requiring certain development proposals be assessed and approved, conditioned, or denied by government. Under the *Planning Act 2016*, the Queensland Government delivers the state interest of ASS through local government planning schemes, with guidance available through the *State Planning Policy* (Queensland Government 2017) and the *State Planning Policy Guideline* (Queensland Government 2021). ASS is contained within the 'Emissions and hazardous activities' theme.

b) Second, the *State Development and Public Works Organisation Act 1971* deals with impact assessment and ASS for major projects, which are declared as 'coordinated projects' by the Coordinator-General.

c) Third, the *Environmental Protection Act 1994* contains provisions requiring the regulatory decision maker to consider potential impacts of ASS when considering applications to undertake activities regulated under that Act ('environmentally relevant activities').

Specific provisions also apply to ASS under the *Fisheries Act* 1994 and the *Vegetation Management Act 1999*. Australian Government approval processes can also be required under the *Environment Protection and Biodiversity Conservation Act 1999.*

**ASS Tip 10: EM plans vs EM programs**

Environmental management plans (EM plans) are often requested by local government to support a development proposal and are prepared by a proponent. The effective and documented implementation of an approved EM plan is the mechanism by which the proponent meets their *general environmental duty*.

No statutory mechanism exists for approval of EM plans, although they may be given legal standing by incorporation into a development approval as a condition (e.g. under the *Planning Act 2016*). EM plans may be simple for smaller disturbances, but the complexity increases with the level of risk for larger disturbances. See Appendix 2 for further information about EM plans.

In comparison, environmental management programs (EM programs) are a statutory tool under Part 3 of the *Environmental Protection Act 1994*. Refer to the Department of Environment, Science and Innovation for more information on EM programs.

## 5.2 Avoiding areas requiring Extra High Treatment

Where the ASS investigation has identified soil or sediment in parts of a site requiring >25 t aglime for neutralisation (i.e. the Extra High Treatment Category defined in Table 3), it is recommended best practice to design or redesign a project to avoid disturbing these soils.

In some cases, these disturbances may be manageable but not necessarily sustainable. The long-term costs may outweigh the benefits when the true expense of building treatment pads, spreading and mixing neutralising materials, generating greenhouse gases, reburying, or disposal of soil, monitoring on- and offsite, and remediating on- and offsite are calculated.

It may be feasible to place fill over these soils (see Section 6.5), however existing acidified soils may require remediation as part of development works. Management plans will be required that particularly address any hydrological or geotechnical issues, particularly any structural stability issues. Such areas can become public and open spaces, parking areas, sports grounds, or similar.

## 5.3 Avoiding ASS in sensitive environments

### 5.3.1 Sensitive wildlife

A precautionary approach is recommended when ASS underlie, are near or are hydrologically connected to the habitat of sensitive species. Avoidance is often the only effective management strategy in situations where ASS underlie habitats and ecosystems that contain sensitive wildlife or where offsite disturbances can indirectly impact upon these areas.

Coastal environments often contain areas of high biodiversity and/or species with high conservation significance—for example, aquatic fauna such as the frogs, fish and other biota that live in the low pH, organic-rich, soft waters of some coastal wetlands. These include pH-sensitive amphibians (e.g. the Wallum froglet (*Crinia tinnula*) and the Cooloola sedgefrog (*Litoria cooloolensis*))*,* as well as coastal freshwater fish like the Oxleyan pygmy perch (*Nannoperca* oxleyana) and the Honey Blue-eye (*Pseudomugil mellis)*. Disturbance and/or treatment of ASS may negatively affect these biotas.

Neutralising agents are an essential component of most ASS management proposals and the impacts of using these products in naturally soft, acidic, freshwater habitats are not adequately understood. What is known is that neutralising agents can alter naturally low pH environments that have organic-sourced acidity and can increase water hardness, causing changes to habitat that ultimately result in species, population, and ecological system shifts.

*Note: Discharge of neutralised waters into tidal creeks with a natural pH that is close to seawater should not be used as an excuse to reduce liming rates.*

**ASS Tip 11: Naturally soft, low-pH waters and neutralisation of adjacent ASS**

Disturbance of acid sulfate soils adjacent to sensitive, acidic soft water environments should be avoided since use of neutralising agents will produce leachates that raise aquatic pH, adding hardness to water and putting acidophilic ecosystems at risk. Essentially, addressing one problem will create another.

### 5.3.2 Algal blooms

The disturbance of ASS should be avoided in situations where the receiving environment is susceptible to algal blooms. Mobilisation of iron (and other nutrients of concern) by drainage of ASS and other coastal soils has been identified as a potential source of micronutrients that may trigger or sustain cyanobacterial blooms such as the toxic *Lyngbya majuscula* blooms in Moreton Bay (Pointon *et al.* 2003; Ahern *et al*. 2006; Queensland Government 2011). The State Planning Policy: State

Interest − Water Quality (Queensland Government 2017) discusses policy approaches to be implemented by local government to minimise the release of nutrients of concern, and the document mentions ASS information as a key decision-making input.

### 5.3.3 Groundwater-dependent ecosystems

The disturbance of ASS should be avoided when the site is adjacent to, or hydrologically connected to, a groundwater-dependent ecosystem that may be drained because of any soil disturbance on site. Management strategies or disturbances that alter the hydrology of adjacent ecosystems may cause temporary or permanent impacts due to the potential oxidation of ASS in dewatered, drained environments. It can be difficult to accurately identify preferred groundwater flow paths to offsite areas without costly and extensive investigations. As such impacts can occur offsite, they can be difficult to manage and monitor. The key to managing the impacts relates to the retardation of oxygen transport to the soils, and this is more difficult when the soils that will be drained are located offsite. Several types of coastal wetland are host to groundwater-dependent ecosystems such as the patterned fens, black water ecosystems and perched lakes of the Cooloola region and K’gari.

# 6. Minimisation of disturbance

Where a sound case for the disturbance of ASS has been made, then efforts must be made to minimise the extent of the disturbance.  Completing a detailed ASS investigation is essential for minimisation of disturbance to be effective.  This includes an assessment of the concentration and spatial distribution of Net Acidity, and assessment of groundwater characteristics, including a consideration of the ASS that will be exposed to oxygen by groundwater dewatering and/or drainage works.

Refer to the latest *Queensland ASS Sampling Guidelines* and the *Guidance for the dewatering of acid sulfate soils in shallow groundwater environments* (Shand *et al.* 2018).  Once the site has been adequately characterised, strategies that minimise the disturbance can be investigated.  These include, but are not limited to, those discussed below.

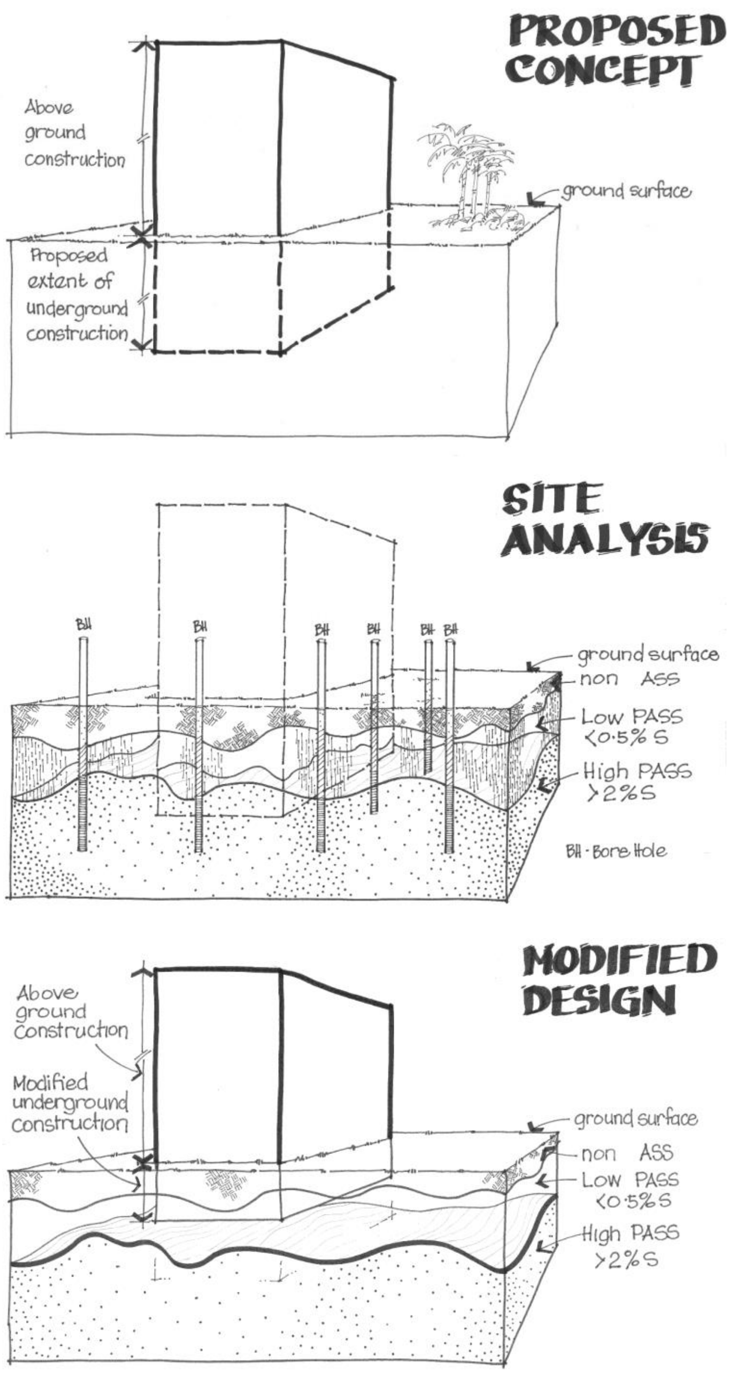
## 6.1 Redesign earthworks layout

Net Acidity results can be low or negligible in some parts of a site, but high elsewhere.  An effective minimisation strategy is the redesign of earthworks or agricultural enterprises to focus disturbances in those areas containing low or negligible levels of Net Acidity.  Agricultural enterprises should avoid cropping soils with ASS close to the surface.

Minimisation is applicable to large construction sites containing variable soil types.  Earthworks should be designed so that excavations avoid or minimise disturbance of areas with appreciable Net Acidity.  These areas should be reserved for minimum impact uses such as ‘open space’ or wildlife corridors.  Conceptual diagrams and CSMs are useful tools to display this management strategy, and for consultants to visualise on-site management (see Figure 1, Appendix A6-1 and A6-2).

Unsuitable soil texture is another reason to avoid certain areas since soil texture may dictate which management techniques will be lowest risk and most effective.  For example, an important consideration is how the material is to be extracted.  Sandy areas might be considered a lower risk for extraction as sandy material could be removed using a floating dredge (e.g. hydraulic separation, Section 8), minimising watertable disturbance.  In contrast, heavier textures cannot be effectively managed using hydraulic separation.  They usually require dewatering prior to extraction, which carries a risk of oxidising surrounding soil and groundwater contained within the cone of depression (see ASS Tip 29).

For redesign of earthworks to be effective, detailed ASS investigations, stratigraphic mapping of the sediments, an understanding of groundwater hydrology and potential for oxidation, and planning for future disturbance will all be necessary.



- Initial concept was a basement with two storeys of underground construction
- The site is located in a coastal area <5 m AHD
- It was agreed that a modified design was required to minimise the overall risk with the proposal

- ASS investigations were carried out as per all relevant guidelines: sampling, laboratory and groundwater dewatering
- The results showed three different layers of soil across the site: non-ASS, PASS with <0.5 %S, and PASS with >2 %S

- Due to the results of the ASS investigation, areas with high PASS were avoided and underground construction was modified
- This included a fully tanked basement with no unconfined groundwater dewatering
- Geotechnical advice was sought regarding structural stability issues
- Groundwater dewatering managed according to Section 10.1

**Figure 1: Conceptual diagram showing plans to minimise disturbance of ASS**

## 6.1.1 Adoption of specific construction methodologies and designs

Evaluating construction methodologies that reduce duration and extent of disturbances and adopting appropriate infrastructure design can significantly minimise the disturbance of ASS and associated environments. This may include using vacuum sewers for a residential development rather than gravity sewers or using caisson construction for a pump station to minimise depth of excavations, or using screw-piling instead of excavation. Simpson *et al. 2018* outline a series of options to minimise the risks to the environment during dredging operations.

As part of redesigning earthworks, alternative methods of excavation may be considered (e.g. wet excavation rather than dry). Installation of services such as pipes and cables may be accomplished using directional drilling techniques (also known as ‘micro-tunnelling’) where practical. Such techniques involve minimal disturbance of soil and groundwater and can effectively exclude oxygen from soil during service installation. Directional drilling has been used in Australia within acid sulfate soil environments, and its applicability is gaining recognition. ‘Trenchless technologies’ can reduce costs of ASS investigations, offsetting the higher costs associated with the technology (Western Australian Government 2011; DER 2015).

## 6.2 Shallow disturbances

The earthworks on a site can be designed to ensure that only shallow disturbances are undertaken. This strategy relies on a detailed understanding of the spatial distribution of ASS and is only viable in situations where sulfidic soils are located in deeper horizons within a soil profile.

## 6.3 Redesign existing drains

Existing drains can be redesigned so that they are shallower and wider so that they don’t intercept ASS. Shallow and wide drains can maintain required flow capacity and increase the efficiency of surface water drainage, while reducing the drain density (number and spacing of drains) and drain depth. Hydrological studies may be needed to design drains that are effective at removing stormwater or floodwater from the site. Catchment management implications will also need to be considered to ensure drainage modifications are compatible with upstream and downstream areas.

Laser-levelling of a paddock is a tool often used along with the redesign of existing drains to enhance surface water drainage and reduce the problematic deep drainage of ASS. Areas where ASS layers are within 0.5 m of the natural land surface should not be drained or laser levelled (Tulau 2007) unless an ASS management plan involving the incorporation of neutralising material (according to the Net Acidity) is implemented. Where ASS occurs more than 0.5 m below the natural land surface, then the vertical distance between the new land surface (including drains) and the ASS layer should be at least 0.5 m.

The relevant local government should always be consulted, and any required permits obtained before undertaking any works that may change groundwater hydrology or surface drainage patterns. Non-ASS materials should be used for drain filling. Properties (e.g. texture) and compaction of material used for filling is important—it may still act as a conduit for acidity, particularly if the sides of drains have not been lime-blanketed to intercept acidity. If this is not possible, any ASS excavated to fill drains will need to be neutralised. See Section 6.9 for drain maintenance.

**ASS Tip 12: Acid and metal export from drains**

While drainage may be necessary, drainage systems are one of the conduits for oxygen ingress to sulfidic sediment layers. This can result in acid and metal export from drained land. By decreasing the number of drains and the drain depth in a given area, the rate of acid and metal production and export should also decrease. Wide shallow drains that do not intercept ASS are preferable.

## 6.4 Minimise groundwater fluctuations

Unmanaged groundwater dewatering activities that cause groundwater fluctuations, and those that permanently lower the seasonally lowest watertable elevation are unacceptable and should be avoided as these may expose *in situ* ASS to oxygen. Acidity can be brought to the surface when the groundwater rises again, through capillary rise, or because of fill emplacement, where decreased soil void space can result in squeezing out of pore water and groundwater. Groundwater in ASS areas is often saline and high in dissolved iron, making it unsuitable for uncontrolled release to receiving environments. ASS impacts on groundwater can also present health hazards. While not a recognised issue in Queensland to date, arsenic contamination of groundwater has occurred in Western Australia (Appleyard *et al*. 2004). Activities to be avoided include:

- construction of deep drains, canals and other types of artificial water bodies that may change the watertable level
- operation of drains which do not have gates or drop boards to maintain groundwater levels
- operation of drains that cause significant water level fluctuations during dry periods
- construction of basements and other structures (e.g. car parks, elevator structures, tunnels etc) below the watertable that need ongoing pumping of sumps or installation of unconfined drainage structures to keep dry and control water ingress to underground structures
- installation of new groundwater extraction bores in ASS areas
- continuing use of existing groundwater extraction bores (and particularly increases in extraction volumes) if they will expose ASS to oxidising conditions, or if that use will result in the discharge of waters containing acid and metals to locations that may result in further contamination of the receiving environment[12]
- unconfined groundwater dewatering or drainage of construction sites, permanent structures, mines, aquaculture ponds, tunnels or sand and gravel extraction pits[13]
- dewatering for installation of infrastructure such as roads, water and sewage mains, underground cabling etc, particularly where large open trenches are involved
- diversion of overland flows, alteration to infiltration and recharge zones, which may influence groundwater quality and quantity, particularly in the longer term
- installation of subsurface drainage, including stormwater systems, which may promote localised dewatering, with the bedding sand and pipework acting as a conduit
- changes in vegetation from pasture to trees, or replacement of native vegetation with crops that can increase transpiration rates and lower the watertable during dry periods, and/or cause rises in acidic watertables
- construction of on-farm water storages, sediment or nutrient ponds, aquaculture ponds or ponded pastures in ASS.

## 6.5 Cover *in situ* soils with clean fill

If groundwater levels are not affected by earthworks, then undisturbed *in situ* PASS can be covered with clean fill. This strategy can be used to provide adequate clearance for building foundations, infrastructure trenches or other incidental excavations such as landscaping, if ASS layers are located close to the soil surface. A minimum clearance for residential development is 1.5 m. This 1.5 m clearance may comprise clean fill over an existing layer of non-ASS material. The minimum clearance may be increased because of such factors as flood levels, proposed land use, high potential acidity, likely depths of any future disturbance and/or any geotechnical issues regarding structural stability. Using clean non-ASS fill instead of treated ASS on site minimises risk. Untreated ASS should not be used as pre-load material. Refer to Section 10.2 on stockpiling ASS.

*Note: Filling on floodplains or drainage lines may interfere with floodplain hydrology, and these effects should be carefully considered. Some jurisdictions may have specific rules in place regarding floodplain management that will affect the design of a project.*

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[12] Controls on overall extraction, and local drawdown from individual bores (through licensing, metering of bore usage, ongoing monitoring) may be appropriate for state and local government to consider.

[13] Sites that need to be dewatered should involve dewatering in small, isolated cells, using containment structures such as sheet piling where practical, and ongoing monitoring should be conducted. See Section 10.1.

**ASS Tip 13: ASS and filling activities**

Filling activities may impact on *in situ* ASS and the environment by one or more of the following processes (see Figures 2 and 3):

- bringing actual ASS into contact with the groundwater via expulsion of groundwater, providing a potential transport mechanism for mobilising and transporting Actual and/or Retained Acidity and soluble metals or metalloids
- altering an acidic watertable, causing the release of acid into waterways
- displacing or extruding previously saturated PASS above the watertable and aerating these soils or sediments, thus creating actual ASS
- circular or rotational stability failures resulting in upward displacement of the softer ASS.

The potential for extrusion or heaving of gel-like sediments is site-dependent, variable and should be evaluated in a geotechnical investigation.

Loading fill on unconsolidated sulfidic sediments, especially dredge fines, can be problematic because such sediments may have high water content (up to 70−80% by volume). Under load, such materials may flow like gels, resulting in subsidence at the load point. Some of the displaced material may be pushed upwards outside the load areas into oxidising environments. In extreme situations, the fill materials may sink into or through these sediments. This is of particular concern in areas where houses, rail, roads or other heavy infrastructure are constructed on such materials. This can also be an issue in poorly managed dredging sites where dredge fines have been historically placed above the watertable and then buried under clean sands. Historic dredging sites should be investigated for the presence of such materials before making changes to land use that may cause such subsidence.

Both geotechnical and hydrological investigations may be necessary to help devise management strategies, including any pre-loading and management of potential impacts on groundwater levels and acidity.

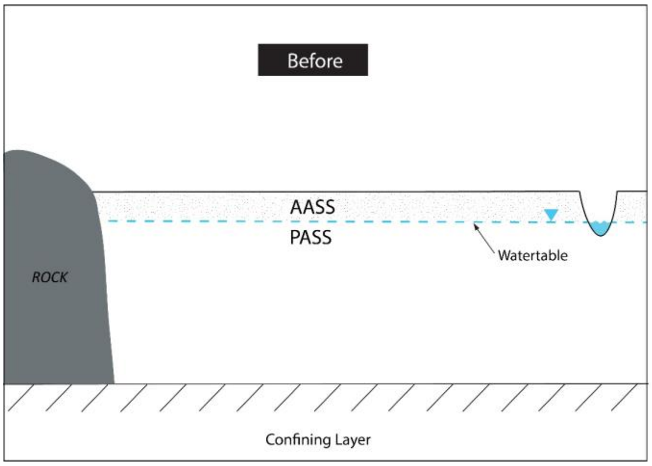

**Figure 2: Cross-section of an ASS before filling**

*AASS are above the watertable and PASS are below the watertable.*

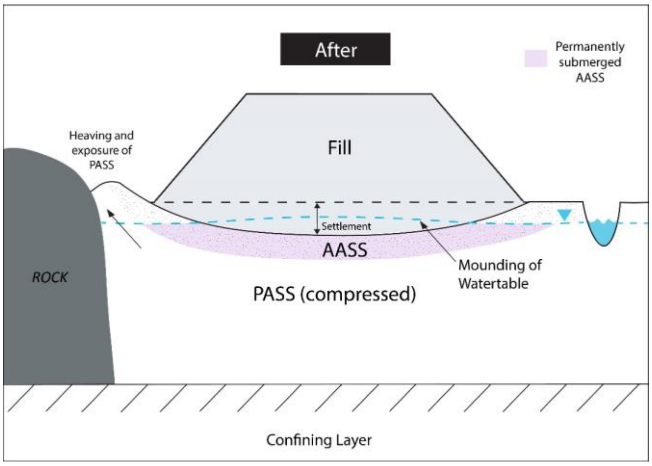

**Figure 3: Cross-section of an ASS after filling**

*The watertable is raised, AASS are brought in contact with the water. PASS and AASS are displaced above the watertable.*

*Note: The extrusion of soils above the surface depends on their load bearing capacity and fluid behaviour, properties that are not necessarily related to sulfide content or soil oxidation status.*

## 6.6 Use filling to compress saturated sediments

Filling can be used to compress and dewater saturated ASS materials before construction, while keeping the soils in anoxic conditions. This is a relatively common practice for large infrastructure projects that intersect with coastal alluvium, but time and expense may make the practice less viable for smaller projects. As the fill is loaded, there is potential for lateral displacement of the ASS.

An experienced geotechnical consultant needs to decide on the details of such works, but some general tips include:

- staging the filling activities to slowly and progressively increase the weight acting on the soil
- using shallow batters around the edges of the fill pad
- containing, treating and appropriately disposing of expressed pore waters.

The first two measures are expected to reduce the risk of lateral displacement.

Dewatering soils using wick drains is a common management strategy available when sediments need to be compressed and dewatered (see Case Study 2). Vacuum settlement (also known as vacuum consolidation) methods can potentially be employed to hasten the compression process. Vacuum settlement involves sealing the surface of the soil with an impermeable membrane and then using a pre-installed drainage network to pump air and water out of the soil, rather than waiting for it to compress under load. Such methods have been used in Europe and South East Asia and more recently in New South Wales and Queensland (NSW Roads and Traffic Authority 2006; Indraratna *et al*. 2013), but documentation of long-term success of this kind of ASS management is lacking at time of publication.

Note that where these techniques are employed, additional water management and treatment may be necessary e.g. extracted water must be treated to meet pH, metals (particularly iron and aluminium) and visual amenity targets prior to discharge, and care must be taken to properly isolate the soil to be dewatered from the surrounding environment.

*Note: These techniques do not necessarily provide a clearance layer of non-ASS or fully treated ASS material for future land uses.*

**Case Study 2: Filling at the Brisbane Airport**

Filling and surcharging have been used extensively at the Brisbane airport. Soft Holocene clay alluvium underlies the Brisbane Airport. This alluvium has a low load bearing capacity and hence compression of the alluvium was required to form a geotechnically stable base on which to enable future development. For the construction of the Brisbane Airport’s second runway, 11 million cubic metres of clean sand was dredged from the Middle Banks Borrow Area in Moreton Bay and placed on 360 ha of land to consolidate the soft alluvium. Consolidation of up to 1.8 m was required in some areas. The installation of wick drains accelerated drainage and therefore consolidation of the alluvium. The site was left to settle for a period of three years. Excess sand was then removed to achieve a final design height of RL 5.2 m (Airport Datum) for the construction of the runway.

A detailed ASS assessment of the 360 ha area was completed prior to placement of the sand fill. This included field investigations to assess the presence and extent of actual and PASS and to establish baseline groundwater quality and depth. Additionally, baseline surface water quality of the nearby Kedron Brook Floodway, the nearest receptor, was established. The baseline water quality data was used to develop site-specific performance criteria for the project.

The ASS assessment revealed a layer of actual ASS above the watertable, and a layer of PASS beneath the watertable. Based on the findings of the geotechnical assessment, it was determined that a large volume of the actual ASS layer would become permanently displaced below the groundwater table due to consolidation of the soft underlying alluvium under the fill load. Hydrogeological modelling indicated that impacted groundwater would migrate, at an increased flux, towards the Kedron Brook Floodway, and eventually Moreton Bay. Parts of Moreton Bay are listed as a Ramsar site under the Ramsar Convention.

Using information from the geotechnical assessment and field ASS investigation, the amount of acidity that would be mobilised from the actual ASS layer into the groundwater was calculated. The corresponding amount of limestone (aglime) required to neutralise the acidity was then determined. A 3.6 km-long Anoxic Limestone Drain, more commonly known as a *lime interception trench* or a *lime cut-off trench*, was designed to treat the water prior to it entering the receiving environment (i.e. Kedron Brook Floodway). The Anoxic Limestone Drain was installed prior to the commencement of filling. The prime function of the Anoxic Limestone Drain was to neutralise groundwater acidity, introduce bicarbonate alkalinity to the groundwater and to maintain redox-active metals (e.g. iron) in solution so that they do not encapsulate the limestone particles and render them ineffective.

Groundwater quality monitoring of ASS parameters was undertaken using numerous groundwater wells located between the Anoxic Limestone Drain and the Kedron Brook Floodway. Monitoring was undertaken during filling and for a period of five years following filling to monitor the performance of the Anoxic Limestone Drain and to assess groundwater quality against the established performance criteria. Surface water monitoring of the Kedron Brook Floodway was undertaken concurrently. The closure reports for the groundwater and surface water quality monitoring program concluded that the Anoxic Limestone Drain had been effective in mitigating an increase in acidic mass flux into the neighbouring Kedron Brook Floodway as a result of the filling of the ASS land.

## 6.7 Minimise disturbance with screw-piles, slurry and diaphragm walls

Screw piles or screw-piers (i.e. load bearing columns) that are driven through an ASS with low load bearing capacity can be used to provide support for surface structures (e.g. buildings, bridges) to prevent settlement. As a result the weight of the building is supported on soils of higher allowable bearing pressures at greater depths. When driven piles are used at a construction site, there is no need for the removal of geotechnically unsuitable material and the disturbance of ASS is minimised. Various other piling techniques (e.g. sheet piling, secant piling, deep soil mixing, jet grouting) can also be used to contain excavations, minimising the effect on the surrounding watertable (Wallin and Asperger 2009; Western Australian Government 2011; DER 2015). Not all techniques are capable of fully sealing an excavation pit and they should be chosen judiciously. Refer to Australian Standard AS2159-2009 – Piling Design and Installation (Standards Australia 2009) for guidance on the use of piles in soils that contain pyrite and/or are saline. It is also advisable to investigate concrete performance in sulfate-rich environments (e.g. Rajasekaran 2005; CCAA 2011) and obtain appropriate engineering advice.

Slurry walls (i.e. impermeable sub-surface structures) are often used to construct tunnels, open cuts and subsurface foundations in areas of soft soils that are close to open water or have a high watertable. The use of diaphragm walls (that are supported by bentonite or polymer mud) and methods of construction, where underground vertical walls are constructed prior to excavation, can significantly reduce the volume and extent of soil and groundwater ASS disturbance. Where dewatering is required, these techniques can reduce the extent of the cone of depression (see ASS Tip 29 and Figure 14) of the watertable, reduce the disturbance of ASS and the amount of dewatering required (DER 2015).

**ASS Tip 14: Acid sulfate soils and infrastructure**

Concrete infrastructure in ASS environments is vulnerable to rapid degradation, particularly when placed in untreated disturbed ASS or in locations where upstream ASS have been disturbed without adequate management. Acid transported by surface and groundwaters can corrode any concrete and metal reinforcing it encounters. Sulfate from pyrite oxidation can allow the formation of a number of other minerals that hasten concrete breakdown (Hobbs and Taylor 2000; Floyd *et al.* 2003; O'Connell *et al*. 2010). Reinforcing is also vulnerable to salt and acid attack. Many modern concrete products have the ability to resist sulfate attack (Rajasekaran 2005; CCCA 2011), but do not have resistance to severe acidity over the long-term. Works in ASS environments should be carried out with reference to existing guidance on construction in these areas. This should be based on expert engineering advice regarding the suitability of geotechnical and chemical properties for the intended use.

Poor placement of infrastructure in areas containing ASS can cause or worsen acidity problems by changing groundwater hydrology or surface drainage patterns, including blocking tidal water flows. As an example, a road culvert in Far North Queensland was placed across a small tidal creek but was not placed deeply enough to allow normal tidal flow—only large tides and rainfall events were able to pass the blockage. Together with another blockage caused by a nearby floodgate, this caused an adjacent area of ASS to dry out and oxidise, producing acid, iron hydroxy-sulfate minerals and sulfate salts. Although the dried area was limited in extent (<1 ha), enough acidity was generated to rapidly damage the culvert, which required replacement after less than five years (expected lifespan: 80 years). Surrounding vegetation was also killed, and surface water quality affected. Similar but more widespread situations have occurred in South East Queensland and Northern New South Wales, where floodgate use and drainage in ASS areas for sugarcane production has resulted in acidic discharges, fish kills and vegetation shifts (Johnston *et al*. 2002; Tulau 2007) and the necessity for frequent infrastructure repairs.

There is also considerable evidence that both sulfate-reducing and iron-oxidising bacteria can directly attack ferrous infrastructure, for example pipes and fittings made of ductile iron (Megumi and Kajiyama 1995; Kajiyama 1997) or steel (Xu *et al*. 2007), even in unoxidised PASS. At least one Queensland local government has discovered extensive damage to pipes consistent with the research quoted above. It is unlikely that neutralisation treatment of ASS (see Section 7) acts as protection against bacterial attack. As a result, it is strongly recommended that pipes, pipe joining components and other underground infrastructure made from ferrous materials not be placed in ASS environments without considerable protective measures in place. Preferably, such materials should not be used in ASS environments at all.

Considerable costs to landholders and government may be incurred if these issues are inadequately addressed. The addition of neutralising agents such as aglime can change soil physical properties over time. Geotechnical properties should be considered for any potential reuse of ASS material, particularly where treated ASS may be used in a load bearing or structural capacity (see ASS Tip 22). Other impacts may also be of relevance at the reuse location (i.e. salinity, release of reaction products etc.).

## 6.8 Trenching

ASS disturbances due to trenching pose a risk to infrastructure and the environment if they are not investigated, planned and managed appropriately. Examples include stormwater, sewer and water piping trenches, and electrical and phone cabling installed underground. The risks increase significantly if actual ASS are present on site or if the pH of the groundwater is less than 5.

Trenching activities are capable of directly disturbing ASS via excavation as well as exposing *in situ* ASS to oxidising conditions by temporarily or permanently lowering the seasonally lowest watertable elevation. Natural watertable variation may temporarily and periodically dry out upper ASS layers, and infrastructure placed into a zone of flux may be periodically exposed to *in situ* acidic ground- and pore water.

An ASS investigation (see *Queensland Sampling Guidelines*) and risk assessment (see Section 3) should be undertaken prior to any earthworks being carried out on site, with the findings used to guide management decisions. Site-specific management strategies relating to any excavated ASS, *in situ* ASS and contaminated waters should be documented in an EM plan. This will help to manage the risk, protect the infrastructure from acidic leachate, and protect the environment.

A combination of the management options listed below will normally be necessary:

- Reroute planned works away from ASS.
- Where ASS are located deep within the soil profile, ensure that the trenching works will not intercept the ASS layers.
- “Trenchless” tunnelling technologies should be used where possible to place infrastructure to minimise disturbance.
- Pipes and cable casings can be constructed from acid-resistant materials. This will help to prolong their life in an ASS environment.
- Groundwater dewatering that results in lowering of the watertable should be avoided due to the difficulties in neutralising *in situ* ASS and groundwater.
- Dewatering sumps and or spears must be kept to a minimum. Suction depths should not exceed 1 m below the invert depth of the trench.
- Steel sheet piling may be useful in trenching, since it is removable, reusable, relatively low-cost, and suited to shallow excavations.
- Groundwater dewatering should be timed to coincide with the dry season, and all pumped groundwater should be stored on the same development site for irrigation (and potential recharge) or dust suppression purposes (depending on water quality).
- During excavation, non-ASS surface soils should be removed and handled separately to ASS. Soil horizons must be replaced back in the trench in the same order that they were removed (after the ASS have been neutralised).
- The excavation of the trenches should be staged, with areas excavated, treated and backfilled within a maximum timeframe of 24 or 48 hours depending on the risk profile. If dewatering is required, a longer timeframe may be required but should not exceed five days. Limit the amount of trench open at any time (e.g. 50 m at a time) to minimise the length of time *in situ* ASS is exposed to air.
- If the ASS risk assessment shows that the risk is high[14], the trench is in a sensitive location and/or dewatering is required, it is recommended that ASS removed from the trench are neutralised on a fully contained treatment pad (see Section 7) and satisfy the

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[14] A ‘high’ risk is the extra high level of treatment – category XH in Table 3 and /or if the Net Acidity is greater than 1870 mol $H^+$/tonne (3 %S).

neutralisation performance criteria (Section 7.2) before backfilling. Alternatively, the ASS can be removed and treated off site with clean non-ASS fill used for backfilling.

- If the ASS risk assessment shows that the risk is not high, the trench is not located in a sensitive environment, and no dewatering is required, alternative management strategies include adhering to all of the following:
    - Guard layers of neutralising agent are spread on the surface of the ground alongside the trench (see Section 7.4.2)
    - Excavated soil from the trench is placed onto the guard layer
    - Neutralising agent is applied to the surface of the excavated soil with an increased safety factor of three without the need to do verification testing. Note that this can lead to over liming
    - The aglime dusted soil is backfilled into the trench.
- Aglime dusting of soils during excavation can assist with mixing and provides a level of buffering to the soils.
- Neutralising agent can be spread or dusted over the open surfaces of excavations before treated ASS or clean fill is placed around the installed infrastructure.
- Monitoring and water treatment may be required in accordance with the requirements of the EM plan—in sensitive environments, automatic dosing of water may be required prior to discharge/release. Refer to *Environmental Protection Water and Wetland Biodiversity Policy 2019* for guidance on water quality objectives.
- Where <100 $m^3$ of ASS are being disturbed by the trench, liming rates can be based on Table 4. See Section 7.5.

*Note: Backfilling untreated ASS is not an acceptable management strategy for trenching.*

## 6.9 Drain maintenance

Drains may be excavated in ASS for a variety of reasons, including stormwater management and improving drainage for agriculture, and may require ongoing maintenance. Risks associated with drain construction, maintenance or sediment removal in ASS areas can include:

- Generation of acid within the spoil/silt excavated from the drain, creek or waterway which will require neutralisation.
- *In situ* oxidation of previously undisturbed ASS due to lowering of the groundwater table, causing a deterioration in soil and groundwater quality.
- Poor water quality (particularly with respect to low pH, low dissolved oxygen, and high dissolved metals content) in drains and waterways because of contaminant export from oxidising ASS.
- Accumulation of MBOs in low-flow areas of the drainage network, necessitating periodic removal and treatment. These materials are more reactive and easily disturbed. They are capable of deoxygenating and acidifying water rapidly when disturbed by flooding events, excavation etc, and are often implicated in fish kill events in coastal Australia. These drains and waterways are often close to sensitive environments.
- Permanent changes to floodplain hydrology, potentially affecting flood distribution and severity during heavy rainfall events.
- Disturbance of resident aquatic biota.

For small drain maintenance activities or minor desilting activities[15], the management options may include:

- Periodic application of aglime to the bed and banks of drains is advisable, since it may reduce or eliminate the need to treat runoff leaving the drained property. Consideration should be given to the type of drain and potential flow rates when determining the particle size of the neutralising agent and how it will be applied. Options include fine aglime applied directly to the drain base (in a sand mixture) or the use of coarser limestone blends (DER 2015).
- The neutralising agent will need to be replenished if it is scoured from the drain or as it develops coatings (i.e. armouring) of gypsum, iron and/or aluminium that reduce its neutralising efficiency by preventing contact with water (DER 2015).
- Additional measures such as lime interception trenches that treat leachate before it enters the drain may also be necessary. These require careful design to ensure the appropriate particle size is used and permeability of the trench is maintained. *Note: this form of treatment will have a finite treatment life due to armouring with iron oxides and gypsum.*
- Settlement ponds and silt fences can also be used to capture and remove metals that have precipitated out (DER 2015).
- The monitoring program for surface and groundwater could be documented in an EM plan, including requirements for treatment before discharge if necessary. Monitoring during and after high rainfall events will be informative.
- Gates and drop boards can sometimes be installed in drains to artificially raise the water level, and to decrease the oxidation of *in situ* ASS. In broadscale agriculture where there has been historic disturbance of ASS, floodgates may need to be opened periodically to improve water quality by allowing saline water into tidally restricted drains. This must be done with careful monitoring and supervision to ensure that there are no detrimental impacts on water quality resulting from the operation (see Appendix 3).
- Periodic removal of accumulated MBOs from the drain may be necessary (see Sullivan *et al.* 2018c). The use of a reed bucket or other similar device may minimise both monosulfide disturbance and the deepening or widening of drains during drain cleaning activities. Any spoil excavated during drain cleaning activities should be placed more than 5 m away from the drain and treated as soon as possible with an appropriate neutralising agent on a suitably constructed treatment pad (see Section 7.4). It can be difficult to transport and treat saturated MBOs.

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[15] That do not require approvals under the *Environmental Protection Act 1994* and/or *Fisheries Act 1994*.

# 7. Neutralisation of acid sulfate soils

Neutralisation of ASS involves the thorough mixing of suitable alkaline materials into the soil. The amount of neutralising agent added must be sufficient to neutralise all Actual and/or Retained Acidity that may be present and all potential acidity that could be generated from complete oxidation of the iron sulfides over time (i.e. the Net Acidity). An appropriate safety factor must be included in that amount. The most used neutralising agent is limestone, commonly known as agricultural lime (aglime), $CaCO_3$ (see ASS Tip 8).

There are various processing options available for carrying out neutralisation (see Section 7.3.7). The first and most common option is a batch process carried out on a dedicated treatment pad (see Section 7.4), where excavated ASS are spread in thin layers, neutralising material is spread over the top, and machinery is used to mix the materials together. Another option is a continuous process in which a mixing machine like a pug mill is employed, with soil and neutralising material fed in at adjustable rates informed by the laboratory determined Net Acidity results obtained as part of the site investigation. In both cases, excavated soil must be stored and treated in an appropriately contained, hydrologically isolated area.

**ASS Tip 15: Soil acid buffering capacity and acid neutralising capacity**

A soil's buffering capacity is the degree to which a soil can intrinsically resist pH change—to either a more acidic or more alkaline state. A soil's ANC is essentially a subset of its buffering capacity, being the ability of the soil to resist becoming more acidic.

In ASS, the first mechanism for resisting acidification is the neutralisation reaction of soil carbonate minerals or small shell fragments when present (smaller than 0.5 mm) with acidity as it is generated by pyrite oxidation. This reaction is irreversible. The addition of alkalinity-producing materials such as agricultural lime (aglime) to the soil simply increases this neutralising capacity.

The presence of certain minerals and/or organic matter in the soil can also enhance neutralising capacity to variable extents. Clay minerals can dissolve, releasing toxic metals, consuming acidity, as well as adsorbing and exchanging cations, including $H^+$ and $Al^{3+}$. Different clay minerals can adsorb/exchange acidity to different extents. Subsequently, however, $H^+$ and $Al^{3+}$ adsorbed or exchanged onto clays may be re-released to less acidic or neutral waters, so buffering via these ion exchange reactions may not be effective in the long-term.

Organic matter can buffer acidity, and release or adsorb cations and toxic metals in a similar way. Because only buffering from carbonate minerals is effective in the long-term in maintaining a neutral pH, these other additional sources of acid neutralising capacity are not part of acid base accounting. Slab incubation tests or other validated kinetic tests are used to simulate the oxidation of iron sulfides and to corroborate neutralising capacity under field conditions.

## 7.1 Environmental risk

There can be significant risks to the environment if neutralisation is performed poorly and when the risk is high (e.g. the extra high level of treatment – Category XH in Table 3 and/or if the Net Acidity is greater than 1870 mol $H^+$/t (3 %S). If the treatment is poorly planned or executed, the costs for remediation are costly and difficult to execute (see Appendix 6 Remediation Case Studies). The following issues are an essential consideration when neutralisation is being proposed.

### 7.1.1 Soil texture

Neutralising coarse sandy soils is inherently risky because these soils dry quickly and can oxidise within hours of exposure to air. If there is a rainfall event while the soils are stockpiled, any acid that has been generated is likely to be mobilised. Large-scale neutralisation of highly sulfidic sandy material requires careful management.

Marine clays can be difficult to work, treat and dry, and may contain variable levels of sulfide within horizons that visually appear to be uniform. In high rainfall areas, such as Far North Queensland or coastal Queensland in the wet season, it may be particularly difficult to dry and treat these soils. A pilot trial may be required to prove that consistent and efficient treatment of the clay can be achieved; one such trial in the Cairns district failed and alternative management strategies had to be used.

Reactive monosulfidic black oozes can accumulate in waterways. These can be difficult to work, treat and dry, and they can oxidise readily once in contact with oxygen. Refer to the National Guidance material on MBOs for further information.

### 7.1.2 Groundwater dewatering and/or drainage

Large excavation sites employing neutralisation are sometimes dewatered for considerable periods to allow dry excavation. Groundwater dewatering or drainage poses a high risk to adjacent *in situ* PASS, which will then need remediation if oxidation occurs. Unconfined groundwater dewatering[16] is an unacceptable management technique (see Section 11.5), except for some minor, short-term disturbances where groundwater effects are temporary and localised, and the groundwater has been modelled using available hydrological information (i.e. dewatering is confined to <50 m radius cone of depression and/or duration of dewatering is <7 days—see Table A3-2). This is conditional on there being no sensitive receptors (e.g. wetlands, conservation areas, contaminated sites etc) within the radius of influence of each dewatered excavation. Areas that may be dewatered even for short periods will need to be neutralised if oxidation occurs, and appropriate management and monitoring strategies for these dewatered areas will need to be developed. This is discussed further in Sections 10.1 and 11.5 and in Shand *et al.* (2018).

### 7.1.3 Impacts on wildlife

Ideally, ASS in or near the habitat of particularly sensitive protected species (e.g. acid frogs and fish) should not be disturbed due to the potential threat to the species. Provisions of Queensland Government legislation including the *Nature Conservation Act 1992*, and protection of environmental values under the *Environmental Protection Act 1994*, and the Australian Government’s *Environment Protection and Biodiversity Conservation Act 1999* must be addressed when making decisions that may impact on protected species.

In sensitive acidophilic environments, liming of high net acidities may have a significant environmental effect and will need to be factored into the risk assessment for the site. This can increase the inherent risks of using neutralisation in coastal areas (see Section 5.3 for further information). Any proposals to reduce liming rates should only be used in legitimate circumstances and clearly justified.

### 7.1.4 Carbon emissions

It should be noted that using neutralising materials such as aglime to treat ASS will generate carbon dioxide in production, transport and spreading as well as in neutralisation reactions. This provides an additional incentive to avoid ASS disturbance. Where avoidance is not possible it may be a

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[16] i.e. groundwater dewatering without appropriate management strategies to limit drawdown and oxidation of *in situ ASS*—either temporarily or permanently.

consideration in selecting the management strategy, particularly for large disturbances.  Expert advice on emissions management may be required.

## 7.2 Performance criteria and verification testing

### 7.2.1 Performance criteria

The following performance criteria must be met for soil that has been treated using neutralisation:

- The Verification Net Acidity of the treated soil is less than zero.
- Record keeping that demonstrates a safety factor of at least 1.5 has been applied in calculating liming rates (see Section 7.3.5 on safety factors).
- Post-neutralisation, the soil pH ($pH_{KCl}$) is to be greater than 6.5 (see Section 7.3.2 on upper limit of pH range).
- Excess neutralising agent should stay within the treated soil until all acid generation reactions are complete and the soil has no further capacity to generate acidity[17].  This generally precludes the use of materials with appreciable soluble alkalinity (e.g. burnt lime, quicklime) for permanent soil amelioration.

### 7.2.2 Verification testing

Verification testing is the post treatment confirmation that sufficient neutralising agent has been thoroughly mixed with the soil to prevent any future acidification.  In a successfully ameliorated soil, the $pH_{KCl}$ will be greater than 6.5 and the Net Acidity will be less than zero.  The more comprehensive the initial ASS investigation and site characterisation, and the better the mixing of the neutralising agent, the more likely the soils are to pass verification.  The laboratory results are assessed against the performance criteria to assess treatment success or failure.  Treatment success can only be verified with a laboratory determination of Net Acidity; pH testing alone is not sufficient.

The equation for Verification Net Acidity from the *2018 National ASS Guidance material* is:

> Verification Net Acidity = Potential Sulfidic Acidity + Actual Acidity + Retained Acidity – (post treatment Acid Neutralising Capacity – initial Acid Neutralising Capacity)

The equation for Verification Net Acidity for Queensland is:

> Verification Net Acidity = (Potential Acidity + Actual Acidity + Retained Acidity) – (post treatment Acid Neutralising Capacity/Safety Factor)

**It is acceptable to follow either approach if the performance criteria are met.**

Suitable laboratory methods for Verification Net Acidity are documented in the *National and Queensland Laboratory Methods Guidelines*.  Treated samples should be submitted to an appropriately accredited (e.g. NATA/ISO 17025) laboratory, and it should be made clear to the laboratory that the soil requires verification testing, whether the soil contained jarosite prior to be treated, and the type of neutralising agent that was used for amelioration.  Retained acidity testing is to be undertaken, regardless of $pH_{KCl}$ if soils are known to have contained jarosite prior to treatment. *Note:  Jarosite can be easy to miss in the field, and therefore Retained Acidity analysis should be included in verification testing in sites where actual ASS have been observed.*

The neutralisation management strategy is most effective when soils and neutralising agents are completely homogenised.  When ASS are moist and/or clayey, this may not be fully achievable.  In

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[17] Choice of an appropriate neutralising agent (e.g. aglime) is important to achieve long-term performance criteria (see Section 7.3.3).

recognition of this, this guideline allows for some individual samples to exceed the verification testing target, as outlined below:

*Fine textured materials (light medium to heavy clays and silty clays):*

1. No single sample shall exceed a Verification Net Acidity of 62 mol $H^+$/t (0.10 %S).
2. If any single sample is between 0 and 62 mol $H^+$/t (0.00 to 0.10 %S), then the average of any four spatially adjacent samples (including the exceeding sample) shall have an average Verification Net Acidity of zero or negative.

*Medium textured material (clayey sands to light clays):*

1. No single sample shall exceed a Verification Net Acidity of 36 mol $H^+$/t (0.06 %S).
2. If any single sample is between 0 and 36 mol $H^+$/t (0.00 to 0.06 %S), then the average of any four spatially adjacent samples (including the exceeding sample) shall have an average Verification Net Acidity of zero or negative.

*Coarse textured material (sands to loamy sands and peats):*

1. No single sample shall exceed a Verification Net Acidity of 18 mol $H^+$/t (0.03 %S).
2. If any single sample is between 0 and 18 mol $H^+$/t (0.00 to 0.03 %S), then the average of any four spatially adjacent samples (including the exceeding sample) shall have an average Verification Net Acidity of zero or negative.

These variations equate to there being no positive calculated Net Acidity in the soil following treatment. Soil that has been treated by neutralisation techniques and does not meet these targets must be re-treated and re-tested until the performance criteria (see Section 7.2.1) are met.

Note verification testing that is reported in the closure report allows a proponent to be confident that neutralisation treatment has been effective (see Section 12).

*Note: inadequate mixing of the ASS and neutralising agent is a common cause of failure of verification testing. It is much more costly to re-treat rather than re-test, and the time to re-treat is often critical to project timeframes. The best option is to ensure thorough mixing in the first place.*

### 7.2.3 Verification testing rates

Verification testing rates are necessarily site-specific and may be set as a condition of approval to disturb ASS. Factors to consider include disturbance volume, treatment area size, Actual and/or Retained and Potential Acidity content, ease of mixing and test scheduling. Suggested minimum volumetric rates (depending on Net Acidity) are:

- volumes of <250 $m^3$ = two samples
- volumes 251–500 $m^3$ = three samples
- volumes >500 $m^3$ and ≤2 %S (≤1247 mol $H^+$/t) = three samples, plus one sample per additional 500 $m^3$
- volumes of >500 $m^3$ and >2 %S (>1247 mol $H^+$/t) = three samples, plus one sample per additional 250 $m^3$.

For larger projects (e.g. exceeding 20 ha of ASS disturbance or >10 000 $m^3$), or projects with low Net Acidity (e.g. <0.06 %S and low variability) a lower verification testing rate may be acceptable, providing the ASS investigation has satisfactorily characterised the various geological/geomorphological units at the site. However, in some situations a higher verification testing rate may be appropriate (e.g. if large scale dewatering of sandy soils is proposed, where there is a highly variable substrate such as the presence of palaeochannels). This would need to be negotiated with the regulatory decision makers.  A pilot trial may be a useful mechanism to demonstrate variation in verification testing rates.

**ASS Tip 16: Examples of verification sampling methods**

Where treatment is carried out as a batch process on a treatment pad:

1. Divide the treatment pad into areas containing a volume of soil equivalent to the nominated verification testing rate (e.g. for a pad holding 500 $m^3$ and a test rate of 1 per 250 $m^3$, divide the pad into two sections).
2. Within each of the two identified sampling areas, use a randomised procedure to nominate at least 6–8 random sub-sampling locations.  Record the location of each subsampling location to ensure tracking against the performance criteria.
3. Within each subsampling locations, use a consistent-volume sampler to gather subsamples of treated soil from each of the pre-defined locations on the pad (e.g. a hand trowel). Subsamples should extend through the total depth of the treated material but avoid sampling the underlying guard layer.
4. Mix the subsamples thoroughly together in a container with a secure lid.  Depending on the wetness and texture of the sample, this may involve rotating or end-over-end mixing of the container.  Subsample ~500 g from the composited material and submit it for analysis.
5. Leave the soil on the treatment pad until the results are made available, or if necessary, stockpile it in a contained area and document its new position (retreatment will be necessary if verification tests fail).

Where treatment is carried out as a continuous process using a mixing machine:

1. Determine (and regularly verify) the discharge rate of the processing machine ($m^3$/hour).
2. Determine the sampling frequency required to meet the prescribed verification testing rate. For instance, a machine discharging 250 $m^3$/hour of material that must be tested at a rate of one per 500 $m^3$ would require one sample to be taken every two hours.
3. Multiply that sampling rate by the number of subsamples (at least 6–8 samples) that will contribute to the sample.  Thus, one sample every two hours would imply one subsample every 20 minutes.
4. Take subsamples at the calculated rate and combine every batch of subsamples into one composite sample for verification, as above.

These methods reduce the likelihood of accidentally sampling a small patch of under- or over-treated soil, and pre-defining the sample locations/sample times helps prevent sampling bias. Variations in the way subsample locations/times are chosen, the number of subsamples contributing to the composite sample, the sampling equipment used, etc, are acceptable so long as they do not compromise the goals of composite, random sampling.  These methods also require that each volume of treated material from which a set of subsamples are taken should be placed or stockpiled in such a way that it can be easily identified and retreated if verification testing fails.

More information on sampling is available in the ISO 18400 series, NEPM (2013) or soil sampling and analysis textbooks such as Peverill *et al.* (1999) and Tan (2005).

An appropriate sampling design for verification testing must be selected and developed by a suitably qualified ASS scientist.  Composite samples (comprising 6–8 samples) are recommended, however composite sampling will not be suitable for marine clays that are difficult to mix.  Sampling design procedures such as those described in NEPM (2013) may be an option.  NEPM (2013) describes probability-based designs such as random, systematic, grid, stratified, transect and composite sampling that have the advantages of being unbiased, and provide the ability to make quantitative statements about level of confidence of the results.  Judgement sampling designs based on expert knowledge or professional judgement may be appropriate for small study sizes. Example sampling procedures are contained in ASS Tip 16.

*Note: Verification testing is an important part of on-site management and internal QA procedures. It is important to conduct verification sampling and laboratory analyses in a transparent manner, followed by prompt remedy of any treatment failures*. ***The action required for any verification failures must be documented in the ASS EM plan.***

*Note: QA/QC procedures will also require the collection of duplicate samples to ensure the quality of sampling and analysis used at the site.*

### 7.2.4 Record keeping

Record keeping that demonstrates a safety factor of at least 1.5 has been applied in calculating liming rates should include:

- calculations of Net Acidity, volume of soil to be treated and liming rates
- receipts showing quantities of neutralising agent purchased
- reconcile quantities of neutralising agent used on site e.g. per treatment pad, dates aglime was used on each treatment pad, aglime used in guard layers, reapplication of aglime in guard layers, dusting on drainage lines and bunds etc.
- evidence of the composition, purity (including presence of metal contaminants) and particle size of the neutralising agent used
- photographic evidence of incorporation of neutralising agent e.g. thorough mixing on a treatment pad (see Section 7.4, Figure 4 and Figure 5).

**Figure 4: Photographic evidence of aglime poorly incorporated into marine clay**

*Photo credit: Sue-Ellen Dear*

## 7.3 Management considerations

When neutralisation treatment is proposed to manage ASS, the following issues are important to consider.

### 7.3.1 Site characterisation and additional laboratory testing requirements

An accurate and thorough initial ASS investigation (as per the latest *Queensland ASS Sampling Guidelines*) is an essential input into a risk assessment and EM plan (if required). It enables regulatory decision makers to assess the level of risk to confidently conclude whether the soils can be managed in a sustainable manner prior to the issuing of any approvals. Significant costs are always associated with site assessment and ASS management, and these can compromise a project's design or financial viability. These costs must be factored into the project management at the earliest stage possible.

During operational works, excavation, dredging etc, further sampling and laboratory analysis is commonly needed to refine the liming rates and on-site management. Verification testing after earthworks ensures correct liming rates and mixing are used in the neutralisation process and is a QA procedure used by the proponent to confirm that the site has been adequately managed. Closure reporting and independent third-party review (see ASS Tip 7) for specific high-risk disturbances (see Section 12) may also be required by regulators to demonstrate whether the management has complied with this guideline and the EM plan.

### 7.3.2 Target pH range

The solubility of iron and aluminium is largely controlled by pH; the solubility of iron is also influenced by the redox potential. Under neutral soil conditions, the solubility of iron and aluminium is low, so the target soil pH should be between 6.5 and 8.5 when managing ASS by neutralisation. **In circumstances where pH-sensitive ecosystems are to be preserved, this target range may pose unacceptable risks.** Management of any adjacent disturbed areas will need to be modified and an appropriate buffer zone may be needed to separate disturbed ASS from the sensitive ecosystems.

Coastal non-ASS in some locations within Queensland may have a natural pH of 8.5 or greater. These soils do not need pH adjustment to bring their pH within the target soil pH range if disturbed.

### 7.3.3 Choice of neutralising agent

A variety of neutralising agents are available to increase soil pH to acceptable levels and neutralise acidity from the past or future oxidation of iron sulfides. Factors to consider when choosing a neutralising agent include solubility, pH, neutralising value, particle size, spreading and transport costs, chemical composition and purity of the agent, and workplace health and safety factors.

Care should be taken when using more soluble neutralising agents such as hydrated lime, $Ca(OH)_2$, to avoid the possibility of 'overshooting' the required pH to alkaline levels that may impact on the receiving environment. Soluble neutralising agents may also be more readily flushed from the system before full oxidation of PASS occurs. Additional workplace health and safety issues are associated with highly alkaline neutralising agents such as hydrated lime $Ca(OH)_2$ and quicklime $CaO$. Excessive inhalation of respirable crystalline silica dust, if present in aglime may cause lung disease.

Fineness, neutralising value (NV) and effective neutralising value (ENV) are particularly important in ASS management:

- fineness influences reaction kinetics, with finer particles capable of reacting more rapidly with acid due to their higher surface area
- neutralising value is a measure of the amount of a neutralising agent needed to neutralise a given volume of acid, expressed relative to that of pure calcium carbonate. This is related to both chemical makeup and purity
- effective neutralising value is a function of an agent's NV and its particle size (if it exists in solid form) and can be used to compare the reactivity of various neutralising agents as well as different size fractions of the same agent.

By-products of sulfide oxidation and neutralisation (such as gypsum, iron and aluminium compounds) may form insoluble coatings on neutralising agents (particularly larger limestone or marble particles). Such coatings reduce the effectiveness of the neutralising agent. Research by Watling *et al*. (2010) indicates that aglime particle size must be less than 0.5 mm to reduce the occurrence of these coatings and for reaction kinetics to be fully effective when treating PASS. Particle size may need to be even smaller when treating actual ASS if the goal is to immediately halt acid leachate generation. Similar research is currently being conducted on other naturally occurring neutralising materials (e.g. shells) (Sullivan *et al.* 2023).

Neutralising agents for treating ASS should produce alkalinity in the pH range 7 to 9 and should have low solubility in this pH range. Such products will not flush out with heavy rain events and have minimal potential to contaminate surrounding waterways and groundwater. The preferred agent for treating ASS is fine aglime, $CaCO_3$, because it only liberates alkalinity in the presence of acid and will not generate high pH leachate. However, it can be difficult to effectively mix fine aglime with wet, lumpy, clayey or cohesive sediments.

**ASS Tip 17: Common oxidation and reaction products**

Many variables affect sulfide oxidation, and the reactions are complex. Some common oxidation and reaction products are listed below:

- Iron sulfate minerals like jarosite are commonly found in disturbed ASS. Jarosite $KFe_3(SO_4)_2(OH)_6$ and natrojarosite $NaFe_3(SO_4)_2(OH)_6$ form in distinct butter- or straw-coloured mottles with a hue of 2.5Y or yellower (see the Munsell colour chart). They are relatively insoluble and are stable at low pH and under dry oxidising conditions. Under wet reducing conditions, however, jarosite can be unstable, releasing acidity, sulfate and iron back into the pore waters (Johnston *et al.* 2009a).
- Schwertmannite $Fe_8O_8(OH)_6SO_4$ is another common brownish to reddish iron sulfate mineral that occurs in disturbed ASS and in the orange precipitates common to ASS-affected waters within the pH range of 2–4. It may exert a controlling influence on the iron, and sulfur cycling, acidity dynamics, and electron flow of these waters (Sullivan and Bush 2004; Schoepher and Burton 2021).
- Gypsum $Ca_2SO_4 \bullet 2H_2O$ is formed in ASS by reaction between sulfuric acid (produced by oxidation of iron sulfides) and calcium carbonate (used for neutralisation). It has moderate solubility in water (2.0−2.5 g/L) and is not a source of acidity. Gypsum has swelling properties and the overall reaction results in nearly a doubling of the volume of gypsum relative to its calcium carbonate precursor (Fanning *et al.* 2017).
- Ettringite $Ca_6Al_2(SO_4)_3(OH)_{12}.26H_2O$ is formed when gypsum combines with excess water in the presence of aluminium from clay. The volume is larger than the minerals like calcite from which it forms, causing swelling.
- Iron products can include the soluble ferrous ion $Fe^{2+}$, highly reactive ferric ion $Fe^{3+}$, ferrihydrite and goethite $FeOOH$, haematite $Fe_2O_3$ and rusty-coloured floccules of ferric hydroxide $Fe(OH)_3$.
- Moderately insoluble aluminium compounds may also be present in disturbed ASS. They can supply large amounts of acidity upon dissolution and hydrolysis, for example, tamarugite $NaAl(SO_4)_2 \bullet 6H_2O$.
- Relatively soluble salts such as the hydrated ferrous sulfate rozenite ($FeSO_4.4H_2O$) can form in ASS by desiccation under extremely acid conditions. The oxidation and hydrolysis of rozenite also produces more sulfuric acid and at the same time produces iron 'oxide' minerals. Other relatively soluble salts include melanterite ($FeSO_4.7H_2O$) and the mixed ferrous-ferric sulfates of the copiapite group minerals e.g. $Al_{2/3}Fe^{3+}{}_4(SO_4)_6(OH)_2.20H_2O$). These salts are transient phases in the formation of jarosite and insoluble iron oxides (Fanning *et al.* 1993; Fanning 1993).

Many more reactions and compounds occur in ASS. Refer to primary literature and the latest version of the *Laboratory Methods Guidelines* for further explanation.

Other agents with low solubility include dolomite $CaMg(CO_3)_2$, magnesite $MgCO_3$ and magnesia MgO. Caution must be exercised with these magnesium compounds as they can react to produce magnesium sulfate during neutralisation reactions. Magnesium sulfate (Epsom salts, a laxative) is quite soluble and may degrade water quality in waterways if large quantities are produced (Ahern and Watling 2000). Water containing high dissolved magnesium levels can be toxic to aquatic animals, stock, and humans. High levels of magnesium in soil can enhance soil dispersion. It is preferable to use a mixed calcium-magnesium agent such as dolomite rather than straight magnesium products. Fine aglime neutralisation reactions in soil produce calcium sulfate instead, which quickly hydrates to form gypsum. Gypsum is less soluble than Epsom salts, so is less likely to affect water quality and is generally considered to have beneficial impacts on soil properties, particularly structure.

More highly soluble neutralising materials such as hydrated lime, $Ca(OH)_2$ and sodium bicarbonate, $NaHCO_3$ may more effectively neutralise acidity at depth in soil profiles where excavation and mechanical mixing will not reach. However, there may be risks to the environment (and workers) due to their high pH, safe handling difficulties, and potential to increase the salinity and sodicity of soils if free sodium ions are introduced. Furthermore, wind or water erosion of stockpiles must also be prevented to minimise impacts on receiving environments. Subsequent rain events may also dissolve and wash these materials out of the treated soil before all the sulfides have oxidised, leaving the soil with long-term net acid-generating potential which will effectively pollute the site. Soluble neutralising agents that generate high pH values should be added in small amounts on a more regular basis to avoid over-shooting the target pH range.

*Note: soluble neutralising agents may not meet performance criterion 4 (see Section 7.2.1).*

Other neutralising agents such as cement kiln dust, crushed concrete, red mud (including processed alumina plant wastes) and other industrial by-products may be appropriate for some sites, subject to their associated risks and legislative approval requirements being addressed. A major risk is their variable composition and thus their variable neutralising value. Also of concern is their potential to release heavy metals, excessive alkalinity and other toxic elements and compounds, which become bound up in these waste products during processing (particularly during combustion). At this stage, verification tests for these products have not been developed and validated. Other neutralising agents such as soda ash $Na_2CO_3$, sodium hydroxide NaOH, and quick lime CaO are not recommended to neutralise ASS (DER 2015).

### 7.3.4 Neutralising material application rates

Short-cut estimates of fine $CaCO_3$ requirements to effectively treat soils can be obtained from Table 3. ASS Tip 18 contains instructions for calculating liming rates. The neutralising value of the neutralising agent must be factored in when determining lime application rates. For example, high quality fine aglime typically has a neutralising value (NV) up to 98%, so for aglime with NV = 98%, a correction factor of 100/98 = 1.02 needs to be applied to reach the equivalent of pure fine $CaCO_3$. For a product that has a neutralising value of 60%, the correction factor becomes 100/60 = 1.67, that is, 1.67 times the amount of product needs to be used relative to the amount quoted in the tables. Neutralising value should be reported on purchase invoices or material safety data sheets.

As discussed earlier, a product of sufficiently small particle size should also be chosen. Finer particles have a greater surface area to react, and the larger number of particles means that the lime can be better distributed through the soil. Generally, the particles should have a range of particle sizes with 100% passing through a 500 µm sieve (0.5 mm), which reflects that the finer the lime, the more effective it is (see Miller 2017). A lower-priced, low-NV aglime product that is not finely ground may turn out to be much more expensive, as more will be required. The economics of paying for transporting and application of more aglime may outweigh the cheaper purchase price per tonne, and there is no guarantee that the coarser product will be effective.

### 7.3.5 The safety factor

Soils require treatment with a neutralising agent using a minimum of 1.5 times the theoretical acid production potential (the Net Acidity). This ‘safety factor’ is used because in most situations the neutralising agent is not fully mixed with the soil regardless of the method used. Furthermore, agents such as fine aglime have a low solubility and hence a low reactivity. Coatings of gypsum, and iron and aluminium compounds can form on the grains of neutralising agents during neutralisation, reducing the neutralising efficiency. In ‘high risk’ situations, greater safety factors may be warranted.

An excess of neutralising agent tends to prevent a build-up of extreme acidity within the soil, despite some oxidation occurring because of the drying of the sediments. Additionally, bacterially aided oxidation may occur in disturbed ASS when the pH is less than 4, accelerating oxidation by a factor of up to $10^6$ if oxygen is readily available. The acid production rate will therefore be kept low if the pH is kept at levels greater than 5.5. Thus, an excess of neutralising agent in the soil is important. Tables 3 and 4 and ASS Tip 18 in this guideline have incorporated the minimum safety factor of 1.5 for calculating requirements of pure fine aglime.

*Note: The safety factor is applied to the liming rate* ***after Net Acidity*** *has been determined (not before).*

*Note: If a higher safety factor has been specified, or a lower safety factor is required due to the presence of acidophilic wildlife on or adjacent to the site, then the assessment against the performance criteria must confirm that the specified safety factor has been used.*

**ASS Tip 18: Calculating liming rates**

Once Net Acidity has been determined, liming rates can be calculated. The weight of pure calcium carbonate needed to neutralise the Net Acidity is calculated using the stoichiometry of the neutralisation reaction, and then converted to the weight of neutralising material needed, using its stated neutralising value (NV). This gives the appropriate treatment rate for oven-dried soil, so it must be converted to the weight required for 'wet' soil (i.e. soil in field condition) using the soil's bulk density. Preferably, bulk densities will have been determined. Otherwise, approximate values can be applied (see Table 5.1 in Sullivan *et al*. 2018b), but they can be a significant source of error in calculations. The appropriate safety factor must also be applied. A worked example follows:

Net Acidity = 300 mol $H^+$/t
Volume of soil to be treated = 850 $m^3$
Safety factor = 1.5
Aglime NV = 98%
Soil bulk density = 1.3 t/$m^3$

*STEP 1: Calculate the weight of pure aglime needed to neutralise the Net Acidity (in mol $H^+$/t)*

To convert from mol $H^+$/t to kg $CaCO_3$/t, divide by 19.98

= 300 mol $H^+$/t ÷ 19.98

= 15.02 kg $CaCO_3$/t

*STEP 2: Consider the neutralising value of the aglime being used*

To convert kg of pure $CaCO_3$ (NV 100%) to kg of aglime/tonne, multiply by (100 ÷ NV)

= 15.02 kg $CaCO_3$/t × (100 ÷ 98)

= 15.33 kg aglime/t

*STEP 3: Include a safety factor*

To add the safety factor, multiply kg of aglime/t by the safety factor (typically 1.5)

= 15.33 kg aglime/t × 1.5

= 22.99 kg aglime/t

*STEP 4: Calculate the aglime application rate to volumetric basis*

To convert from mass to a volume basis, multiply by the bulk density (this gives an aglime application rate in units of kg aglime per cubic metre of soil)

= 22.99 kg aglime/t × 1.3 t/$m^3$

= 29.89 kg aglime/$m^3$

*STEP 5: Calculate overall aglime requirement using the volume of the disturbed soil*

Multiply the lime rate in kg aglime/$m^3$ by the total volume ($m^3$) of the soil to be disturbed (this gives the total quantity of aglime required)

= 29.89 kg aglime/$m^3$ x 850 $m^3$

= 25 406.5 kg aglime

= 25.4 t aglime

Application rates can also be expressed on a volume:volume ratio basis, which can be easier to use in practice. The bulk density of the neutralising material and the soil must be known. Continuing the above example and assuming an aglime bulk density of 1.4 t/$m^3$, the calculations are:

Vol. of 29.89 kg aglime = 29.89 ÷ (1.4 × 1000) $m^3$
= 0.02 $m^3$

Vol. aglime:Vol. soil = 1:(1 ÷ 0.02)
= 1:50

(i.e. a field operator could be advised to mix one volume of aglime to each 50 volumes of soil)

Any laboratory-provided calculations should be checked before applying them. Some are provided on a dry-soil basis, and the safety factor missing or incorrect. Where a neutralising material other than aglime will be applied, the same general steps should be followed, but a different initial stoichiometric conversion and a different neutralising value will need to be used. A web-based lime rate calculation tool to calculate the amount of lime required to treat ASS is available (search at <http:www.wa.gov.au>).

**ASS Tip 19: Self-neutralising soils**

Some ASS can be partially or completely ‘self-neutralising’ due to an abundance of naturally occurring calcium carbonate (e.g. crushed shells, skeletons, coral or foraminifera). These soils usually have a $pH_{KCl}$ and $pH_{OX}$ greater than 7.5. In Queensland, small areas of partially or completely self-neutralising soils have been identified in Queensland Government ASS mapping projects around Brisbane, Yeppoon, Gladstone, Proserpine, Armstrong Beach, and East Trinity near Cairns, where the ASS have been formed in low energy environments. Self-neutralising soils are also often found in harbour and estuary sediments. Other calcareous soils are comparatively rare in Queensland coastal zones but can be found in South Australia and some parts of Western Australia and Victoria.

In calculating the acid neutralising capacity (ANC) of these soils, ANC particle size needs to be taken into consideration just as when sourcing externally produced $CaCO_3$ for neutralising treatment. The finer the shell, the greater the surface area, and the more reactive it is likely to be—shells less than 0.5 mm should contain appropriately sized particles to ensure they are sufficiently reactive to prevent the acidification of ASS (Sullivan and Watling 2023). Larger shells will generally have a smaller surface area and hence gypsum and insoluble coatings of iron and aluminium are more likely to form on them, preventing complete reaction. There may be opportunities to consider the effectiveness of different sized shell fractions contributing to ANC during capital dredging operations of harbours and estuaries (see Simpson *et al.* 2018).

Laboratory methods can be used to quantify ANC, but as fine grinding is used during sample preparation, these methods can overestimate its environmental effectiveness. All visible shell should be removed before grinding. This can be relatively easy for sands but will be more difficult for wet clays.

If shell particles are mostly >0.5 mm, it is likely that there will be insufficient neutralisation to avoid acidification. The addition of neutralising agent will still be required due to the potential for incomplete reaction of shells through either slow reaction kinetics or formation of coatings. Where shell particles are mostly <0.5 mm, there will be a degree of neutralising capacity from this material, however the reaction kinetics may still be unknown, and the effectiveness of any neutralising capacity from the shells must be corroborated by an incubation test or similar kinetic testing.

For many disturbances, timeframes between the stage of seeking approvals and the commencement of site works should be sufficient for applicants to confirm whether the ANC from shells <0.5 mm is available via slab incubation tests.

*Note: fresh samples are required for slab incubation tests—not dried and ground samples.*

**ASS Tip 20: Analysing ANC**

Laboratory methods used to analyse ANC may result in an inflated ANC value i.e. they overestimate the actual ANC available under *in situ* field conditions.  This may be due to various factors e.g. the method itself (applying excess strong acid to the soil and back-titrating unreacted acid will commonly give an inflated ANC), or sample preparation techniques (grinding coarse shell(s) in the soil sample into smaller fragments will inflate the ANC).

The amount of acidity that is leached to the environment depends on the amount and rate of acid generation, and the amount and reactivity of the neutralising components of the soil.  The amount of neutralising capacity available under real field conditions is influenced by the particle size of the acid neutralising material, coatings with insoluble or sparingly soluble gypsum silica or iron compounds and reaction kinetics.  ‘*In Western Australia, there have been situations where the level of ASS management undertaken was reduced because laboratory analyses indicated that the ASS materials had sufficient ANC to render them self-neutralising.  It was subsequently found that under real field conditions, disturbance of the soil profile resulted in the generation of significant acidity, with the release of heavy metals into groundwater and surface waters’* (DER 2015).

A variety of laboratory methods are available to determine ANC, including: Total Inorganic Carbon ($C_{IN}$), ANC by back titration ($ANC_{BT}$), Reacted Calcium ($Ca_A$) and Reacted Magnesium ($Mg_A$), and Excess ANC ($ANC_E$) as outlined in the National and Queensland Laboratory Methods Guidelines.

ANC should only be included in the quantification of Net Acidity when the effectiveness of a soil material’s measured ANC has been corroborated (e.g. slab incubation tests and kinetic testing) and demonstrates the soil material does not experience acidification during simulated field oxidation.  A representative number of samples will be required to ensure confidence in the results.  Other methods such as sequential leaching and column leaching used in AMD may be useful.

### 7.3.6 Laboratory results and application rates

Depending on the results of the site investigation, different approaches to calculating liming rates may be used.  For some disturbances, particularly smaller ones, simply choosing the worst laboratory result (i.e. the highest Net Acidity) as a basis of calculation will be the most prudent method (accepting that this could lead to an over-liming scenario).  For larger disturbances, a high-quality site investigation may sometimes reveal spatial clusters of similar Net Acidity results within the planned disturbance area.  Sometimes these clusters are the result of a partially oxidised soil layer overlying unoxidised PASS with higher %S, and sometimes they will be related to the local geomorphology.  Where it is practicable to separate soil from these zones for treatment, an application rate for each zone (or placed lot) may be calculated.  However, site investigations don’t always reveal a useful spatial pattern and it may simply not be feasible to separate out material successfully on a construction site—be cautious and do not over-extrapolate from the data.

It is inappropriate to use the arithmetic mean laboratory result to calculate liming rates—a significant proportion of soil will be under-treated if the mean result is used, even though some other proportion of the soil will logically be over-treated.  The over-treated soil cannot compensate for the under-treated soil.

For disturbances greater than 1000 t, the liming rate could be based on the arithmetic mean plus one standard deviation provided a sufficient number of laboratory analyses have been undertaken to satisfactorily characterise the ASS.  In some cases, the 95th upper confidence limit of the mean of the lab results may be sufficiently low risk for use.  Using statistical techniques to calculate application rates is best left to those with significant statistical experience and must be justified very clearly in reporting.

### 7.3.7 Lime application

To treat the ASS, the neutralising agent must be effectively incorporated into a sufficiently dry soil. All lime treatment and application methods must be carried out in an appropriately contained area. Treatment and application methods (modified from DER 2015) may include:

- mechanical mixing in pugmills or in soil mixing machinery (Figure 7)
- mechanical mixing in small windrows using conventional earth working equipment[18]
- mechanical mixing of aglime into dry soil using a rotary hoe, tillage or excavator
- application of lime slurry to the surface of a soil and further blending
- placement of an aglime slurry into an up-hydraulic gradient lime trench, perpendicular to the direction of groundwater flow
- injection of an aglime slurry into dredging pipelines during dredging operations—this method is suitable for sandy sediments
- using ‘lime buffer’ on exposed ASS and covering with clean fill or sandbagging the face and incorporating lime under and in the sandbags—this method is suitable for infrastructure earthworks or rehabilitation of undisturbed ASS landscapes. *Note: this form of treatment will have a finite treatment life due to armouring with iron oxides and gypsum.*

## 7.4 Treatment pads

Neutralisation of ASS should be carried out on a fully contained (i.e. hydrologically isolated) treatment pad (see Figure 5). The treatment pad must collect and isolate the leachate from the surrounding environment, while being able to efficiently accommodate the machinery (in terms of size and weight) and the ASS itself. Soils may be neutralised on a temporary treatment pad, mixed *in situ* as part of the removal process, or alternatively the soils may be neutralised as they are placed permanently. Treatment pads are often located within licenced treatment facilities.

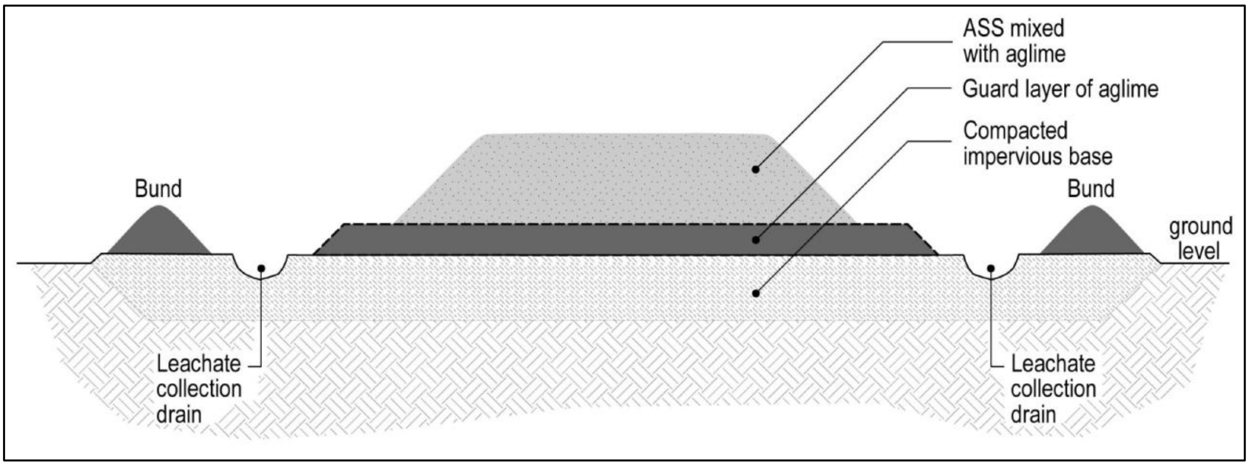

**Figure 5: Schematic cross-section of a treatment pad**

### 7.4.1 Basal layers

A layer of 300 mm thick compacted non-ASS clayey material placed on the surface of the treatment pad can reduce the infiltration of leachate to the soil and groundwater, provided the level of compaction has produced an appropriately low permeability. In fully contained situations, an impervious physical barrier may also be an option, such as a bunded concrete slab. An impervious

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[18] Mixing of aglime and ASS via bucket and excavator buckets can be difficult and result in poor mixing, even in sands. Good mixing makes all the difference.

base is particularly beneficial if the treatment pad is situated in a sandy area. The basal layer should be slightly domed or sloped to prevent leachate from pooling in the treatment pad area. The impervious base should extend beyond the leachate collection drains to prevent seepage into the ground. Some of the basal layer may be removed during treatment (e.g. scraped off during mixing operations) and would require routine replacement during further soil treatment. See Figure 5 for an example of a layer of 300 mm thick compacted non-ASS clayey material used to reduce the infiltration of leachate to the soil and groundwater.

*Note: aglime can be mixed into the basal layer to provide additional buffering capacity. Regardless a guard layer is still required for all treatment pads.*

### 7.4.2 Guard layers

A guard layer of neutralising agent should be spread on top of the compacted layer before the placement of soils requiring treatment. This will reduce risk by neutralising acidic leachate generated in the treatment pad which is not neutralised during the treatment process. This is especially relevant to the first layer of ASS that is placed for treatment before application of the neutralising agent. The guard layer will help protect groundwater quality.

The guard layer is not a primary means of soil treatment for the following reasons:

- gypsum and insoluble iron and aluminium coatings can form on the neutralising agent placed in the guard layer, which reduces the neutralising capacity of the layer
- over time, excess water passing through the treatment pile may channel its flows through preferred paths, whereby only a fraction of the guard layer is intercepting and neutralising acid flows
- there is no mixing of the neutralising agent with the soil
- the amount of neutralising agent in the guard layer will generally be insufficient to treat all the acidity from the overlying soils placed on the pad.

The minimum guard layer rate is 5 kg of fine aglime per square metre, per 300 mm of placed ASS requiring treatment. Where the highest detected Net Acidity is more than 1.0 %S, the guard layer rate is a minimum of 10 kg of fine aglime per square metre, per 300 mm of placed ASS requiring treatment.

*Note: ASS are usually placed at a maximum depth of 300 mm to increase the efficiency of mixing and drying*.

*Note: Reapplication of the guard layer will be necessary under treatment pads if the treated soil is being removed as the guard layer could also be removed with the treated soil.*

*Guard layers may need to be applied between each 300 mm of placed ASS requiring treatment in situations where multiple layers of ASS are placed on the same treatment pad.*

*The higher basal rate of 10 kg of fine aglime per* $m^3$ *should apply as a precaution where soils are difficult to mix.*

**Figure 6: ASS treatment pad in South East Queensland**

*Note: The shape of the treatment pad was modified to account for site specific constraints.*

*Photo credit: Healthy Land and Water*

### 7.4.3 Containment

The treatment pad should be hydrologically isolated. Stormwater runoff and leachate should be contained within the treatment pad by suitable bunds and may be collected in a sump or detention basin. Diversion drains should be installed to prevent stormwater run-on into the treatment pad. Surface liming of earth bunds and diversion drains can help neutralise any acidic stormwater. Bunds and diversion drains should not be constructed out of untreated ASS or other materials that may be a source of contaminants to the environment. The materials used should have low permeability to avoid leakage. Waters should be monitored and if necessary, treated before reuse or release.

Where the site is adjacent to an acidophilic ecosystem, additional management mechanisms and monitoring will be required to ensure the discharge waters will not lead to unnaturally alkaline environments, which can result in ecological damage to the acidophilic organisms that rely on the acidic nature of the environment. These management mechanisms will need to be identified in the risk assessment.

### 7.4.4 Treatment pad location and dimensions

Treatment pads should be located on stable ground, at least 50 m away from overland flow paths, drainage lines and creeks, and in a location where bund and leachate collection pond construction does not disturb *in situ* ASS. Keeping treatment pads some distance from surface water bodies will help to avoid instances of accidental release of pollutants to water. Treatment pads should be set up to allow maximum treatment batch sizes of 500 $m^3$, as it is difficult to representatively sample larger batches, and re-treatment of large, failed batches is expensive.

The design of a treatment pad should also consider:

- adequate area available for handling of materials including drying and reworking
- replacement of basal layers and guard layers
- storage of treated material awaiting verification and clearance
- sufficient capacity for stormwater collection and management while facilitating ongoing treatment operations.

For permanently placed treatment pads, design considerations include siting, stormwater management, minimisation of potential migratory pathways for leachate, reaction products and salinity, and the creation of a stable and non-erodible final landform.  This final landform must be accurately surveyed, and both the extent and depth of the treated soils should be recorded (e.g. survey with Global Navigation Satellite System (GNSS)).  Examples of GNSS measurement techniques with varying accuracy and precision include Real Time Kinetics (RTK), differential GPS, and GPS averaging.  Other methods of survey may include conventional survey (e.g. Total Station Surveying).  The method employed will depending on the level of accuracy and precision required to be reported to the relevant local government or other authorities.  Other relevant information such as lot/plan and address should also be provided.  Local governments will need this information to enable them to make informed decisions about future land uses that could potentially impact on these areas.  This information should be recorded in the closure report (see Section 12).

**ASS Tip 21: Offsite treatment of ASS**

As a general principle, ASS should be treated on site, as this minimises handling costs and the potential for environmental harm offsite.  There are circumstances where ASS need to be treated offsite at a licensed treatment facility (e.g. if space is not available on site for a treatment pad, or in urban areas where neutralisation works would create amenity problems for residents).  The responsibilities of all involved parties should be clearly specified in a work contract and in any ASS EM plan produced and may in some cases be directly conditioned by the regulatory decision makers.  **At no time should a proposal for offsite treatment reduce the requirement for an adequate ASS investigation, or for comprehensive verification testing.**

The treatment facilities must be provided with a copy of the ASS EM plan and the laboratory results to ensure that the appropriate amount of neutralising agent is applied at the facility.  The treatment facility will also require additional hydrological isolation/containment, monitoring and record keeping confirming there has been minimal risk to the environment.  Records must be maintained for auditing purposes.  Any soil recycling facilities that accept treated ASS should be provided with copies of all the documents confirming that the ASS have been adequately treated to ensure that there has been no disposal of contaminated materials.

At present, the party disturbing ASS remains responsible for the material and any harm it causes until its full treatment is verified.  Documentation of volumes taken offsite, and evidence of full treatment must be presented in the closure report.  This includes documents from the treatment facility that transported soils have been fully treated (see Section 12).

Refer to Section 9 for management strategies for offsite treatment using Strategic Reburial—all documentation and records will also be required to be maintained for auditing purposes.

At no time should ASS be disposed of to an unlicensed facility or private property.

*Note:  Fire ant restrictions may also apply that limit soil movement.*

### 7.4.5 Soil treatment procedure

Acid sulfate soil material should be placed on the treatment pad (see Figure 5) in layers up to 300 mm thick. Thinner layers of soil can be more easily and thoroughly dried and mixed; 300 mm is suggested as a maximum, not only to prevent inadequate mixing but to prevent equipment from bogging and to allow compaction to improve strength. Once the ASS is dry enough to work, the appropriate amount of neutralising agent, calculated to include the safety factor, should be spread. The ASS may need reworking several times to achieve adequate mixing of the neutralising agent and/or drying of the soil.

The treated layer will require verification testing (see Section 7.2 and ASS Tip 16) to confirm whether enough neutralising agent has been incorporated into the soil. Treated and verified soil should be subsequently compacted before treatment of the next layer begins, or when moved to the permanent placement area if first mixed on temporary treatment pads. Compaction is not necessary if the treated soil is permitted to be disposed of or reused elsewhere.

Where soil mixing machinery (e.g. Figure 7) is used (e.g. in confined workspaces), soil treatment should still be carried out in a bunded/contained and sealed area as per Section 7.4.3. Treated batches should be spatially arranged in such a manner that re-treatment is possible in cases of verification test failure. Operators must be provided with a copy of the ASS EM plan and the laboratory results to ensure that the appropriate amount of neutralising agent is applied. As with all other liming techniques, verification testing will also be required to confirm that sufficient neutralising agent has been incorporated into the soil or sediment.

*Note: It may be beneficial to add aglime into the soil while it is being excavated to potentially achieve an extra means of mixing. This should not be relied on as the only means of mixing.*

*Note: ASS placed on a fully contained treatment pad (see Section 7.4) are not limited by the stockpiling timeframes listed in Section 10.2.2. These soils will need to be sufficiently dry to allow the incorporation of aglime.*

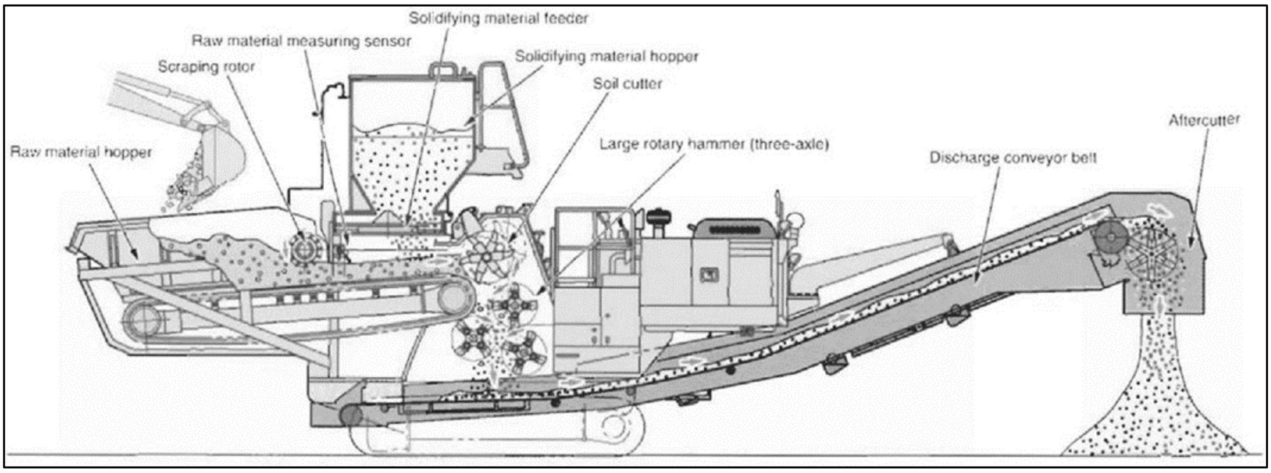

**Figure 7: Cross-sectional view of soil mixing machinery (Komatsu, 2003)**

*Note that soil treatment with such machinery should be carried out in an appropriately contained area, including bunding and measures to prevent leachate infiltration.*

### 7.4.6 Earthworks strategy

The earthworks strategy must make sure that enough space is available for:

- treatment pads
- storage of treated soil awaiting verification test results (if not left on the pad)
- water collection and diversion structures (including sumps and detention basins)
- neutralisation material storage structures
- vehicle passage and wash-down facilities.

This involves consideration of excavation rates, drying times, treatment throughput rates and sampling and laboratory turnaround times. Weather conditions and soil texture will affect these rates.

### 7.4.7 Spatial tracking

Accurate spatial tracking of large volumes of ASS during the neutralisation process (e.g. survey with GNSS, RTK, differential GPS, and conventional survey etc.) is essential to make sure that initial soil testing can be correlated with prescribed treatment and required verification testing.

### 7.4.8 Drainage lines

Neutralising agents can be incorporated into artificial drainage lines in contained treatment areas to aid the neutralisation of acidic stormwater runoff, and to neutralise acidic water entering from acidified groundwater inflows. Such design measures will prevent development of highly acidic waters and the transport of mobilised metals. By treating acid as close to its source as possible, the volume of contaminated waters requiring treatment should be minimised. This reduces treatment costs and environmental risks.

Consideration should be given to the type of drain and potential flow rates in determining the particle size of the neutralising agent, and how it will be applied. In slow-flow drains, fine aglime can be incorporated into a sand bund, which water will infiltrate through to a drain. The use of geofabrics can also promote the separation of materials and aid in the filtration process. Alternatively, fine aglime applied directly to the drain base, in a sand mixture or through use of coarser limestone blends may be considered. The neutralising agent will need to be replenished if it is scoured from the drain (into other treatment areas) or as it develops gypsum, iron and/or aluminium coatings that reduce its neutralising efficiency by preventing contact with water.

Because contact of acidified water with the neutralising agent will cause some precipitation of metals from solution, consideration should be given to capturing and removing such metals; for example, by constructing settlement ponds or silt fences across drains at intervals. These will need periodic cleaning, maintenance and appropriate disposal of floc.

It is inappropriate to apply neutralising agents into natural watercourses or water bodies unless carefully planned, approved and monitored. Site containment should be designed to prevent potentially contaminated waters from entering such areas in the first place. This is particularly important for waters where pH-sensitive wildlife may be present such as in acidic coastal wetlands (e.g. black water ecosystems). See Appendices 3 and 4 for water quality monitoring requirements.

**ASS Tip 22: Uses for treated ASS**

The re-use of fully treated and verified ASS is generally encouraged, however further research in this area and geotechnical advice will be warranted.

Neutralised ASS may be used as backfill or preload, but its suitability for load-bearing applications and for construction fill may require further investigation. ASS continue to chemically react after treatment for some time, and resultant physical effects are difficult to predict. These soils may also have characteristics aside from their pyrite content (e.g. shrink-swell clays) that make them unsuitable for load-bearing applications. Note that the *State Development Assessment Provisions* preclude soils with ‘contaminants including acid sulfate content’ from use as road base or in fill in state-controlled roads, tunnels, railway or busway corridors (Queensland Government 2017c).

Untreated ASS should never be disposed of to landfill. Treated ASS can be buried in licensed landfills or used as daily or final cover; however, some debate exists as to whether this is appropriate. Limited space is available in licensed landfills, and ASS retain some minor risk of generating acid even when treated, until all the pyrite and secondary sulfate minerals are completely consumed by neutralisation reactions. Alternatively, several operations in Queensland accept treated ASS to refill wet excavation pits for sand and gravel, restoring the former landscape. This is not always a low-risk activity and must follow the requirements of the approved ASS EM plan and verification testing. Similarly, monitoring and reporting requirements will be required.

Treated ASS can sometimes be used in landscaping and similar works but may require considerable further amendment or investigation first. Newly limed ASS may be low in organic matter, high in salts, with variable water-holding capacity and poor structure. The soil pH is likely to be slightly alkaline due to the excess calcium carbonate. Soils treated with other neutralising agents (e.g. hydrated lime) may be even more alkaline.

Treated ASS may also swell over time due to the formation of minerals like gypsum and ettringite (Simpson *et al. 2018)* and is not always a stable geotechnical construction material. Proponents should seek expert advice regarding the suitability of the geotechnical and chemical properties of the treated ASS and consult the relevant Australian Standard(s) before using neutralised ASS for fill within construction sites.

### 7.4.9 Treatment of water

Drainage structures on site may collect appreciable volumes of water, especially after rainfall events. Other large bodies of water on site may also exist (e.g. dredge ponds). These may require pH adjustment, aeration and removal of iron and aluminium floc. Treated site water may be used for dust suppression and rewetting of stockpiles. The optimum pH range is 6.5–8.5—refer to the *Environmental Protection (Water and Wetland Biodiversity) Policy 2019* for more information. Containerised water treatment plants are available which use more soluble neutralising agents than aglime to treat acidic waters and control the pH. Care is required not to overshoot pH adjustment when these more soluble and more alkaline neutralising agents, such as hydrated lime $Ca(OH)_2$ are being used. Sodium bicarbonate $NaHCO_3$ has a less alkaline pH and is very soluble but more expensive and will increase local sodicity. Refer to the *Treatment and management of soil and water in acid sulfate soil landscapes* (DER 2015) for further information on treatment of water. Additional time may also need to be factored to allow the oxidation of all ferrous ions and release of acidity—aerating the water column and/or the neutralising slurry can hasten ferrous ion oxidation (see Figure 8). Additional water quality parameters, monitoring requirements and contingency measures are included in Appendix 3 and Appendix 4.

**Figure 8:** ***Evolution of water treatment at East Trinity in North Queensland***

*In 2001, a hydrated lime slurry was pumped through a slotted pipe to treat the water. The green coloured water is the result of hydrolysis, but not oxidation of the ferrous ion. Ten years later, sprinklers were used to ensure the hydrated lime slurry was highly aerated before it reached the water.*

## 7.5 Treatment of small-volume disturbances

Disturbances of small volumes (<100 $m^3$) of soil are not triggered by the Queensland State Planning Policy. However in the course of minor works (usually but not always of a residential nature) small volumes of ASS may be disturbed. In these circumstances, it is neither practical nor economical to expect a field based site investigation and laboratory analysis prior to works being carried out, but some soil management is still expected to meet the general environmental duty under the *Environmental Protection Act 1994*. Considering these issues, nominal aglime application rates are suggested in Table 4.

If the site is located below 5 m AHD and ASS indicators are present (e.g. presence of jarosite, schwertmannite, steely/dark grey marine clays or marine sands, phragmites etc), a preliminary desktop assessment (see Sullivan *et al*. 2018a) may be useful to gauge the overall site risk and appropriate management for small volume disturbances.

*Note: In most circumstances the disturbance of small volumes of soil (e.g. general site preparation, landscaping and fencing etc) are unlikely to cause discernible harm to the environment. Some notable exceptions include legacy disturbed ASS sites and former mangrove swamps where shallow ASS may be encountered.*

The liming rates in Table 4 are based on an examination of laboratory results from soil samples collected by the Queensland Government during ASS mapping from 1998 to the time of writing and stored in the State's Soil and Land Information database (Biggs *et al*. 2000). They were generated from the 95th percentile Net Acidity[19] result, split by texture category, for samples where the action criterion of 18 mol $H^+$/t (0.03% S) was exceeded—consequently, this is a subset of the entire ASS dataset. The suggested rates assume 98% pure aglime, a soil bulk density of 1.7 t/$m^3$, and incorporate a safety factor of 1.5. The use of the 95th percentile cut-off implies a potential failure rate of five in 100 applications, a risk that must be accepted by those choosing to employ nominal liming rates. Where the soil texture is stratified, or unknown, it is recommended to use the more conservative fine texture liming rate. To ensure a conservative liming rate is used, the texture

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[19] Potential Acidity was determined by Chromium Reducible Sulfur ($S_{CR}$) or Peroxide Oxidisable Sulfur ($S_{POS}$), Actual Acidity was determined by Titratable Actual Acidity (TAA) and Retained Acidity was determined by Net Acid Soluble Sulfur ($S_{NAS}$) or Residual Acid Soluble Sulfur ($S_{RAS}$) (with appropriate corrections). Acid Neutralising Capacity was not considered in the Net Acidity calculations.

categories differ slightly from the action criteria of Table 2, with peats listed separately. See Appendix 7 for an explanation of the methodology used to create these liming rates.

**Table 4: Nominal liming rates for small-volume (<100 m$^3$) disturbances of ASS**

| Type of material | | 95th percentile Net Acidity | Kilograms of aglime / m$^3$ of soil |
|---|---|---|---|
| **Texture range (NCST 2009)** | **Approx. clay content (%)** | **Equivalent acidity (mol H$^+$/t)**<br>**Equivalent sulfur (%S)** | |
| *Coarse: sands* | <10 | 449 mol H$^+$/t<br>0.72 %S | 58 |
| *Medium: loams* | 10–35 | 1067 mol H$^+$/t<br>1.71 %S | 139 |
| *Fine: clays* | >35 | 1634 mol H$^+$/t<br>2.62 %S | 213 |
| *Peats* | - | 1478 mol H$^+$/t<br>2.37 %S | 192 |

The dataset underpinning Table 4 cannot be considered truly representative of iron sulfide occurrence in Queensland ASS because the sampling strategies involved in gathering the data were designed for a specific purpose—in most cases to produce a map of ASS occurrence. At best, the dataset can be considered to represent the iron sulfide content in coastal soils under 5 m AHD elevation, which were considered important to sample by local government/state government and/or the soil surveyor, and

- were sufficiently accessible to gather a sample; and
- were of a character suitable for laboratory analysis (i.e. field tests and site description data indicated that analytical results would be useful for mapping).

Coastal ASS environments that are probably under-represented include dense mangroves, national park or other environmental reserves and areas beneath the built environment. However, these under-represented areas are less likely to be disturbed. Peats are also under-represented as only 117 samples across Queensland were analysed.

***WARNING****: These nominal rates are not appropriate for soil volumes greater than 100 m$^3$ under any circumstances. The risk of mismanagement and environmental harm becomes unacceptably high when large soil volumes are treated without proper care. The volume of the disturbance must not be split into separate 100 m$^3$ cells to avoid requirements of the SPP or requirements to complete an ASS investigation in accordance with the latest Queensland Sampling Guidelines.*

## 7.6 Non-sulfidic acidic soils

Within some ASS landscapes, it is not always easy to accurately predict or formally prove whether soils with high Titratable Actual Acidity (TAA) results are due to the oxidation of sulfides. High TAA results may be attributed to a variety of reasons including age, landscape position, geochemical interactions or other soil-forming processes. These soils can include highly organic peats, heavily leached iron and aluminium rich tropical soils, and some coffee rock horizons in coastal Podosols which may overlie or are adjacent to ASS.

*Note: Research in Western Australia has concluded that minerals within coffee rock of the Podosols of the Bassandean Dunes can contain trace amounts of microcrystalline pyrite and native sulfur but no ANC. Small amounts of these minerals can generate acidity (Prakongkep et al. 2012). To date* *the pyrite content of coffee rocks of Queensland have not been sufficiently researched. It is however known that some of the Podosols and coffee rocks of SEQ and the coastal islands also contain microcrystalline pyrite with no ANC.*

If the acidity is derived from the oxidation of iron sulfides, there is likely to be evidence of:

- mottles and coatings with accumulations of jarosite or other iron and aluminium sulfate or hydroxy-sulfate minerals such as natrojarosite, schwertmannite, sideronatrite, tamarugite
- underlying sulfidic material (Sullivan *et al*. 2010)
- $S_{CR}$ greater than or equal to 0.01 %S
- soluble sulfate (e.g. $S_{KCl}$ >0.03%).

Groundwater quality parameters can also be used to indicate the presence of ASS. For example, a soluble sulfate to soluble chloride ($SO_4^{2-}:Cl^-$) ratio greater than 0.5 is a strong indicator of an extra source of sulfate from sulfide oxidation. Note that the utility of the $SO_4^{2-}:Cl^-$ ratio to identify ASS materials diminishes as the salinity of groundwater approaches that of freshwater. In freshwater systems, a sulfate to alkalinity ($SO_4$:alkalinity) ratio of greater than 0.2 may indicate sulfide oxidation (Mulvey 1993; Shand *et al.* 2018; Sullivan *et al*. 2018a).

In strongly acidic soils, and situations where acidic groundwater interacts with highly weathered sediments (commonly found at the Sunshine Coast, Maryborough and Burrum Heads), exchangeable or dissolved iron and aluminium present at low pH can be a source of acidity through hydrolysis reactions. Acidity from organic acids can be released over a range of pH values. While acidity from these scenarios would normally be released slowly in a natural setting, excavation and disturbance alters the soil structure and hydrology, resulting in the breakdown of organic matter, mobilisation of acid and acidic cations, and an increase in the rate of acid, iron and aluminium export from such soils.

There are scenarios where there is a mix of strongly acidic soils and PASS within the same soil profile. For example, in areas around Coolum on the Sunshine Coast, deep coring identified PASS below acidic Podosols with Pleistocene aged coffee rock (Malcolm *et al.* 2002). Any deep soil disturbances in this landscape would require a thorough risk assessment, as it would be difficult to separate the non-sulfidic acidic soils from the ASS.

Management within all ASS terrains where the source of acidity is unclear should be based on an appropriate risk assessment, which has quantified risks relating to the volume of soil disturbed, soil morphology, geomorphology, laboratory results, the end use of the product, whether it will be compacted and have a low leachate flow through rate, and its proximity to sensitive areas such as acidophilic ecosystems (whose health depends on maintaining the acidic environment). The risk assessment should determine what management is required (e.g. no management for leached kaolinitic non-ASS clays that are being re-used on site; versus management of organic acidity via incorporating lime-enriched perimeters around temporary stockpiles). Risks to the structure of in-ground infrastructure may also need to be considered, along with the fertility requirements for any post disturbance land uses—in these situations, seek expert advice from the relevant suitably qualified expert. At all times, the general environmental duty will apply.

*Liming of naturally acidic ecosystems, leading to unnaturally alkaline environments, can result in ecological damage to the acidophilic organisms that rely on the acidic nature of these ecosystems (Sullivan et al. 2018b).*

The treatment of these soils should be assessed on a case-by-case basis and the regulatory decision makers should consider the results of the risk assessment, the sensitivity of the landscape and specifics of the management that is proposed. The key is to minimise risks while aligning with the natural environment.

### 7.6.1 Acidic groundwater

There may need to be consideration of other complicating factors such as the presence of acidic groundwater on site occurring in conjunction with deeply weathered sediments (such as those commonly found around the Sunshine Coast, Maryborough and Burrum Heads). Upon excavation of soil or sediment, acidic groundwater can encounter clay particles, causing aluminium and other metals to dissolve. Dilution and use of natural groundwater buffering is not an accepted management practice for the treatment of acidic groundwater. If sustainable management options cannot be used with these soils, then avoiding disturbance would be the most appropriate solution.

# 8. Hydraulic separation

The process of hydraulic separation involves the partitioning of sediment or soil fragments or minerals using natural or accelerated differential settling into two or more fractions, based on differences in grain size and grain density. Hydraulic separation techniques are commonly used in the development industry for wet excavation of artificial water bodies, in the sand and gravel extraction industries, as part of maintenance dredging in lakes and canals, or as part of capital dredging of navigation channels in ports and harbours.

Hydraulic separation of fine-textured sulfides from coarse-textured material can be a cost-effective form of ASS management in areas where the sediments contain less than 10–20% clay and silt and have low organic matter content. For hydraulic separation techniques to work effectively, soil fragments or mineral grains must be easy to 'liberate' from each other in the separation process. The separation of sulfide grains into one fraction will be poor if the grains are well cemented, if the soil contains too much clay, and/or if the sulfides are contained in the organic matter or peaty material. These materials do not separate easily.

**ASS Tip 23: Hydraulic separation as affected by soil texture**

As a general rule:

- 10% clay and silt, and low organic matter: should work
- 10–20% clay and silt: worth investigation, but can be problematic, particularly if high in organic matter
- >20% clay and silt: unlikely to work. Consider alternative management strategy.

Hydraulic separation will not be successful unless all the material can be adequately dispersed and kept in suspension. Dredging areas with highly variable textures will be problematic. Dredge operators should avoid distinct clay layers and treat them separately (e.g. through screening), but thin clay layers or lenses within low-clay sediments may be unavoidable. Dredging such variable composition sediments together may generate sulfidic clay balls in the dredged product, necessitating subsequent treatment of the entire volume. Other factors may also influence whether hydraulic separation is suitable at a site, including discharge water quality, long-term storage and management.

Types of hydraulic separation that will be discussed in this section include hydro-sluicing and hydrocycloning. As the process names imply, the sediment particles to be separated must be suspended in large volumes of water for the processes to work. This is important as it minimises the exposure of the fine sulfide particles to oxygen during the separation process. Sulfidic fines or 'slimes', are generated because of the process, and need specialised management, similar to the principles outlined in Sections 7 and 9. Other hydraulic separation techniques such as 'boiler-box' or 'sluice-box' may efficiently separate sulfides, but they too should be validated, and similar management considerations applied.

Both hydro-sluicing and hydrocycloning separation methods can be added to a dredging process stream, where the dredging activity directly supplies the feed slurry for the separation process, or as an addition to other processes. Dredging works require approval under the *Environmental Protection Act 1994,* the *Planning Act 2016, SDPWO Act 1971* and/or the Australian Government's *Environment Protection and Biodiversity Conservation Act 1999*.

The associated costs involved are the intensive management and monitoring of the process itself and final management of the concentrated sulfidic fines, but despite these costs, savings on earthmoving and neutralising agents may be achieved using hydraulic separation techniques.

Rigorous site management is a necessity as no form of hydraulic separation will remove 100% of the sulfidic fines. Hydrocycloned or hydrosluiced sand may still produce significant amounts of acid, requiring guard layers, water pH control, in-line dosing and neutralising procedures to reduce long-term risk.

**Hydro-sluicing** is the process whereby sulfidic fines are hydraulically separated from higher density sands at the discharge point during a dredging operation and the sands are then used as fill. The 'sluice' is the artificial channel for conducting water or regulating flow from or into a receptacle (e.g. still water body or pond). Sluicing is a form of settling-based separation run as a continuous process stream, as opposed to a batch-type settling process that might apply to a sedimentation basin removing suspended solids. Operationally, hydro-sluicing is a relatively difficult form of settling separation due to it being a continuous process. Further complexity is added by the goal to 'settle' the heavier or larger particles out of the slurry at a given location, while retaining the fine particles (including sulfides) in suspension until the end of the hydro-sluicing channel where fine particles are either collected or settled in a still water body. The water body should be sufficiently deep to avoid resuspension if it is to be the final repository of sulfidic materials.

The sulfidic fines remain in a stable, wet and largely unoxidised condition throughout the process as they are kept in suspension by the turbulence of the water. They are then returned to an anoxic, preferably anaerobic (reducing) environment, at the base of the water body where they may be capped (if possible). Alternatively, the sulfidic fines may be washed down to a collection point for partial dewatering and neutralisation (Dobos and Neighbour 2000).

Hydraulic separation using **hydrocyclones** is used extensively in the mining and extractive industries, particularly in sand and gravel screening. Cyclones are centrifugal classifiers used primarily to separate particles based on their size and density (see Figure 9). During operation, a slurry feed is introduced to the hydrocyclone under pressure and the solid particles of different weights in the 'feed' are separated by centrifugal drag and to some extent gravity.

Hydrocycloning is one of the most effective mineral separation methods for uniform or constant feeds, however, greater process control is needed when the material fed to the hydrocyclone becomes increasingly variable. Hydrocycloning may not be effective in separating the fine-grained sulfides if the material is too variable, clayey or cemented.

A sand particle suspended in the slurry rotating in the hydrocyclone will tend to move towards the wall of the cyclone if the centrifugal force acting on it is greater than the drag force created by the velocity of the feed flow. If the drag force of the fluid velocity is greater than the centrifugal force generated by the hydrocyclone, then the fine particle will tend to move inwards.

Hence, larger particles tend to move to the outside wall of the cyclone and are discharged from the spigot at the bottom of the hydrocyclone. The resulting process stream is called the target-flow and should contain the desired sand or gravel product. The target-flow must meet the performance requirements stated for ASS being treated by hydraulic separation techniques (see Section 8.2). Smaller particles (including the sulfidic fines) generally move to the centre of the hydrocyclone and are discharged through the vortex finder at the top of the cyclone, along with most of the fluid from the feed slurry. This process stream is called the reject flow or overflow and must be managed to prevent the oxidation of sulfides (e.g. by strategic reburial) or treated using neutralising techniques.

Like hydro-sluicing, hydrocycloning is not a perfect separation method, hence the requirement for both constant management of the process and verification testing of the target flow product. Problems can result from taking short-cuts resulting in some coarse particles in the reject flow, or (of greater concern to an ASS manager) entrainment of fine-grained sulfidic particles with the target-flow product.

Occasionally, the source material may be reprocessed to produce multiple size fractions (e.g. gravel, coarse sand, fine sand). The sulfidic fines should be removed during the first round of separation during the hydrocycloning process, so that they are processed once with minimal exposure to oxygen.

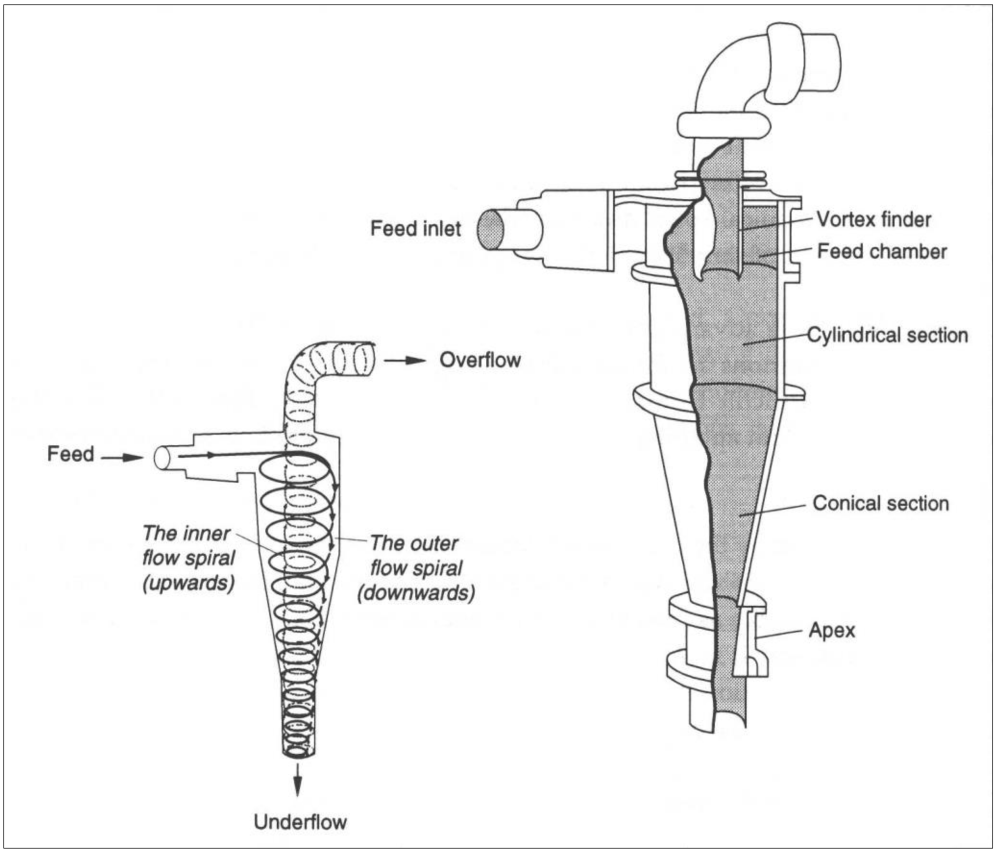


**Figure 9: The hydrocyclone, showing main components and principal flows**

*Note: This figure has been reproduced from Napier-Munn et al. (1996) with permission from the Julius Kruttschnitt Mineral Research Centre (JKMRC) at The University of Queensland.*

## 8.1 Environmental risk

Considerable risks to the environment are associated with the process of hydraulic separation. These are outlined below.

*Note: Refer to latest National guidance material for dredging ASS for more specific information on the potential risks during dredging operations (specifically to the water column and surrounding aquatic environment) and during disposal of dredged spoil materials within water bodies (open-water disposal), including confined (dyked) disposal resulting in creation of new land or on existing land.*

### 8.1.1 Site management

High process and site management standards are required when applying hydraulic separation techniques due to the significant reliance on technology and the inherent limitations in performance when dealing with variable materials. In situations where washed sands are trucked offsite, such as in the sand and gravel extraction industry, then QC procedures should be in place to make sure that only material that has satisfied the performance criteria is allowed to leave the site. Alternatively, further management offsite may be needed, and this can be difficult to carry out and enforce. This approach contains greater environmental risk as management protocols can no longer be controlled by the supplier.

### 8.1.2 Oxygen exposure

Exposure of the sulfides to oxygen can occur during several stages of the process and this increases the level of risk. Measures to avoid oxygen exposure should be put in place during:

- extraction
- delivery of the sediments to the separation process stream
- during each step of the separation procedure itself
- following the separation procedure.

There are greater risks to the receiving environment if acidity is generated when stockpiles of sandy material dry out while waiting to be hydrocycloned. Coarse sand stockpiles will dry out faster than stockpiles of fine sand. If there is a rainfall event while the soils are stockpiled any generated acid is likely to be mobilised.

The risks of acidification and/or deoxygenation of the water body also increase if monosulfidic black oozes are being dredged and are exposed to oxygenated water during the process (either through oxygenated water or by inefficient separation and placement in aerobic conditions in the washed sands). Refer to the National Guidance material for MBOs.

### 8.1.3 Inefficient separation

Neither hydro-sluicing nor hydrocycloning will remove 100% of the sulfides and not all source material is suitable for separation by these processes. Poorly separated fill material may result in clumps of peaty or clayey sulfidic material, scattered throughout the washed sands. Fill containing these clumps can cause long-term problems associated with acid leachate.

Addition of neutralising agents will be necessary if the separation process is inefficient. Mixing insoluble neutralising agents such as fine aglime below the usual working depth of incorporation for earthmoving equipment is difficult. Working stockpiles of dredged sand that are up to a metre high may need considerable effort to achieve sufficient mixing of the neutralising agent. Alternatively, the materials will need to be reprocessed. In-line treatment may be feasible, but the neutralising agent will need to be graded to ensure it remains mixed with the extracted material on deposition. A pilot trial to verify its effectiveness may assist.

Water treatment will also be necessary if enclosed water bodies become acidified. This may be a warning signal that separation processes are not working as predicted. Refer to DER (2015) for more information on water treatment.

### 8.1.4 Process waters

Hydrocycloning generally uses a closed water circuit, which may become progressively enriched with non-settling fines. These fines may impede the separation process. Eventually this dirty water will need separate treatment or replacement. Such process waters may become acidic, and if so, will require neutralisation.

### 8.1.5 Stratigraphy

In general, sites with highly variable soil stratigraphy pose the greatest risk when undertaking hydro-sluicing or hydrocycloning. Hydrocycloning needs a feed of consistent composition to be most efficient and this is rare in most sandy sites. While small bands of marine clays within the sandy sediments may wash sufficiently, large bands of heavy marine clays or cemented coffee rock layers may be difficult to isolate and treat. The result can be unacceptable levels of pyritic clay and/or organic clumps in the final product.

Good site characterisation provides a detailed understanding of local stratigraphy, allowing potential issues with poor separation to be avoided in the planning phase.  This is particularly important for large extraction projects.

### 8.1.6 Volume of sulfidic fines

It can be difficult to accurately project the volume of sulfidic fines from any proposed large hydraulic separation project if the *in situ* materials are heterogeneous.  The fines volume will increase due to a 'bulking by water' effect as fines are separated from the coarser (ideally largely sulfide-free) fraction.  These fines are poorly draining and will take significant time (i.e. years) for large volumes in their final location to dewater and compress.  The uncompacted wet volume of fines must be considered (not the final compacted volume) when calculating the volume of void for the reburial of the sulfidic fines (i.e. enough void needs to be available to accommodate the uncompacted fines).  A mineralogical assessment of the fines is needed to better predict the extent of bulking that will occur.  Sufficient allowance must be made to account for unexpectedly high volumes of sulfidic fines in sites that have a highly variable stratigraphy.  It may be difficult to calculate the volume of the void needed for reburying the fines in these situations and the volume of the fines generated after hydraulic separation.

### 8.1.7 Post-separation risks

At the completion of hydraulic separation, the sulfidic fines will be concentrated and may be either stored in an anoxic environment or dried sufficiently to allow treatment for their Net Acidity using neutralisation techniques.

Two further management issues will need to be addressed if the fines are to be stored in an anoxic environment.  Firstly, the stream of suspended fines must be managed to minimise any further exposure to oxygen following separation.  This should include avoiding spraying or increasing the turbulence in this stream as it may increase the concentration of dissolved oxygen within the suspension water.  Secondly, the suitability of the anoxic storage location to be used should have been proven before any works commence.  This storage is a form of strategic reburial (see Section 9).

Treating fines with a neutralising agent poses a high environmental risk due to the amount of Potential Acidity that may be produced by the fine textured material while drying.  Hydrological isolation of the treatment area from the receiving environment is essential.  The risk may be unacceptable if pH-sensitive environmental values are in proximity and threatened by the quantities of acid and/or neutralising agent involved (see Section 7).

There may be opportunities to consider the effectiveness of different sized shell fractions contributing to ANC during capital dredging operations of harbours and estuaries (see Simpson *et al.* 2018).

### 8.1.8 Large deposits of previously dredged fines

Sluicing large deposits of previously dredged fines to recover sand is unlikely to be cost-effective.  The value of the sand recovered will be offset by higher levels of management needed to achieve acceptable levels of environmental risk (assuming the sand can be recovered with acceptably low sulfide content).  Rehandling of older (potentially partly oxidised) dredge fines may entail a much higher usage of neutralising agents to keep pH of water and soil at acceptable levels.

### 8.1.9 Sulfidic fines and Actual and/or Retained Acidity

There may be risks to the environment if soils that have significant measurable Actual and/or Retained Acidity are hydraulically separated.  After these fines have been reburied in anoxic conditions, Actual and/or Retained Acidity may still contribute to the acidification of the waterways or extraction pond. Furthermore, aluminium, iron and other metals that are more soluble in acidic waters may be mobilised. Other oxidising agents, which may be present in partially oxidised soils, such as $Fe^{3+}$ ions in pre-existing acidic pore waters, may cause further sulfide oxidation and generation of acid despite the exclusion of oxygen. This will continue until readily available $Fe^{3+}$ ions have been consumed by the reaction (see Section 10.3).

### 8.1.10 Sulfidic fines and potential for oxidation

Dissolved oxygen can sometimes be high enough to cause significant oxidation of the reburied submerged sulfidic fines. Risks may increase when the oxygen transport mechanism is not limited to diffusion. Moving water can transport oxygen much faster than diffusion, and if the sediments are also resuspended, oxidation reactions may happen even faster. Both oxygen concentration and oxygen transport mechanisms should be considered.

In some cases, strategic reburial is below non-flowing surface water, for example, in a lake. However, even in these situations, the above risks may increase when vertical water circulation or mixing is driven by high winds, rainfall and flood events, etc.

There may be risks to the environment if large bodies of acidic water develop because of situations where anoxic, preferably anaerobic (reducing) conditions cannot be permanently maintained, allowing sulfidic sediments to oxidise.

## 8.2 Performance criteria, verification testing and failures

### 8.2.1 Performance criteria and verification testing

The target performance criteria for hydrosluiced or hydrocycloned non-fines fraction (i.e. washed sand) is a Net Acidity of ≤18 mol $H^+$/t (0.03 %S).

To account for the fact that there may be some residual level in the washed sand, the performance criteria are:

- No sample shall exceed 25 mol $H^+$/t (0.04 %S).
- If any single sample exceeds 18 mol $H^+$/t (0.03%), then the average of any 6 consecutive samples (including the exceeding sample) shall have an average not exceeding 18 mol $H^+$/t (0.03 %S).

Laboratory analysis of samples from the hydro-sluiced/washed sand should be undertaken to assess compliance with the performance criteria for verification testing. A run of consecutive sample failures should alert managers to the possibility of processing failure, and these failures should be treated or reprocessed to pass the performance criteria—otherwise the site will likely fail any required verification testing. The failures should be recorded in the closure report (Section 12).

In some circumstances, a site may be conditioned to more stringent performance criteria than those listed above. An example would be the processing of large volumes of extremely poorly buffered sands in a sensitive environment. In such circumstances, the above criteria may be halved. Where separated sediments are to be permanently placed, the regulatory decision makers may choose to set performance standards around the geotechnical properties of the created landform(s).

Performance criteria are also required for separated fines and are dependent on their final setting. If neutralisation treatment is planned, the criteria are as for Section 7. If strategic reburial (e.g. immediate reinterment in the extraction pond) is planned, the criteria are as for Section 9.

### 8.2.2 Verification testing rates

Verification testing rates are necessarily site-specific and may be set as a condition of approval to disturb ASS. Factors to consider include disturbance volume, treatment area size, Net Acidity content, ease of mixing and test scheduling. Suggested minimum volumetric rates (depending on Net Acidity) are:

- volumes of <250 $m^3$ = two samples
- volumes 251–500 $m^3$ = three samples
- volumes >500 $m^3$ and ≤1247 mol $H^+$/t (≤2 %St) = three samples, plus one sample per additional 500 $m^3$
- volumes of >500 $m^3$ and >1247 mol $H^+$/t (>2 %St) = three samples, plus one sample per additional 250 $m^3$.

An appropriate sampling design for verification testing must be selected and developed by a suitably qualified ASS scientist. Composite samples (comprising 6–8 samples) are recommended. Sampling design procedures described in NEPM (2013) may be an option. Example sampling procedures are contained in ASS Tip 16 and is relevant to verification sampling for both neutralisation and hydraulic separation.

*Note: Verification testing is an important part of on-site management and internal QA procedures. It is important to conduct verification sampling and laboratory analyses in a transparent manner, followed by prompt remedy of any treatment failures*. ***The action required for any verification failures must be documented in the ASS EM plan.***

*Note: QA/QC procedures may also require the collection of duplicate or triplicate samples.*

### 8.2.3 Failure to meet performance criteria

If the performance criteria of the washed sands are not met, the material will need to be fully treated with a neutralising agent (see Section 7) or reprocessed to achieve the above performance criteria. A neutralising guard layer beneath processed materials will serve to reduce risks.

Reprocessing may be preferable to neutralisation if the material has been placed to a depth of greater than 300 mm and has failed the above performance criteria. It may be difficult to effectively mix sparingly soluble neutralising agents (e.g. fine aglime) in thick layers of placed material. There can be problems with the reprocessing if the fill material has been exposed to oxidising conditions long enough to cause partial oxidation of the sulfides. Reprocessing would only be appropriate if Actual and/or Retained Acidity can be neutralised (e.g. by in-line dosing of the process water) and the resultant sands meet the performance criteria.

These points highlight the importance of placing fill in thin layers until verification testing has been completed. If further neutralising treatment is needed following separation processes, re-processing costs will be lower for fill in thin layers, compared to fill placed in thick layers. This also highlights the need for quick turnaround of the verification tests, and the need to take into account time delays related to verification.

Geotechnical issues may also arise if gypsum and ettringite products are formed as a result of any neutralisation reactions. Expert geotechnical advice will need to be sought regarding the suitability of this material for its intended purpose.

**ASS Tip 24: Dredging legacies and ASS**

If dredge spoil is placed permanently on land (especially above Mean High Water Springs), there is a need for a rigorous verification testing regime to confirm the effectiveness of the management. If management has been inadequate, the volumes are generally so great that re-treatment (effectively remediation) becomes a monumental task, and similar to groundwater, once oxidation has occurred, it is difficult and costly to repair.

There are multiple sites across Queensland where the legacy of mismanaged dredging of ASS sediments is now costing time and resources to solve the complex site management to reduce environmental impacts. Bund wall breaches, oxidation of spoil, generation and mobilisation of leachate and insufficient neutralising capacity are common issues that require management. Further impacts may be associated with any proposed pond re-purposing/development and the engineering requirements for structural stability issues may also prove challenging.

It is likely that in the future there will be more pressure for land-based disposal of dredge spoil, rather than ocean disposal.

## 8.3 Management considerations

The following management issues should be considered when hydraulic separation methods are proposed for dredging (hydro-sluicing, maintenance dredging or capital dredging), or sand and gravel extraction.

### 8.3.1 ASS site characterisation

Where hydraulic separation activities are proposed in areas below 5 m AHD, an ASS investigation that shows the concentration and spatial distribution of the sulfides is required. Areas with high sulfide levels should be avoided, since further management may be needed. In some circumstances, it can be cost-effective on large sites to survey the sampling holes and test pits to work up a three-dimensional model for the distribution of sulfide content and for the delineation of clay and peat lenses and horizons. Dredges should be fitted with GNSS units, and an experienced operator should be able to position the dredge within one metre of specific or problematic materials (Dobos and Neighbour 2000).

### 8.3.2 Pilot trial in previously unworked terrains

A pilot trial should be conducted on a relatively small area of up to one hectare to determine whether enough separation can be achieved prior to overall approval of the operation being issued. In some circumstances this may occur after approval but before starting full works. Dobos and Neighbour (2000) stated that in sites with considerable clayey silts and sands, it might be necessary to take representative composite samples of 10 kg and run bench tests in the laboratory to check the efficiency of the separation process. These can be costly and might ultimately prove unsuccessful. Alternatively a full cost-benefit analysis with a ‘go wrong plan’ may be a more appropriate method to use in previously unworked terrain.

**ASS Tip 25: ASS site characterisation for dredging operations**

The following documents refer to site characterisation for dredging operations:

- *National Acid Sulfate Soils Guidance: National acid sulfate soils sampling and identification methods manual* (Sullivan *et al.* 2018a)
- *National Acid Sulfate Soils Guidance: Guidelines for the dredging of acid sulfate soil sediments and associated dredge spoil management* (Simpson *et al*. 2018)
- *National Assessment Guidelines for Dredging 2009* (Commonwealth of Australia 2009).

In general, for all dredging projects involving ASS, the recommended reference is the *Guidelines for the dredging of acid sulfate soil sediments and associated dredge spoil management* (Simpson *et al*. 2018).

Appendix B from Simpson *et al*. 2018 states:

'*The choice of sampling locations and number of samples taken for a dredging project may significantly influence the assessment outcomes. The sampling and analyses required will vary from project to project but should adequately represent the area under consideration. It will involve collecting many samples to cover both the location area and depth of dredging. A rationale for the sampling site selection and analyses at each site should be provided*.'

***How many sampling locations?***

Table B1 (Simpson *et al*. 2018) specifies the number of sampling locations, based on the volume of material to be dredged (up to 509 000 m$^3$). However, more detailed sampling (e.g. as per Sullivan *et al*. 2018a) may be recommended for some dredging activities (e.g. high-risk proposal, land based disposal of dredged material, known ASS areas, preliminary lab testing shows high and/or variable levels of Net Acidity, sediment composition or distribution of ASS and contamination is potentially very variable, geographically complex dredge area etc.). Also, sampling at regular intervals (rather than randomised across a dredge area) is recommended for linear dredging activities. Any variation from the recommended sampling rate will require negotiation with regulatory agencies and will require scientific evidence as justification.

*Note: For projects involving dredging of greater than 509 000 m$^3$, either divide the area into smaller zones and use Table B1 or use the formula in the National Assessment Guidelines for Dredging 2009 to calculate the number of sampling locations.*

***How deep to sample?***

Sampling should include the full depth of the proposed dredging, and a buffer to allow for dredging inaccuracy (at least 1 m below the proposed level).

***How many samples to collect and analyse?***

Samples should be collected every 0.5 m down the core. Field tests ($pH_F$ and $pH_{FOX}$) should be carried out on all samples collected. Laboratory testing to determine the Net Acidity should be conducted on all samples collected, unless adequate justification is provided. It is customary in core sampling to collect composite samples at 0.5 m intervals (0–0.5 m, 0.5–1 m, 1–1.5 m, 1.5–2 m etc) which can then be sub-sampled for field and laboratory testing.

*Note: Care must be taken when sampling bottom sediments in drains, or sediments likely to contain appreciable monosulfide materials. These will require specialised sampling, storage and treatment.*

### 8.3.3 Guard layers

An essential risk reduction system for all hydraulic separation techniques involves spreading a neutralising agent on the soil surface before placing any washed sand. A thin layer of washed sand with the neutralising agent incorporated into it may also suffice. This layer is intended to intercept and neutralise any acidity that may flow downwards through the washed sand and will help protect groundwater quality. Guard layers are not a primary management tool and should not be used as a leachate treatment system.

Hydrocycloning operations should also use a guard layer, unless a concrete surface is in place and a containment system is installed that will capture and treat all leachate. A compacted layer of crushed limestone below the guard layer is an additional means of reducing the risk.

The rate of neutralising agent used in the guard layer in hydraulic separation operations will depend on the projected thickness of the washed sand and the Net Acidity of the sluiced/washed sediments. The rate may need to be increased where the receiving environmental values need higher protection, or after poor performance of the hydraulic separation process.

Most sites will require a minimum blanket rate of 5 kg fine aglime/m$^2$ per vertical metre of placed washed sand. For example, if two metres of washed sand are to be placed, then 10 kg of fine aglime/m$^2$ should be spread as a guard layer. This rate may need to be increased at sites that have difficulty achieving effective separation or in an area where the receiving environmental values need higher protection.

### 8.3.4 Quality control

Clumps of ‘cemented’ grains, clay balls, clay-silt aggregates and dense matted organic matter (peat or coffee rock), which may contain significant quantities of sulfide not separated from the sand via hydro-sluicing operations, can inadvertently be buried within the washed sand. These materials can cause long-term problems associated with acid leachate. Quality control (comprising visual inspection, sampling and laboratory analysis) is needed to make sure that inadequately washed soils are detected. Washed sand should meet the performance criteria in Section 8.2.

Hydrocycloning operations should be optimised to produce materials with an absolute minimum of sulfides due to their potential for corrosive leachate production. In NSW and Queensland (as well as overseas), legal complications have arisen after supplies of extracted material contaminated with sulfides have been sold. Such materials need to be identified and treated before sale or use and should satisfy the performance requirements stated for ASS being treated by hydraulic separation techniques. Note that large quantities of coarse textured sand with Net Acidity less than 18 mol $H^+$/t (0.03 %S) may still generate appreciable amounts of acidity. Depending on final application and placement of the hydrocycloned sands, even these low levels of sulfides may need management, for example, the addition of some neutralising agent. The presence of salt within the sand matrix may also need to be addressed in any reuse application.

Accurate spatial tracking of soils is critical to make sure that the location of soils requiring re-processing or liming can be readily identified.

### 8.3.5 ‘In-line’ addition of neutralising agents

Hydraulic separation techniques provide unique opportunities for in-line addition of neutralising agents. Such applications may serve more than one purpose, including:

- keeping process waters in a neutral pH range during processing should any oxygenation of fines occur during processing
- providing more neutralising capacity to the sulfidic fines fraction:

  - to protect against minor acidification that might occur during separation and before storage
  - to achieve a well-mixed neutralising agent application to the fines if they are to be treated by neutralisation
- providing more neutralising capacity to the coarse fill or sand and gravel product fraction:
  - to manage the risk of any inefficiency in the separation process that might leave sulfidic fines entrained within the coarse fraction (this does not negate the need for verification testing)
  - to directly treat Actual and/or Retained Acidity that may already be present in the soil.

In-line methods to neutralise washed fill and sulfidic fines are generally untried and will require validation using small-scale pilot trials. For such methods to work in the field, management issues that will need to be addressed include:

- correct choice of the type of neutralising agent to treat the target fraction. For example, a soluble neutralising agent to treat the water fraction or a relatively insoluble neutralising agent to be deposited with the sediment fraction
- correct choice of the particle size of neutralising agent to ensure its entrainment and deposition with the target fraction of the suspended sediment. For example, a superfine particle to be entrained with the sulfidic fines or coarser particles to be entrained with the coarse sand and gravel fractions
- dosing with a high enough rate of neutralising agent to make sure that the total amount added is in excess of the Net Acidity. This rate will be greatly dependent on the soil type, the Net Acidity characteristics, and the rate of slurry pumping; all will vary dynamically, depending on the source material. If the latter is too variable, this technique may need overdosing, which in turn will raise treatment costs. The upper pH level also needs to be kept in mind
- deciding where in the process stream to add the neutralising agent to the slurry for most effective treatment
- determining the mixing efficiency that can be achieved
- determining whether the neutralising agent dose will settle with the processed material rather than escaping in process waters (this is where the in-line treatment process is most likely to fail). Bulk density characteristics of the sediment and neutralising agent need to be considered along with allowance for potential tail waters loss of neutralising agent
- selecting an appropriate rate for verification testing and adjusting the rate depending on performance.

### 8.3.6 Earthworks strategy

An earthworks strategy should be formulated to make sure that the capacity of fill placement and treatment areas and sulfidic fines strategic reburial areas are sufficient to accommodate the projected extractive rates and volumes; and appropriately located to minimise environmental risk. The quality of the earthworks strategy is critical to the smooth running of the project, particularly on smaller sites.
An earthworks strategy should consider construction sequence, interfacing with other work fronts, total volumes and daily rates of soil excavated and/or filled, treatment rates, timing between excavation, temporary stockpiling, treatment, verification and reuse/ disposal of sulfidic fines. It is important to consider all activities that will be taking place on site (preferably against a timeline with the earthworks), to make sure that time factors will not affect the availability or capacity of treatment and storage areas.

Sulfidic fines need to be placed into an anoxic, preferably anaerobic (reducing) storage area.  If provision of that storage area entails prior over-excavation of a void, then the earthworks strategy will need to define the needed time, location and volume of that void.  Sufficient space must be available within the void to accommodate the volume of the sulfidic fines slurry.

An earthworks strategy should be timed well enough to make sure that stockpiles of sulfidic sandy material are not allowed to dry out while waiting to be separated.  If this is unavoidable, further management measures must be undertaken (see Section 10.2).

### 8.3.7 Location of sulfidic fines

The location of the sulfidic fines and the depth of the reburial should be recorded (e.g. survey with GNSS, RTK, differential GPS, conventional survey etc depending on the level of accuracy needed) and reported to the relevant local government and other regulatory decision makers.  Local governments will need this information to enable them to make informed decisions about maintenance dredging, and future land uses that could potentially impact on these areas.

Hydrographic surveys may also be needed after strategic reburial of sulfidic fines to assess whether the fines have been placed and/or stayed where they were supposed to be.

Any management requirements associated with the location of sulfidic fines should be clearly listed for all stakeholders to make sure that responsible short- and long-term management occurs at the site.

### 8.3.8 Management of sulfidic fines

At the completion of hydraulic separation, the sulfidic fines will require further management (refer to Figure 10).  See Section 9 if the fines are to be strategically buried.  See Section 7 if the fines are to be dried and treated by neutralisation techniques for their Net Acidity.  Other management options are also required for dyked or bunded proposals, as also depicted in Figure 10.  These are further described in the *National ASS Dredging Guidelines*.  For land-based disposal, refer to Section 4.5.2 of the *National ASS Dredging Guidelines*.

*Note: Dredged sulfidic fines have a greater risk of re-suspension and oxygen transfer than non-dispersive clays.  A limnological investigation may be needed to decide whether such a risk is significant (see Appendix 5).*

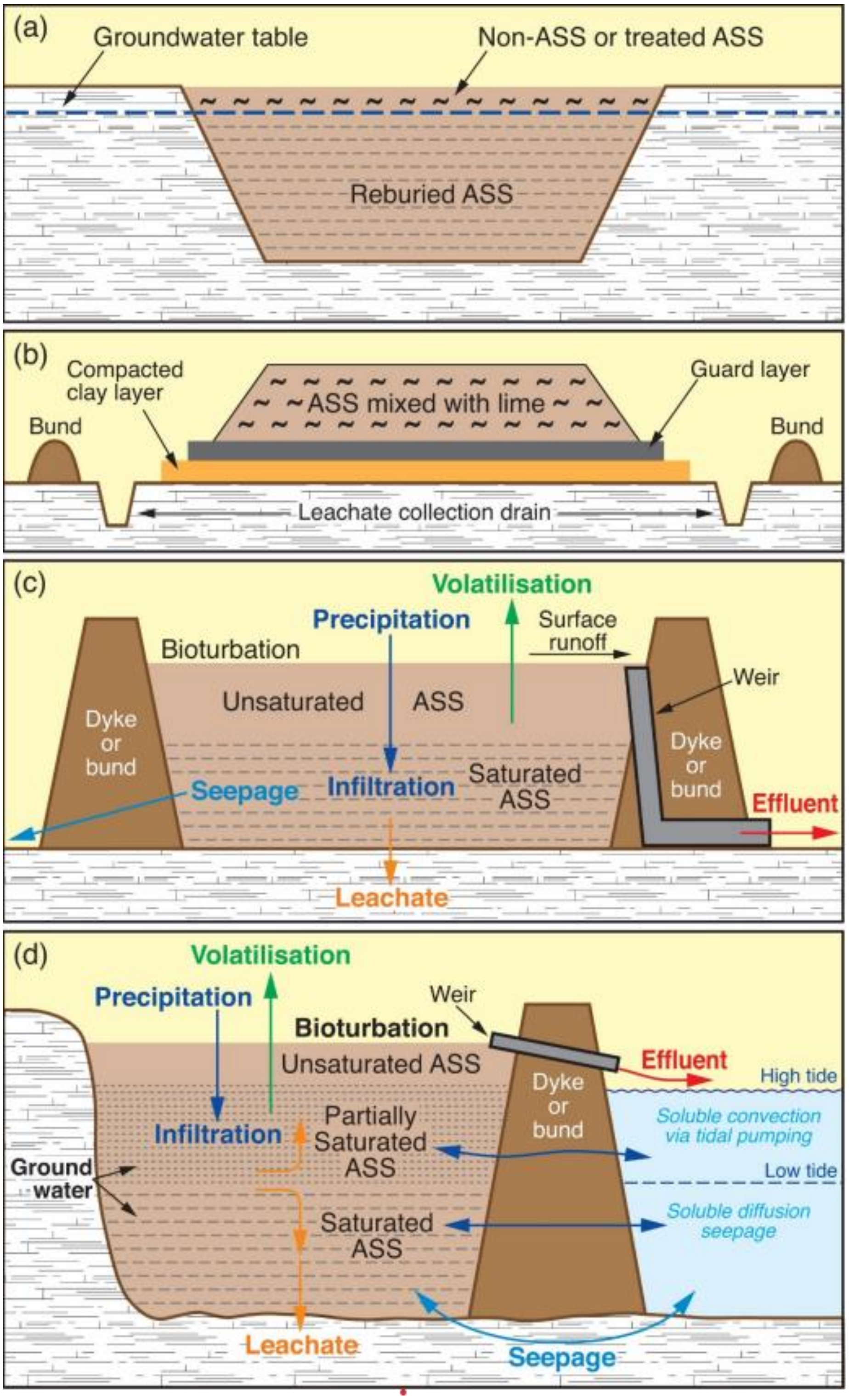


**Figure 10: Future management options for sulfidic fines**

*(a) strategic reburial, (b) and (c) on-land placement with different treatment and containment measures, and (d) shoreline containment (modified from USEPA 2004; Dear et al. 2014 and reproduced from Simpson et al. 2018). Note that other containment structures may also exist.*

### 8.3.9 Enhancing the removal of sulfidic fines during hydro-sluicing

Several methods are available to enhance the removal of sulfidic fines during hydro-sluicing. The following dredging operation control features have been shown in South East Queensland sites to aid separation of sulfidic fines from the coarse fraction (Dobos and Neighbour 2000):

- use of a ‘bucket wheel cutter suction dredge’, not a ‘suction dredge’
- ensuring that dredge material that contains significant amounts of sulfidic clay lenses or coffee rock layers also contains enough sand to ensure the break-up of clumps of clay and coffee rock
- dredging continuous peat or clay horizons separately and handling them independently at the discharge point by strategic reburial or neutralisation. When the dredge head intersects basement clays or continuous clay horizons, there is greater potential for the material to form clay balls
- increasing the water-to-solids ratio if dredging materials high in sulfides or organic matter; pausing repeatedly, or pumping slugs of water at the end of each arc
- using pumps and pumping arrays that produce high turbulence in the flow. This will promote abrasion and liberation in the pipeline
- ensuring a turbulent flow by incorporating tight bends or right angles in the pipe
- increasing the residence time in the pipeline by increasing its length
- keeping the discharge channel relatively small and water in it turbulent to ensure that the fines stay in suspension and do not settle out and concentrate near the discharge point
- having a swamp dozer or excavator continually working and shaping the discharge area. This keeps the sulfidic fines overflow in one well-defined, steep, fast-flowing channel all the way from the point of discharge to the permanent sulfidic fines storage location
- monitoring the discharge point and using the swamp dozer or excavator to prevent the build-up of fines ‘fans’ that drain through previously washed sands, potentially leaving the fines buried in the fill
- flushing the hydro-sluicing channel with excess water at shut down. This will help prevent the exposure of fines over nights and weekends, resulting in acidification.

The above may be used on a case-by-case basis, depending on the site, the materials to be dredged and the cost-benefit analysis. However, the process requires expert supervision, experienced machine operators and specialised equipment.

**ASS Tip 26: Lime treated sulfidic fines**

Potential issues may arise if aglime treated sulfidic fines are used for construction-fill purposes. These materials may have swelling properties that can cause impacts on surface and sub-surface infrastructure due to the formation of minerals like gypsum and ettringite (Simpson *et al. 2018)*. These soils may be strongly alkaline and/or saline and will continue to react post-treatment, with some of the impacts difficult to predict. Geotechnical advice will be required when applicants are considering re-use of this material for construction purposes.

### 8.3.10 Enhancing the removal of sulfidic fines during hydrocycloning

Hydrocyclone separation performance can be affected by the following:

- design variables – dimensions, spigot diameter etc (and hence design classification performance)
- operating variables – feed rate, feed pressure and concentration of solids in the feed slurry
- compositional variability of the feed slurry—grain size distribution, ratio of clays to sand, sulfide content etc.

If the material being processed is homogenous, it is theoretically possible to find a relationship between the quantity of fines entrained with the target flow and the mass fraction of water discharged with the reject flow. This may help the ASS manager if a relationship can also be found with the results of verification testing. Cyclone efficiency can be graphed for various particle size fractions and may aid the choice of a hydrocyclone that can achieve the best results.

### 8.3.11 Maintenance dredging

Maintenance dredging operations, as approved under the *Environmental Protection Act 1994* (especially in older canal estates and poorly flushed artificial water bodies) may encounter monosulfidic black oozes in large volumes. These substances oxidise rapidly and may be difficult to handle and treat. Under no circumstances should maintenance dredging spoil be left untreated on the banks of constructed or natural watercourses, as this would constitute a violation of Section 440ZG of the *Environmental Protection Act 1994*. See the National Guidance on MBOs for further information.

*Note: all licenced maintenance dredging activities should be carried out in accordance with an approved EM plan. Offsite treatment may be required on a fully contained treatment pad (see Section 7.4).*

# 9. Strategic reburial

Strategic reburial involves the excavation of PASS and its placement in anoxic, preferably anaerobic (reducing) conditions at the base of a void, where sulfide oxidation and hence acid generation is permanently precluded. Areas of non-ASS or soils that can be effectively treated by other means can be excavated for the creation of such voids. The void may be deep (e.g. within the base of a lake, canal or artificial wetland) and covered by low or no-flow surface waters. Alternatively, the void may be a safe distance beneath the seasonally lowest watertable elevation, and hence also below compacted non-ASS or neutralised material (see Figure 11 and Figure 12). The reburial site will require management in perpetuity.

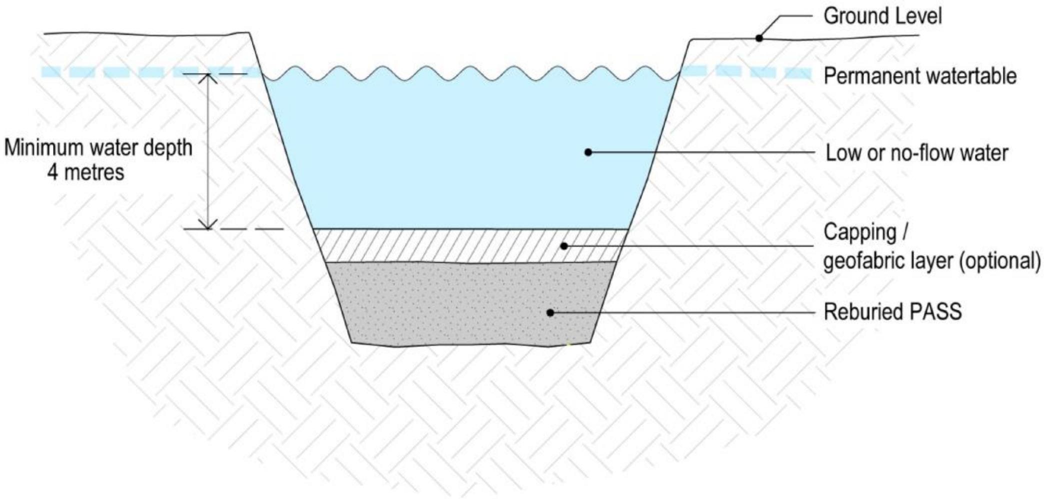


Figure 11: Strategic reburial under surface water

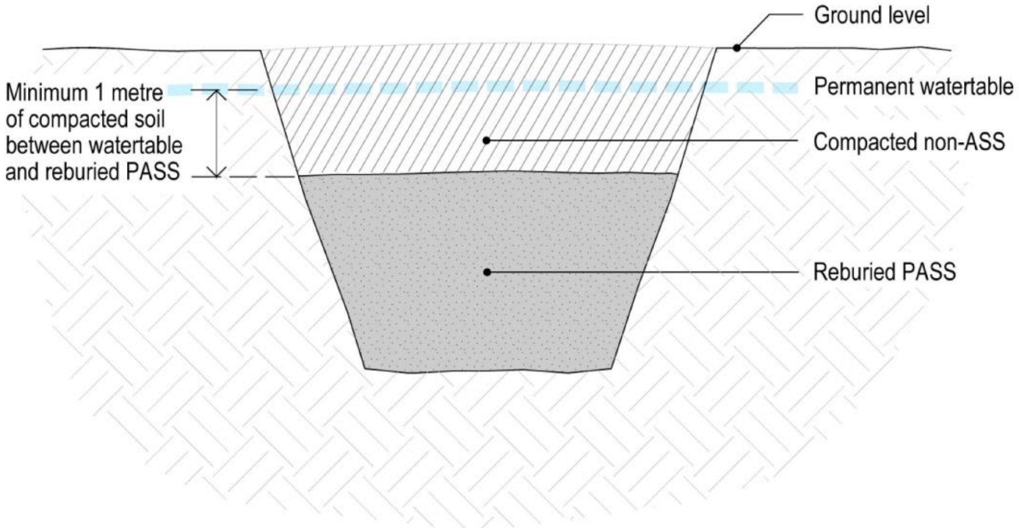


Figure 12: Strategic reburial below groundwater and compacted soil

A range of different materials can be strategically reburied, varying from blocky non-dispersive clays through to sulfidic fines created during hydro-sluicing and hydrocycloning. The risks associated with strategic reburial depend in part on the nature of the material to be reburied. Materials that are easy to resuspend (e.g. sulfidic fines) pose much greater risks than blocky non-dispersive clays (see Section 9.1.3). The level of risk associated with different elements to be strategically reburied is represented in Figure 13.

Strategic reburial without treatment is only appropriate for PASS, although it may sometimes be appropriate to rebury fully treated and verified ASS.

The technique of strategic reburial is based on the principle of keeping PASS in anoxic, preferably anaerobic (reducing) conditions in perpetuity. Limiting or excluding oxygen from the reburied soils governs the effectiveness of strategic reburial as the amount of sulfide oxidation is largely dependent on oxygen supply. When considering strategic reburial, it needs to be remembered that oxygen can be carried by both water and atmospheric gas, and can be transported into and through soils by:

- physically disturbing the soils and exposing them to air (including during transport)
- stockpiling soils, which promotes their drainage, opening up pore spaces within the soil, and allowing both advective and diffusive flow of oxygen into the soils
- placing soils under the watertable where flowing groundwater may cause the steady delivery of potentially oxygenated waters through the reburied soils. This is of most significance to porous or uncompacted soils, for example, under appreciably sloping ground or in a preferred groundwater flow pathway such as a palaeochannel.

During periods of extended drought, the predicted watertable may lower dramatically. While seasonal fluctuations are expected and safety margins can be modelled, of greater concern are the occasional extremes that occur tens or hundreds of years apart, such as strong El Niño periods extending over several years.

Essential to the success of the technique is the strategic component. Soils to be reburied must have undergone zero or minimal oxidation, and their reburial location must be one that permanently excludes oxygen. The reburial location must be carefully planned to ensure void space (plus a substantial safety margin) is available when needed. Timelines for an earthworks strategy need to be calculated and met to ensure that the above conditions are consistently achieved.

Strategic reburial has been used at licensed treatment facilities to inter PASS at the bottom of former extractive industry pits. These soils still require compliance with the performance criteria, verification testing and monitoring of water quality (see Section 9.2). The treatment facilities must be provided with a copy of the ASS EM plan and the laboratory results to ensure that the appropriate management can be applied at the facility. The treatment facility will also need to ensure hydrological isolation/containment, monitoring and record keeping, and confirm there has been minimal risk to the environment. Records must be maintained for auditing purposes.

At present, the party disturbing ASS remains responsible for the material and any harm it causes until its full treatment is verified. Documentation of volumes taken offsite, and evidence of full treatment must be presented in the closure report (see Section 12).

At no time should PASS be strategically re-buried offsite at an unlicensed facility or private property. These sites need to be managed in perpetuity.

*Note: A void that is suffering from acid mine drainage would not be considered an appropriate site for strategic reburial of ASS.*

## 9.1 Environmental risk

The main sources of environmental risk in strategic reburial are related to maintaining oxygen exclusion at all stages during the process. A further risk is the ability to keep oxygen away from the final placement area in the long-term. Finally, difficulties may be encountered in defining the position of the seasonally lowest watertable elevation.

### 9.1.1 Locating the seasonally lowest watertable elevation

Successful strategic reburial below groundwater and compacted soil (Figure 12) is highly dependent on accurately defining the position of the seasonally lowest watertable elevation in the reburial location. Watertables are largely dependent on evapotranspiration, rainfall (although this may fall at some distance from the reburial site) and tides and can vary with the seasons. They can also vary due to longer climatic cycles, which can operate on a scale of decades or even centuries and are likely to be impacted by climate change. An experienced soil scientist or hydrogeologist may be able to identify the local minimum watertable depth under protracted drought conditions based on soil profile features (Bryant *et al*. 2008; DERM 2011), but ideally, identification should be based on long-term local monitoring activities. Climate change and prolonged periods of drought makes this increasingly difficult to identify. Coastal watertables are particularly prone to spatial and temporal variation. It is because of these factors that it is important to rebury ASS not only beneath the predicted seasonally lowest watertable elevation, but a safe distance below it.

The minimum acceptable safety margin for strategic reburial below groundwater and compacted soil is at least one metre below a seasonally lowest watertable elevation. The safety margin will need to be increased in some locations to minimise the probability of the strategically buried ASS ever drying, particularly in sandy soils.

If this watertable depth is not accurately determined, the reburied sediments will potentially be exposed to oxygen, acidify, release contaminants and may physically collapse if water drains out of them. Apart from climate, aspects of the covering material such as the texture, particle size, water-holding capacity, drainage, recharge and vegetation, as well as the buried material itself, can influence the watertable elevation.

### 9.1.2 Potential for oxidation in transit

There may be risks to the environment if the PASS are temporarily stockpiled above the watertable before reburial, or in a situation where it has to be transported in trucks for reburial offsite.

### 9.1.3 Potential for oxidation and the nature of the material to be buried

Key considerations when evaluating placement methods (including transport and handing) are the physical characteristics of the material proposed to be strategically buried, along with associated risks such as potential oxidation, reburial, resuspension and capping complications and managing a legacy area.

There is a limited prospect for soils with a low hydraulic conductivity that are reburied (under either surface waters or groundwater and compacted soil) to oxidise. However, there may be instances where dissolved oxygen concentration in water is high enough to cause significant oxidation of some submerged sediments (e.g. dredged sulfidic fines). Risks increase when the oxygen transport mechanism is not limited to diffusion. Moving water can transport oxygen much faster than diffusion can, and if the sediments are also resuspended then oxidation reactions may happen even faster. Oxygen concentration and oxygen transport mechanisms need to be considered, as does the stability of the entrained material.

Strategic reburial under surface waters relies on the principle that the transport of oxygen to sulfides, and hence reactivity and acid generation, may be completely or almost completely halted in favourable circumstances.  The applicability and effectiveness of this management method relies, firstly, on the nature of the sulfidic materials to be reburied.  Materials that have low hydraulic conductivities, such as blocky non-dispersive clays and clay-rich soils, may 'expose' only a small fraction of their sulfide contents to ambient dissolved oxygen in the water, and may tend to generate surface skins or rinds that resist further oxygen transport into the 'blocks'.  These materials may tend to resist resuspension during episodes of water mixing and potential oxygen transport, such as may arise in high-flow periods after heavy rains or floods, or from tidal flushing, or from sustained high winds.

At the other end of the spectrum, fine-grained unconsolidated sulfidic materials, such as sulfidic fines produced by hydro- as part of dredging-for-fill, or by hydrocycloning during sand extraction, generally have much less favourable physical properties, and hence may pose higher risks if reburied under standing water.  The potential for oxidation rises if significant amounts of these materials are resuspended or kept in contact with oxygenated water, such as may occur during tidal flushing, or after heavy rains or flooding, or during sustained periods of high winds.  In general, the risk of resuspension will decrease with increasing water depth, but that is not the only factor that needs to be considered.

Monosulfidic black oozes can be difficult to manage and can oxidise readily once in contact with oxygen.  MBOs exposed to oxygen are generally not suitable for strategic reburial.  Refer to the *National guidance on MBOs* for further information.

Geological features may allow oxygen transport into the void via groundwater.  There may be risks to the environment if large bodies of acidic water develop because of situations where anoxic, preferably anaerobic (reducing) conditions cannot be permanently maintained, and the sulfidic sediments have oxidised.

Figure 13 is a schematic representation of the level of risk associated with a variety of storage conditions including:

- stockpiling ASS above the watertable where oxygen delivery to the stockpile occurs by diffusion and advection, and there is an infinite supply of oxygen
- strategic reburial below still surface water conditions where oxygen is transported to the sediments by diffusion
- strategic reburial below moving surface water conditions where oxygen is transported to the sediments by diffusion and advection.

**ASS Tip 27: Diffusion and advection**

Diffusion is the movement of a substance (in this case oxygen) through a static medium (in this case soil or water).  Advection is the movement or transport of oxygen with a moving medium (flowing or stirred water).  Advective transport can be hundreds to thousands of times faster than diffusive transport.  Convection is a particular type of advective transport in which components of a water body circulate or mix.

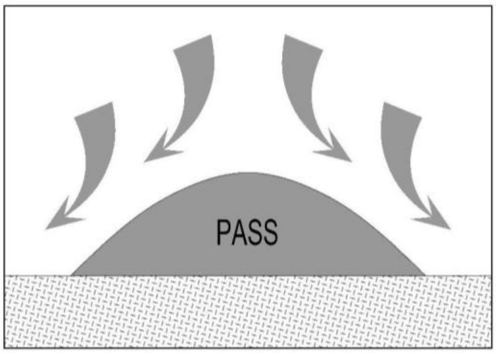
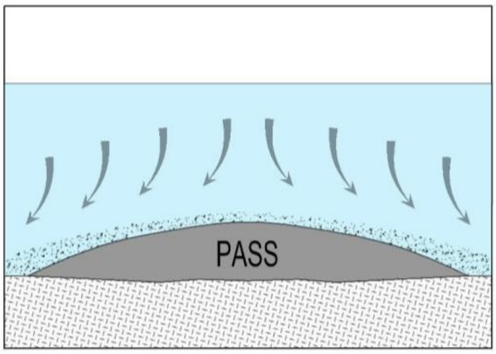
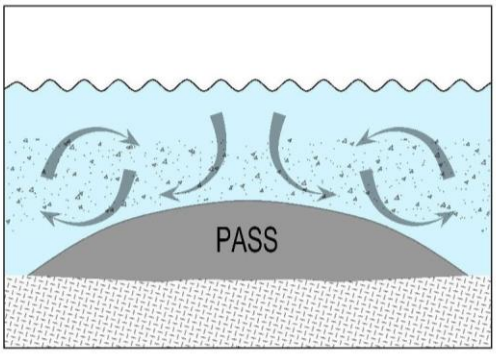
| | |
|---|---|
|  | **Risk of stockpiling**<br>• atmosphere has relatively high $[O_2]$—about 21%<br>• oxygen delivery to material via advection and diffusion<br>• effectively infinite source of oxygen<br>**= *High Risk*** |
|  | **Risk of strategic reburial in absolutely still water**<br>• relatively low $[O_2]$— about 9 ppm (0.0009%)<br>• oxygen delivery via diffusion and is slow<br>**= *Low Risk***—provided a safe depth of water is maintained above the PASS |
|  | **Risk of strategic reburial in moving water**<br>• relatively low $[O_2]$—about 9 ppm (0.0009%)<br>• oxygen delivery principally via advection, with some slow diffusion<br>**= *Variable Risk***—depending on the rate and duration of water movement and mixing |

**Figure 13: Schematic representation of the risk of stockpiling ASS and strategic reburial of materials under water**

*Note: This figure shows that the level of risk associated with strategic reburial of PASS below water is significantly less than stockpiling untreated PASS aboveground. It also shows that the level of oxygen transport to reburied sediment can increase in moving water where oxygen transport is not limited to diffusion.*

## 9.2 Performance criteria and verification testing

Performance criteria for strategically reburied PASS are:

- PASS are kept in anoxic, preferably anaerobic (reducing) conditions at all times.
- Soils must be placed at the agreed safe distance below the seasonally lowest watertable elevation.
- Soils with untreated Actual and/or Retained Acidity must not be reburied.
- ASS must not be reburied in acidic groundwaters.

A verification testing procedure should be used to prove that materials with Actual and/or Retained Acidity are not being reburied. During the reburial process, water pH should be regularly monitored to provide an indication of any oxidation of PASS or dissolution of any acid salts. If water pH drops below 6.5, the excavation and reburial process should cease as it indicates the materials may contain Actual and/or Retained Acidity. Samples of the remaining soil should be taken, and laboratory analysis conducted to measure how much Actual and/or Retained Acidity is present. If soils continue to fail to meet these performance criteria, they may need to be re-excavated and treated again, and the site may be unsuitable for strategic reburial.

The proponent and the regulatory decision makers must ensure that the performance criteria have been satisfied before the release of the land for sale or other purposes.

## 9.3 Management considerations

To reduce the level of risk associated with strategic reburial, the following management issues should be considered.

### 9.3.1 Site characterisation

The effectiveness of this strategy is largely based on the quality of the ASS investigation and resulting characterisation and understanding of the stratigraphy of the soils on site and the successful exclusion of oxygen from the reburial site. The better the characterisation of the site is, then the better the understanding of the stratigraphy of the soils on site will be. This will lower the environmental risks, particularly if a large volume of material is to be strategically reburied.

If creating or deepening a void for strategic reburial, sampling (according to the latest *Queensland ASS Sampling Guideline*) must be undertaken to at least one metre beyond the proposed depth of the void, and soils analysed to ensure that limited or no ASS are present. This is to ensure that sufficient void volume is available for strategic reburial (including an allowance for bulking). It may not be economically viable or environmentally acceptable (or logical) to excavate and then rebury ASS that were already in the pit.

High-risk geological features that should not intersect with a reburial site need to be identified and avoided. These may comprise geological discontinuities along which oxygenated groundwater might preferentially travel (e.g. faults, shears, well-jointed basement rocks), and zones of flow for oxygenated groundwater (e.g. coarse sand lenses and buried prior stream channels).

Information about groundwater levels should be accompanied by information on preferred flow paths. Reburied PASS must stay a safe distance below the seasonally lowest watertable elevation at all times (e.g. at least 1 m when covered by non-ASS materials, probably more in sandier soils). Much greater safety margins (e.g. >4 m) will be required for burial in water bodies due to the potential for mixing (see Section 9.4.1 on water column depth).

### 9.3.2 Timing

Ideally, all material should be excavated, transported and reburied without delay (within 8–10 hours) (i.e. placed at the base of the void in anoxic, preferably anaerobic (reducing) conditions). Delays due to unforeseen circumstances should be at most one night (18 hours) for coarse-textured material such as sands, or a weekend (70 hours) for medium- and fine-textured material such as silts and clays. At some sites the times listed above may be not conservative enough (e.g. during hot weather some sands may begin to oxidise within a matter of hours, particularly in Far North Queensland). Bulk excavation beyond the capacity for reburial is indicative of poor project planning and increases the risk that AASS will be reburied, rather than PASS.

### 9.3.3 Staging the excavation

Staging the excavation activities to make sure that enough void space is available for immediate reburial is recommended. Multiple handling of the sulfidic soils increases the risk of exposure to oxygen as well as the costs associated with the technique. Ideally, the material should be directly placed into its final, permanent reinterment location. In some cases, a minor amount of temporary reinterment and subsequent double-handling may be justified if a thorough investigation and detailed earthworks strategy with timelines can be presented, along with appropriate environmental management proposals.

### 9.3.4 Future land use constraints

Once reburial has occurred, the presence of the sulfidic material in that location may become an issue affecting future landowners, as future activities or uses of the land that might cause exposure of the material to oxidising conditions will not be appropriate. Exposure to high nitrate concentrations in leachate from excessive fertiliser use on turf and gardens is also an issue. Nitrate is a strong oxidising agent that can trigger the oxidation of sulfides (Jørgensen *et al.* 2019). This will not necessarily produce a large amount of acidity however, metal release into groundwater may occur. It is important that the local government and any potentially affected landowners are informed of this issue and have a clear understanding of any long-term environmental or geotechnical implications that the reinterment may have on land use.

Locations must be accurately surveyed, and both the extent and depth of the burial should be recorded (e.g. survey with GNSS, RTK, differential GPS, and conventional survey etc, depending on the level of accuracy needed) and reported to the relevant local government and any other relevant authorities. Local governments will need this information to enable them to make informed decisions about future land uses that could potentially impact on reinterment areas. Local governments should consider making this information publicly available. This information should be recorded in the closure report including engineered design and signoff of the risk (see Section 12).

### 9.3.5 Future disturbance

PASS that have been reinterred below the watertable may be disturbed by the construction of swimming pools, foundations, drains and other neighbouring land uses that drain the soils, or by groundwater extraction through bores. Such disturbances should be avoided.

Water bodies that will need to be dewatered or drained in the future are also unsuitable reinterment locations. For example, if a lake or canal is to be dewatered for the construction of revetment walls (and management issues associated with that dewatering cannot be addressed), then dewatering should be performed before use of that area as a reinterment location.

### 9.3.6 Hydrographic surveys

Hydrographic surveys may be needed after strategic reburial of PASS to assess whether the material has been placed in its intended location and has remained there. Surveys should be capable of monitoring the condition of any capping materials placed so that maintenance can be carried out if needed.

## 9.4 Management considerations for strategic reburial under surface water

Strategic reburial under surface waters within a lake, canal or artificial wetland may be workable when the following conditions can be met on a permanent basis:

- An appropriate water balance occurs or can be permanently maintained to ensure the storage of sulfidic material under reducing conditions.
- The material to be reburied will stay in its intended location, that is, it will not be moved by currents or other forces such as wind mixing or seasonal turnover.

**ASS Tip 28: Is strategic reburial going to work?**

The following questions need to be answered before a decision to try strategic reburial under surface water can be made:

- How much material is being buried?
- What is the nature of the material to be buried? Consider, for example, sulfide concentration, texture, dispersivity, presence of $Fe^{3+}$, and the effects of the removal and placement methods.
- Is there enough room in the void allowing for the freeboard distance below the permanent water surface?
- What is the worst (i.e. highest) predicted rate of oxygen transport?
- What are the characteristics of the chosen water body that may affect the rate of oxygen transport? Consider the depth of water column, frequency of flushing, water chemistry (fresh, brackish or saline), potential for drainage, potential for mechanical disturbance of the bottom sediments etc.
- What are the characteristics of the surrounding environment that may affect oxygen transport through the water or contribute to disturbance of the material (e.g. presence of strong prevailing winds, seasonal mixing processes, severe storms, siltation rates etc).
- Does the material need a cap, and if so, will it support a cap?

Where strategic reburial is proposed at an offsite treatment facility, the treatment facility must be provided with a copy of the ASS EM plan and the laboratory results to ensure compliance with the performance criteria (see Section 9.2). The treatment facility will also require additional hydrological isolation/containment, monitoring and record keeping confirming there has been minimal risk to the environment. Records must be maintained for auditing purposes.

*Note: A limnological assessment might be required to consider oxygen transport and sulfide oxidation rates when considering strategic reburial under surface water. Information that should be considered in this limnological assessment is detailed in Appendix 5.*

### 9.4.1 Reducing the risk of oxidation of buried sulfidic fines

Some options are available to reduce the level of risk associated with buried sulfidic fines. Two of these, increasing neutralising capacity and capping below surface waters, are discussed below.

***Increasing the neutralising capacity***

Increasing the neutralising capacity of reburied sulfidic fines can reduce the environmental risk of reinterred material. However it would not be appropriate to rely upon this management technique in cases where regular resuspension may result in regular acidification events.

Buffering or neutralisation may be achieved by co-interment of an insoluble neutralising agent with sulfidic fines, or by applying a layer of the neutralising agent at the fines−water interface. The grain size and density of the neutralising agent should be such that it will not sink through or segregate from the sulfidic fines should mixing or resuspension occur. The amount of neutralising agent applied should be calculated beforehand. It would be generally unacceptable to add alkalinity to naturally low pH waters supporting acidophilic biota.

***Capping below surface waters***

A cap is a layer of cover material placed over reburied ASS to prevent infiltration or to reduce exposure to oxygen. Capping may be necessary when investigations show that the dissolved oxygen is high enough in water to cause significant oxidation of the submerged sulfidic sediments; and/or if the sulfidic sediments are likely to be scoured or resuspended.

Similar to dredging and ocean disposal, settlement and dispersion factors also need to be considered as fine un-cohesive material can be difficult to place. Even installing a geofabric under water is difficult, and when being used for capping, it may heave and displace the material. Capping below surface waters will be technically challenging and expensive and impossible at most sites.

## 9.5 Management considerations for reburial below groundwater and soil

Voids can also be created below the level of the seasonally lowest watertable level for the strategic reburial of PASS. The material can then be placed a safe distance below this elevation of the re-established permanent watertable and a layer of compacted soil placed on top of it (see Figure 12). This technique will not be suitable for sites where the watertable takes many months or even years to re-establish or where temporary dewatering can affect the groundwater quality, aquifer properties and/or the built environment. As stated earlier, the long-term site conditions control the oxidation of the reburied materials. Factors or conditions that might result in the transport of significant amounts of oxygen to the reburied sulfides (e.g. by providing unexpected or preferred pathways for oxygen or oxygenated groundwater flow either right after reburial or in the future) should be identified on a site-specific basis. These include:

- geological discontinuities such as faults or shears, or well jointed basement rocks, through which large groundwater flows might occur
- the accuracy of the groundwater modelling
- the geomorphology of the floodplain
- placement of PASS where groundwater flows will transport significant oxygen to the sulfidic materials
- placement of PASS where groundwater levels are lowered due to seasonal fluctuations or drought
- placement of PASS materials in locations where future offsite development might periodically or permanently lower the watertable around the reburied materials
- placement of PASS materials in locations that are likely to be disturbed in the future by re-development or the need to install or upgrade in-ground services
- placement of wet, low-density dredge or hydrocycloned fines without first dewatering, which may lead to the sinking of the capping material, squeezing the fines upwards and above the permanent watertable
- cost, availability and effectiveness of capping material.

*Note: The PASS should be placed at a safe depth (e.g. at least 1 m) below the lowest recorded watertable level to ensure that they are not exposed to a source of oxygen during periods of extended drought. Areas with limited reliable groundwater information should ensure reburial occurs below a conservative estimate of the lowest possible level of the watertable.*

Some materials may be unsuitable for reburial due to their inability to support the compacted soil. Saturated sulfidic fines may slowly dewater under the weight of the capping material, leading to subsidence, heave and pore-water release. Some of the reburied material may be pushed into oxidising conditions above the watertable, depending on its load-bearing capacity.

# 10. High-risk management strategies

Several ASS management strategies involve considerable environmental risk and there is limited documentation of their successful use. Regulatory decision makers may require detailed risk assessment information (potentially including pilot trials) before they can be satisfied that these risks can be effectively managed without impact on the environmental values of the receiving environment. If sufficient scientific justification cannot be provided, the following activities will not be supported. For many situations, a risk assessment may need to cover a variety of these higher risk management strategies within the same development application.

The ASS investigations and associated management proposals for all high-risk management strategies must be undertaken by suitably skilled and experienced persons in ASS science (see Section 3.2) with experience that reflects the associated elevated level of risk. Required expertise may span across disciplines. Independent third-party review (as used in contaminated land assessments—see ASS Tip 7) of management proposals and closure reporting (see Section 12) may also help ensure that the risks are adequately identified, managed and reported.

## 10.1 Groundwater dewatering and drainage

Earthworks and/or pumping that result in localised drainage or lowering of groundwater may expose ASS to oxygen and generate acidity as a function of soil type(s), sulfide contents, area exposed and length of time the excavation stays ‘dry’. The rate and duration of dewatering are variables that can be optimally managed to minimise risk (Shand *et al*. 2018). The risk of the dewatering can be assessed using the predicted size of the radial extent of the cone of depression (see ASS Tip 29 and Figure 14) and an assessment of estimated pumping rates and times necessary to achieve the required groundwater drawdown for dewatering operations. The impact on ASS environments of lowering watertables for short and long-term durations is not well understood (Shand *et al.* 2018) and over-zealous dewatering (well below the required depth and for periods much longer than required) can lead to impacts which are not immediately apparent. Before dewatering commences, a groundwater investigation should be conducted to ensure there is a good understanding of groundwater within and adjacent to the site (see Appendix 3 and 4 and Shand *et al.* 2018).

Where disturbance of the groundwater is unavoidable, management measures may need to be implemented in the immediate vicinity of pumping bores, but also throughout the area underlain by the cone of depression for the bores, which may extend beyond the development site. Large-scale dewatering activities are high-risk and should not be undertaken without management measures sufficient to reduce risk to levels acceptable to administering authorities. Such measures will necessarily include physical confinement strategies.

Groundwater drainage or dewatering may trigger the same acid-generating processes as those described in Section 10.3. It follows that all dewatering operations in ASS areas carry a high environmental risk, except those which cause limited or localised drawdown and promote maintenance of field moisture capacity, minimising sediment oxidation. For example, shallow infrastructure trenching, if it is staged and of short duration, may only cause limited or localised drawdown, and hence carries a lower risk. The risks also decrease if the dry excavation exposes predominantly clayey soils with very low hydraulic conductivity resulting in limited drawdown.

Dewatering ASS is unacceptable without appropriate management strategies to limit drawdown (both horizontally and vertically) and sediment oxidation, due to the potential for acid production and damage to neighbouring buildings and infrastructure (see Section 11.5). Measures may include sheet piling or sealing of excavated shafts to prevent free drainage. A thorough understanding of the hydrogeology prior to any dewatering is required to ensure that any dewatering operations can be designed and managed appropriately. The extent of the dewatering should be limited by the ability of the operators to treat the area of oxidised soil—the treatment of *in situ* oxidised ASS is extremely difficult, expensive, and not always feasible. The drawdown must also be managed and confined to within the site boundaries. Acidified groundwater or oxidised soils need to be confined to enable appropriate treatment before the removal of any containment structures. The use of natural buffering within groundwater and soil, or sacrificing of concrete structures, is not an appropriate treatment for acidified groundwater (see Section 11.3).

**ASS Tip 29: Cone of depression**

The radial extent of the cone of depression (Figure 14) is the predicted volume of soil around a dewatering point that can become unsaturated (i.e. partially drained) during unconfined groundwater dewatering. The eventual cone of depression will be influenced by the permeability of the soil, rainfall events, evapotranspiration, groundwater flow paths and palaeochannels. The acid generation within the cone of depression will be a function of the above factors as well as the duration of the dewatering, the Net Acidity, and organic matter content. In coastal situations, the calculation of the cone of depression is seldom a simple process.

Before dewatering ASS, the extent, location and soil characteristics of the radial extent of the cone of depression should be measured and modelled. This should be undertaken by a suitably qualified and experienced hydrogeologist. A preliminary estimate of the cone of depression can be made using the online calculation tool provided by the Western Australian Department of Environment Regulation (search at <https://www.der.wa.gov.au>).

Modelling should be supported by appropriate groundwater investigations of aquifers and aquitards, including undertaking assessment of hydraulic conductivity (i.e. slug testing), permeability and flow. After this is completed, correlation with the ASS investigation is used to determine appropriate management.

'*All models are wrong, some models are useful'* (Box 1976). Experience indicates that the modelling can sometimes be seriously flawed because the materials surrounding the excavations are rarely homogenous and layers of clays, peat and coffee rock often alternate with sandier deposits. The models often yield significant uncertainty and fall short of the complexities required to predict groundwater systems that are drained. Areas/zones of perched groundwater also need to be considered. Physical containment is the expected approach for groundwater disturbances.

Physical containment is rarely perfect, and some leakage may be expected. Some dewatering may result, and contingency plans should be in place to handle the effects of this.

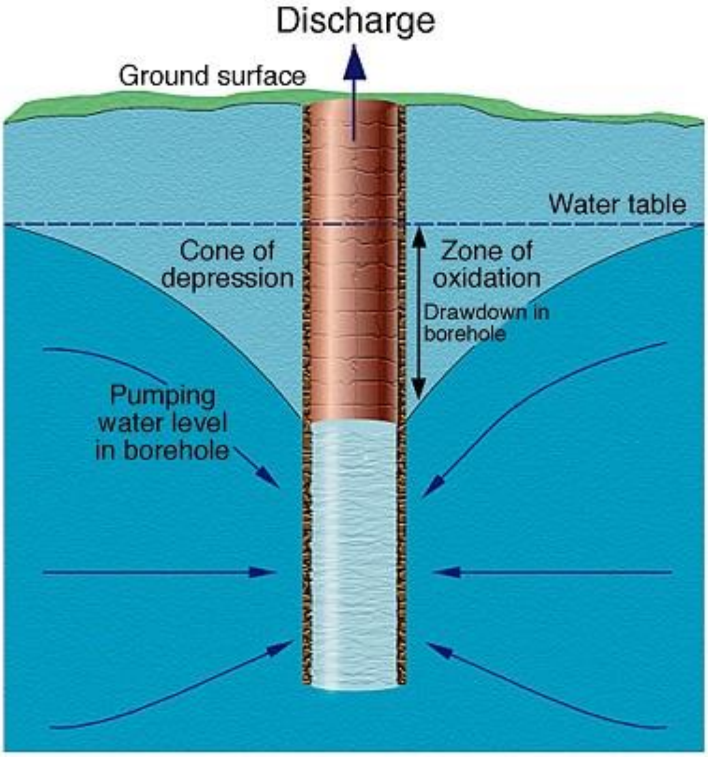


**Figure 14: The formation of a cone of depression during pumping from a bore**

*(Modified from UK Groundwater Forum, Groundwater: our hidden asset, and reproduced from Shand et al.* 2018). *Note: The degree and shape of the cone will depend on the duration of pumping and the hydraulic properties of the soil or aquifer.*

### 10.1.1 Environmental risk

A risk assessment will need to be undertaken in circumstances where dewatering or drainage of ASS is proposed and consultation about the proposed management should be undertaken with the relevant administering authorities. This should include options for its reuse and disposal back into the receiving environment. The following factors must be considered:

- the influence of soil permeability, organic matter, bacterial activity and availability of dissolved oxygen
- oxidation and subsequent acidification of the *in situ* soils drained within the radial extent of the cone of depression—the effect will be greater in acidic, highly permeable sandy soils with high levels of sulfides and low levels of organic matter, and also in peats—the overlying land use (urban areas) and soil coverings (concrete and bitumen) will also influence the movement of oxygen into the ASS layers
- processes that influence oxygen delivery to the radial extent of the cone of depression during the dewatering or drainage operation, for example, rainfall events and evapotranspiration
- baseline groundwater quality regarding its suitability for discharge or reinjection once extracted; treatment may be required before release or reuse
- acidification of the groundwater that will ultimately reside in the cone of depression once the system is reflooded
- iron, aluminium and heavy metal contamination of the groundwater that will ultimately reside in the cone of depression

- acidification and contamination of any water (e.g. pit or lake water or adjacent groundwater-dependent ecosystems) that interacts with the groundwater that will ultimately reside in the cone of depression
- lowering of surface water or the watertable on- or offsite via continuous flow into the excavation, along preferred flow paths or palaeochannels
- higher than expected permeability in some soil horizons. This may be associated with relict root channel macropores and structural ripening of sulfuric horizons and may influence groundwater movement and acid export (Johnston *et al*. 2002)
- changes in soil strength from dewatering, including settlement and collapse
- shrinkage of drained soils and impact on overlying infrastructure from subsidence
- fish kills in dewatered water bodies that were not adequately destocked
- difficulties associated with prevention of drying and subsequent acid generation of *in situ* ASS
- difficulties associated with neutralising deep *in situ* actual ASS that have formed in the radial extent of the cone of depression
- monitoring and treating discharge waters that may contain elevated concentrations of dissolved iron and aluminium and suspended iron floc
  - iron floc can be problematic and may need to be physically removed
  - due to groundwater fouling, chlorination may be necessary; and then elevated salinity levels may require treatment
- strategies used to treat groundwater (e.g. air sparging) may also impact ASS.

ASS impacts may not become apparent during the period of groundwater disturbance. Post groundwater dewatering monitoring will be required. Due to the environmental risks and the complexity of the above factors, dewatering frequently poses unacceptable risks. Dewatering may cause unacceptable environmental impacts if full containment is not possible, if adjacent groundwater-dependent ecosystems (or water supplies) are impacted upon, or if works will occur in a built-up area with potential impacts on adjacent infrastructure. In such instances, the dewatering would be classified as unacceptable (see Section 11.5). Obligations under the *general environmental duty* will also remain.

Dewatering and excavation on some ASS sites may release hydrogen sulfide gas from groundwater. This gas may reach toxic levels within excavations and in confined spaces. It is recommended that onsite gas monitoring and occupational health and safety measures are implemented to deal with this contingency during dewatering on such sites (DER 2015).

**ASS Tip 30: Irrigation from shallow aquifers and ASS**

In many coastal areas, groundwater commonly has elevated levels of ferrous ions ($Fe^{2+}$) particularly when associated with ASS. Irrigation with groundwater containing elevated levels of ferrous ion will leave orange or brown splash stains on driveways and concrete structures. Continued use of such groundwaters will cause acidification of the soils and may kill vegetation. Aluminium salts and free $Al^{3+}$ may be present in significant amounts, and these can be toxic to plants and aquatic creatures in nearby drains or waterways.

With continued groundwater extraction from these aquifers, the groundwater resource can become increasingly acidic due to further oxidation of ASS as the watertable is lowered. In some localities, contamination with arsenic or heavy metals may result. The local groundwater may also become saline due to saltwater intrusion from adjoining tidal waters. Proponents and regulatory decision makers need to be aware of the risk of contaminating groundwater and soil resources if uncontrolled groundwater extraction occurs.

### 10.1.2 Management considerations

The key to managing large-scale dewatering is the retardation of oxygen transport to ASS. Management of the rate and duration of dewatering and controlling the volume of the area dewatered need to be optimally managed to minimise risk. Management considerations will depend greatly on site-specific factors, and on larger projects these may vary across the site. The following management strategies will need to be considered when dewatering is proposed:

- undertake a groundwater investigation and establish baseline groundwater quality data and seasonally lowest watertable elevation (in accordance with *Guidance for the dewatering of acid sulfate soils in shallow groundwater environments*) in conjunction with an ASS soils investigation (in accordance with the latest *Queensland ASS Sampling Guidelines*)
- design the layout of the dewatered void to make sure that the dewatering of highly permeable sulfidic sands is avoided—the drained area needs to be managed, with strategies in place prior to any drainage to ensure either minimal oxidation occurs, or an appropriate neutralisation strategy is planned[20]. If neither of these can be achieved, then groundwater dewatering should not proceed
- minimise the volumes of soil excavated and thus soils dewatered at any one time. Excavate within a series of smaller bunded cells, rather than one large, dewatered void
- minimise the duration, depth and volume of dewatering, allowing recharge to occur as soon as possible. Reinjection of extracted groundwater will be appropriate if water quality is managed correctly
- physically confine the cone of depression to the excavation void as far as possible, for example:
  - use sheet piling or caisson construction to minimise groundwater drawdown and to prevent seepage into the dewatered void, keeping the adjacent watertable relatively intact
  - use deep soil mixing or continuous piles (i.e. driver-reinforced concrete piles) to create a sealed wall around the excavation void (such structures are permanent and may form the foundations of a structure)
  - identify, avoid or if necessary, use physical barriers to temporarily slow down or stop flow from any preferred groundwater flow pathways and/or palaeochannels

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[20] Neutralisation of acidified groundwater is virtually impossible to do and highly risky.

- if discharging to surface water, monitor and treat discharge waters based on receiving waters discharge criteria during dewatering (before and after any treatment) (see DER 2015 for further information on basic dewatering effluent treatment systems and Figure 15)
- install piezometers and monitor the groundwater levels and water quality outside the excavation void before (to establish baseline), during (at short intervals) and for a period after (typically for a period of at least 6 months) the dewatered excavation (see Table 4.6 and Table 4.9 in Shand *et al.* 2018)
- if the radius of the cone of depression is greater than 50 metres, or is located in an environmentally sensitive area, additional bores should be installed and monitored to determine if the dewatering is affecting groundwater quality
  - ideally, a minimum of three bores arranged in a triangle should be installed, and carefully positioned to enable assessment of the impacts on the groundwater and groundwater flow direction
- where the cone of depression is likely to impact ASS beyond the required area, or where large trenches have to be dug, recharge trenches that use the pumped water to maintain saturation around the site can be established—care is needed to ensure that oxygenated water is not pumped into deeper reduced sediments, inducing oxidation
- the use of permeable reactive barriers (e.g. comprised of crushed limestone) can be used to reduce or mitigate the migration of acidity and contaminants, forming a passive treatment system. These systems have a finite lifespan and require monitoring for the duration
- triggers for the cessation of groundwater dewatering and contingency planning.

*‘Note that monitoring is not simply a dewatering and post-dewatering activity. Sufficient monitoring data should be collected prior to any operations information to assess natural or background variations in the soils and groundwater. A baseline will help quantify changes and to select criteria beyond which such changes require action. This will include water levels, where the data help determine that the required area of dewatering is being met, and minimising excess dewatering. Trigger values for groundwater should be selected that are indicative of pyrite oxidation and acidification. In detail, they are generally developed on a site specific basis and will depend on the groundwater characteristics at the site, to be agreed with relevant authorities. Plotting trends is a good way to visualise change and rate of change (for example decreasing alkalinity) which may help avoid more expensive mitigation requirements’ (Shand et al. 2018).*

For further information on management strategies for groundwater dewatering, refer to Shand *et al*. (2018) and the tables in Appendix 3.

A significant knowledge gap still exists around contaminant mobilisation following groundwater rebound after dewatering is finished (Shand *et al.* 2018). Where management measures have not been successful in preventing *in situ* oxidation of ASS around the void, management of the acidity produced will be required. This may become an ongoing and costly commitment, particularly where damage to neighbouring structures and infrastructure occurs and litigation is involved.

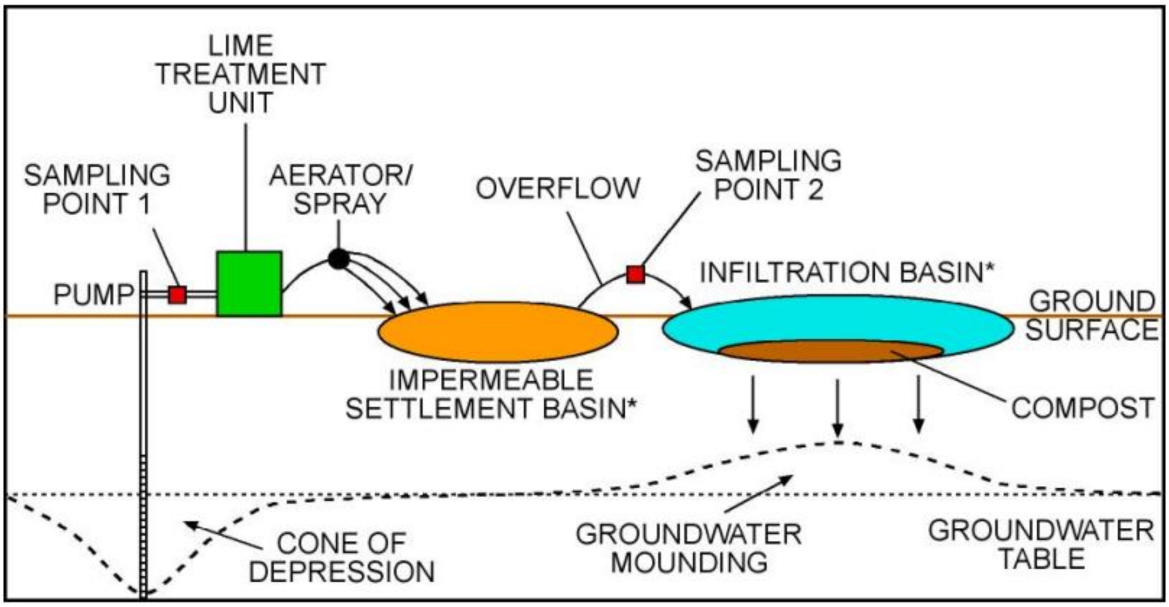

**Figure 15: Schematic view of a basic dewatering effluent treatment system**

*(Reproduced from DER 2015).*

## 10.2 Stockpiling acid sulfate soils

The risks of stockpiling large volumes of untreated ASS may be high even over the short-term. Ideally all material should be excavated, transported and reburied/placed on a fully contained treatment pad without delay (within 8–10 hours). Stockpiling small volumes of untreated ASS should only be undertaken as a short-term activity. For example:

- Part of a day's extraction of clay may be stockpiled over a weekend before strategic reburial.
- Due to poor weather conditions or problems with obtaining laboratory results, treatment scheduling may be disrupted, leading to the creation of small stockpiles before changes can be made to earthworks programs.

All ASS EM plans should allow extra space in treatment areas for such contingencies.

**ASS Tip 31: Stockpiling**

On becoming aware of an emerging situation that will result in the need for stockpiling, action should be taken to:

- prevent further increases in stockpile volumes and/or the duration that these remain untreated
- quickly treat the stockpiles that have resulted.

It can be more efficient to treat (and verify) the stockpile as it grows. This will obviate the need to manage the stockpiled soil as recommended in this section.

### 10.2.1 Environmental risk

The risks associated with stockpiling increase with the rate at which the materials dewater. Coarsely textured, highly permeable sandy soils will drain or dewater at a faster rate than fine-textured soils. In sandy soils, the rate of oxygen transport to the sulfides is likely to be high. The risk will multiply if the pH of the material being stockpiled drops to 4 or less, if there is limited organic matter present, or if the material has high levels of sulfides. The rate of oxidation of these soils can be rapid (hours), particularly in hot conditions.

Substantial quantities of acid can build up in stockpiles if they are left in oxidising conditions for even short periods. Management of acidic leachate can become a concern. Large stockpiles are difficult to neutralise, primarily due to the earthmoving needed. Liming rates for such oxidised materials will need to be based on the Actual and Retained Acidity and the Potential Acidity. Representative sampling of the stockpile must be performed, and all laboratory results should be considered in calculating treatment rates because of variability within a stockpile and changes due to oxidation. When representative sampling cannot be achieved, the highest laboratory result may be used, acknowledging that this may lead to over-liming (see Section 5.3).

**ASS Tip 32: Secondary iron hydroxy-sulfate minerals**

Secondary iron hydroxy-sulfate minerals (e.g. jarosite, natrojarosite and schwertmannite) may slowly produce acid with wetting and drying of the stockpiles. These minerals may be 'stores' of acidity that do not need further oxygen to generate acid and may form the main component of acidity in older stockpiles.

Due to varying solubilities, some of these minerals are measured by the TAA test, while others (such as jarosite) are estimated using calculations of Retained Acidity—by using Net Acid Soluble Sulfur ($S_{NAS}$) or Residual Acid Soluble Sulfur ($S_{RAS}$). Actual and Retained Acidity are not accounted for by $S_{CR}$ or $S_{POS}$ tests. See ASS Tip 4 and ASS Tip 5 for the calculations.

### 10.2.2 Management considerations

Stockpiling untreated ASS should be minimised by preparing a detailed earthworks strategy that documents the timing of soil volumes to be moved, treatment locations and capacity of those areas to accept materials. Stockpiling may mean double-handling and increased earthmoving costs. It is important to account for risk from inclement weather and plan for other contingencies.

***Short-term stockpiles***

The recommended maximum time for which soils can be temporarily stockpiled before treatment is detailed in Table 5. The total volume of material that is placed in short-term stockpiles should not exceed 20% of a day's total extraction, as **immediate treatment should be the norm**.

**Table 5: Indicative maximum periods for short-term stockpiling of untreated ASS**

| Type of material | | Maximum acceptable duration of stockpiling |
|---|---|---|
| Texture range (NCST 2009) | Approximate clay content (%) | |
| Coarse: sands to loamy sands and peats | <5 | Overnight (18 hours) |
| Medium: clayey sand to light clays | 5−40 | 2 nights (42 hours) |
| Fine: light medium to heavy clays and silty clays | >40 | 3 nights e.g. a weekend (66 hours) |

*Note: These timeframes do not apply to MBOs and monosulfidic materials. It is not acceptable to stockpile untreated MBOs and monosulfidic materials under any circumstances.*

Under some circumstances these figures may be overly conservative, and under others, not conservative enough (e.g. during hot weather some sands, clay sands and peats may begin to oxidise within a matter of hours—these soils should be excavated and treated without delay and should not be stockpiled for the maximum acceptable duration). It is recommended that appropriate operational delay times be decided (preferably well before the creation of the stockpile) for the specific circumstances. A guard layer under short-term stockpiles will be required. A neutralising agent (e.g. aglime) should also be spread over the stockpile to limit the generation of acidity from the surface of the stockpile, but this will not prevent acid exiting the stockpile via leachates emerging near the base. Temporary bunding is needed around the stockpiles to collect any leachate, soil or lime washed off during overnight/weekend storms or rainfall events. It may be beneficial to add aglime to the ASS while they are being excavated and formed into a stockpile.

**ASS Tip 33: Guard layer rate for stockpiles**

The minimum guard layer rate beneath any stockpiled ASS is 5 kg of fine aglime per m$^2$ to a maximum depth of 300 mm of stockpiled ASS. Where the highest detected Net Acidity is more than 1.0 %S, the rate is a minimum of 10 kg of fine aglime per m$^2$ per 300 mm of stockpiled ASS.

*Note: Reapplication of the guard layer will be necessary under areas of repeated temporary stockpiling.*

***Longer-term stockpiles***

Any stockpiling exceeding the above timeframes is unacceptable. If ASS are to be stockpiled longer than the above timeframes, the soils must be placed on a fully contained treatment pad (see Section 7.4)—and the soils must then be fully treated as a priority. Regulatory agencies should be notified of the existence of historical stockpiles and consulted on their management. If stockpiles are assessed as likely to cause environmental harm, then voluntary submission of an environmental management program under the *Environmental Protection Act 1994* is recommended. Failure to act on signs of high environmental risk may result in other action being taken under the Act.

If soils have been excavated and stockpiled with no regard to layers or horizons of soil that require different liming rates, the predictability of the soil's sulfide variability will be lost. This makes it more difficult to correlate liming rates with soil layers. These stockpiles will need to be resampled before treatment. See the *Queensland Sampling Guidelines* and NEPM (2013) for information on sampling of stockpiled ASS.

### 10.2.3 Stockpiles of topsoil

It is routine practice to scrape topsoil and store it until it is needed for top dressing as it often contains organic matter, nutrients and is a seedbank for regeneration. All topsoil should be tested before stripping and stockpiling. Some of the management options listed above may be appropriate for managing topsoil stockpiles if they contain low levels of sulfides. Low levels of sulfides or Actual and/or Retained Acidity may occur in topsoils because of 'over stripping' that has occurred during its collection, or it may be intrinsic to the topsoil.

It is not appropriate to use treated ASS as topsoil because the ASS is likely to continue to react after treatment for some time—also potential reaction products may leach from the soil and cause secondary impacts.

### 10.2.4 Stockpiles and preloading

Soils are preloaded in many coastal development sites after the sites have been 'filled' to increase the rate of consolidation and resulting settlement. In the past, untreated ASS have been used as preload. This is unacceptable due to the potential risks to the environment associated with acidic leachate generated within the preload material. Acid sulfate soils that have been fully treated and verified (as per performance criteria and verification testing in Section 7.2) may be used as preload, as can the sulfide-free fraction of a hydraulically separated ASS.

## 10.3 Strategic reburial of soils with Actual and/or Retained Acidity

Strategic reburial as a management measure for soils with only Potential Acidity is discussed in Section 9. The use of strategic reburial in situations where the soil has Potential and Actual and/or Retained Acidity is a high-risk activity, which needs more complex site management and site supervision, a greater reliance on technology and higher costs. Use of this management strategy is only acceptable when the soil horizons with Actual and/or Retained Acidity **can be stripped and managed separately**. The Actual and Retained Acidity within these separated horizons must be fully treated, and adequate safeguards to protect the surrounding environmental values must be guaranteed. Environmental risks and management considerations associated with the strategic reburial of soils with Potential Acidity will also apply to the strategic reburial of soils with Actual and/or Retained Acidity.

There may be risks to the environment if soils that have significant measurable acidity are reinterred without first neutralising Actual and/or Retained Acidity. Strategic reburial is inappropriate for untreated actual ASS, as any Actual and/or Retained Acidity may be a source of leachate that may enter waterways at some time in the future. Furthermore, aluminium, iron and other heavy metals that are more soluble in acidic waters may be mobilised from the actual ASS.

*Note: The placement of untreated ASS with Actual and/or Retained Acidity in landfills is unacceptable. Interactions between acidity and other substances in the landfill are likely to produce toxic leachates. Furthermore, if putrescible material is buried with soils containing Actual or Retained Acidity in contact with sulfate-rich waters, anaerobic conditions may develop and may lead to the generation of toxic hydrogen sulfide gas. Landfill operators should be aware of these risks and manage them appropriately.*

### 10.3.1 Environmental risk

***Forms of Actual and Retained Acidity***

The acidic pore waters in partially oxidised ASS are the most common and obvious source of Actual and/or Retained Acidity. Other oxidising agents which may be present in partially oxidised soils (e.g. $Fe^{3+}$ ions in pre-existing acidic pore waters) may cause further sulfide oxidation and generation of acid, despite oxygen being excluded after strategic reburial. This oxidation will continue until the readily available $Fe^{3+}$ ions have been consumed by the reaction. The reaction liberates $Fe^{2+}$ ions, which if transported out of the reburied soils into the receiving environment, will oxidise and generate acidity through a hydromorphic soil-forming process known as ferrolysis. Sulfidic soils that have undergone oxidation may also contain Retained Acidity (e.g. in sparingly soluble precipitates such as jarosite) that can hydrolyse and generate more free acidity in the absence of oxygen. These hydroxy-sulfate minerals need only steady infiltration and groundwater flow (not necessarily oxygenated) to export acidity.

***Incorporation of neutralising agents***

Soils intended for strategic burial with Actual and/or Retained Acidity that have been stripped separately may be neutralised only for that component of the acidity, rather than Net Acidity. If the ASS cannot be stripped and managed separately, the level of risk will increase, and this management strategy may become unacceptable.

There are difficulties in incorporating insoluble neutralising agents such as fine aglime $CaCO_3$ into ASS that are to be buried. The soils need to be worked and sufficiently dried before incorporation of the neutralising agent. During this time, oxidation processes may release more acidity that would also require neutralisation. Fine aglime is slow to react and may be unable to neutralise the initial volume of acidity. Liming rate calculations for Actual and Retained Acidity should use a larger safety factor than the minimum in order to compensate for this issue (i.e. a safety factor of 2.5–3.5). Following treatment, field pH values should be comprehensively checked and must be greater than 6.5 before reburial can proceed.

If the water in a reburial void acidifies despite these precautions, the water may be managed using a soluble neutralising agent such as a slurry of hydrated lime, $Ca(OH)_2$.  Hydrated lime is strongly alkaline, and this activity needs a cautious approach and extensive monitoring to avoid overshooting the required pH.  It may take considerable time for the pH of the water body to recover if excess hydrated lime is added to the system and this may affect any environmental values of the water body.  The sensitivity of the receiving environment and the degree of containment of the site will need to be considered where the use of a soluble neutralising agent is proposed.  Sodium bicarbonate may also be used to neutralise water and has the advantage of high solubility, a less alkaline pH and fewer workplace health and safety risks but is more expensive and contains sodium, which in large enough quantities degrades the soil’s physical and chemical properties.

#### *Performance criteria and verification testing*

Soils with Actual and/or Retained Acidity that are to be strategically reburied (after neutralisation of the Actual and/or Retained Acidity) will need to meet the performance criteria and verification testing requirements listed in Section 9.2.

## 10.4 Basements and other in-ground infrastructure below the watertable in ASS

Basements and other in-ground infrastructure (e.g. elevator shafts, tunnels and car parks) are often located in ASS, under multi-story complexes in urban coastal environments.  As these structures are often excavated during urban in-fill (where urban development and re-development occurs over long periods of time), the management requirements can be complicated and are associated with a higher level of risk.  They should not be undertaken without management measures sufficient to reduce risk to levels acceptable to administering authorities.  Where structures are located below the watertable, additional engineering is considered essential to minimise the impacts on water quality, the receiving environment and neighbouring buildings and infrastructure.

Hydrological investigations will need to be conducted to assess connectivity between the groundwater in the ASS layers and the groundwater in areas subject that will be drained.  Refer to Section 10.1 and 10.1.2 for management considerations.

Treatment of ASS below the watertable is not usually a feasible option once oxidation and acidification of *in situ* ASS has occurred unless the ASS are quite shallow.  Proposals where deep *in situ* ASS will be exposed to oxidising conditions are unlikely to be approved by administering authorities.  Unconfined groundwater dewatering (temporary or permanent) around these structures (e.g. basements with sump pumps) is an unacceptable management strategy (see Section 11.5).  Additionally, structures such as elevator shafts, tunnels and carparks should not be in drained ASS due to the significant potential for damage to infrastructure and replacement costs if they are exposed to acidic leachate (see ASS Tip 14).  It may necessitate the whole redesign of the basement to minimise ASS impacts—this can be costly and may threaten a project’s viability.

### 10.4.1 Environmental risk

The risks associated with installation of basements and other in-ground infrastructure below the watertable in coastal ASS are varied and include similar risks covered in Section 10.1 *Groundwater dewatering and drainage* and Section 10.2 *Stockpiling ASS*.  A risk assessment will need to be undertaken in circumstances where structures are located below the watertable in coastal ASS areas.

The risk assessment should focus on the following factors:

- oxidation and subsequent acidification of the *in situ* soils drained within the radial extent of the cone of depression (see ASS Tip 29 and Figure 14), including acidification beyond the development site
- delivery of acid, iron and other contaminants to the receiving environment along preferred flow paths or palaeochannels
- acidification and contamination of any water or adjacent groundwater-dependent ecosystems that interacts with the groundwater that will ultimately reside in the cone of depression
- damage and corrosion to neighbouring buildings and infrastructure due to exposure to acidified groundwater—this is particularly relevant in urban in-fill projects
- soil shrinkage
- lowering of surface water or the watertable on- or offsite via continuous flow into the excavation and/or construction infrastructure through installed drainage structures, preferred flow paths or palaeochannels
- confirmation of connectivity or isolation of groundwater aquifers—this is particularly relevant in urban in-fill projects
- oxidation of ASS during onsite stockpiling or during transport offsite for treatment
- additional construction costs not factored in during the approval process for waterproofing, management, remediation and offsite treatment.

The risk assessment will also need to factor in the requirements listed in Section 10.1. It is appropriate for the risk assessment to be considered with the approval process (and not only as a condition of a development approval), due to the additional costs and engineering required to ensure the structures are waterproof.

### 10.4.2 Management considerations

The key to managing the risk associated with in-ground infrastructure in ASS is the retardation of oxygen transport to ASS. Management considerations will depend on site-specific factors. On larger projects these may vary across the site. The following management strategies will need to be considered for use when the construction of structures below the watertable in ASS environments are proposed:

- undertake a groundwater investigation, including baseline groundwater quality data and seasonally lowest watertable elevation (in compliance with *Guidance for the dewatering of acid sulfate soils in shallow groundwater environments*) and conduct an ASS soils investigation (in compliance with the latest *Queensland ASS Sampling Guidelines*)
- engineer the basements, tunnels or below watertable structures to be fully tanked to ensure there is limited groundwater ingress (that may lead to lowering of the watertable) during all phases (i.e. construction and operation) of the development. The waterproofing must ensure the installed structures do not require permanent pumping of sumps, or installation of unconfined drainage structures to keep dry, and will subsequently limit the potential for acid production and potential damage to the environment and neighbouring infrastructure
- adhere to the management considerations for large-scale dewatering (see Section 10.1.2) to ensure that the rate and duration of dewatering variables are optimally managed to minimise risk to water quality, the receiving environment and neighbouring infrastructure

- ensure that there is minimal oxidation of deep *in situ* ASS and identify methods to treat the drained ASS and drainage waters—methods to treat the *in situ* drained ASS are not currently feasible or recommended
- ensure that all stockpiles are managed according to Section 10.2
- ensure that all ASS that are transported elsewhere are treated offsite at a licensed treatment facility and documentation is received that confirms all transported material has been treated effectively and completely.

## 10.5 Vertical mixing

Vertical mixing of ASS is a high-risk management technique that relies on using the buffering capacity of non-ASS horizons to dilute and neutralise the ASS horizons. This technique is suitable for soils with significant ANC, low levels of sulfides and that are reasonably coarse (i.e. sands and loams). The effectiveness of this method should be corroborated by slab incubation tests/kinetic testing conducted on the mixed sample, and this should be confirmed prior to any application of this management strategy. This technique has been used historically in the Netherlands in the unique situation where the ASS overlay a calcareous shelly horizon at shallow depths. To date there has been no validation of this method in Queensland.

*Note: It is incorrect and unacceptable to classify the soil as a non-ASS by averaging the acidity or %S within one or more samples or soil horizons to generate a reading below the action criteria.*

### 10.5.1 Environmental risk

A risk assessment will need to be undertaken in circumstances where vertical mixing of ASS is proposed and consultation about the proposed management should be undertaken with the relevant administering authorities.

A high level of skill and effort is needed to effectively ‘mix’ the soils during vertical mixing. Where there is insufficient mixing of the soil profiles, high levels of sulfides may be placed in potentially oxidising conditions without adequate buffering capacity to neutralise all the acidity. Long-term problems can be associated with the remediation of poorly treated ASS, so there are significant risks to the environment when this occurs.

Vertical mixing places a significant reliance on ASS site characterisation and interpretation of the stratigraphy, as there may be less natural buffering capacity than predicted in poorly characterised situations. There can be no justification for a sampling or analysis rate lower than those outlined in the latest *Queensland ASS Sampling Guidelines* when vertical mixing is the proposed management solution, and verification testing must be rigorous. Further addition of a neutralising agent may be required at some sites. Independent third-party review may be required (see ASS Tip 7).

### 10.5.2 Management considerations

The following management strategies will need to be followed when vertical mixing is proposed:

- a neutralising agent will need to be incorporated into the mixing process unless there is an abundance of fine, highly reactive neutralising materials within the soils (that has been corroborated by appropriate kinetic laboratory testing)
- a guard layer of a suitable neutralising agent will need to be placed under the processing area
- the processing area should be bunded and diversion banks installed upslope to prevent run-on water during mixing. Bunds and diversion banks should not be constructed out of untreated ASS or other materials that may be a source of contaminants to the environment. The bund materials used should have low permeability to avoid leakage

- soils must be adequately mixed with the neutralising agent
- extensive monitoring of surface and groundwaters must be carried out.

## 10.6 Pre-excavation neutralisation (*in situ* treatment)

On sites where space is a constraint (e.g. small excavations in a high-density urban area or where there is no space for a treatment pad), the preferred management strategy is offsite treatment at a licensed soil treatment facility. In some situations, ASS can be neutralised *in situ* before excavation, rather than being excavated, placed on a treatment pad and neutralised. Aglime can be incorporated into the top 300 mm of soil *in situ*, with added mixing via soil scraping operations into temporary stockpiles. Such treatment may only be effective for sands and sand-dominated soils, as clay-rich soils need much more drying and working to achieve a homogenous mix. See Section 7.3 and 7.2 for a discussion of management considerations (including verification testing) that would be relevant for this management strategy.

*Note: Depending on the effectiveness of the mixing, these soils may need further treatment at the permanent soil disposal area, after the results of the verification testing have been assessed.*

Treatment in this way removes most of the safeguards intrinsic to well-constructed treatment pads and is likely to increase the risk associated with the neutralisation. Mixing the neutralising agent *in situ* can be more difficult, and to offset the risks, a higher safety factor (e.g. 2–3) and more rigorous monitoring will be necessary. The earthmovers will need to act with extreme caution to make sure that only treated ASS is removed offsite. *In situ* neutralisation is not the best strategy for all sites; particularly if this approach will increase risks through the extension of the dewatering period (see Section 10.1).

# 11. Unacceptable management strategies

The following management strategies have been shown to carry unacceptably high environmental risk, or to be generally ineffective, and/or lack rigorous scientific data to support their sustainability. In these situations, the classification of these activities as unacceptable is based on the precautionary principle. Some of these activities may occasionally be sustainable and may produce suitable environmental outcomes with a low level of risk, and in these situations, their use is not precluded. A risk assessment will have to be undertaken to show this in sufficient detail. Note that if risks cannot be reliably quantified, these management strategies are unlikely to be approved.

## 11.1 Above-ground capping

Above-ground capping involves the placement of untreated ASS above ground, with the ASS under a non-porous cap. The cap is placed over the ASS to prevent water infiltration and to reduce exposure to oxygen. Capping ASS above the ground is a high-risk activity and is not recommended. Above-ground capping is not to be confused with the placement of treated compacted ASS as fill over the original undisturbed natural ground surface to elevate the finished land surface level, where the natural *in situ* soils below the fill layer comprise undisturbed PASS.

### 11.1.1 Environmental risk

A significant risk to the environment occurs if the above-ground cap fails and the sulfides are exposed to oxygen. The soils are then able to generate acidic leachate.

Various kinds of capping have been employed in the mining industry, where acidic mine tailings are often a management problem. These may be effective in the short-term when applied to ASS; however, ASS generally react more rapidly than mine tailings. Long-term risks arise from the potential loss of cover integrity, which can result from:

- settling of the underlying soils
- erosion of the capping material
- inability to keep some designs sufficiently saturated to minimise oxygen transport
- loss or replacement of overlying vegetation due to bushfires and/or natural reseeding in the case of store-release covers.

Capping ASS is therefore an unacceptable management strategy since it will need a commitment to monitor and maintain the cover's integrity in perpetuity.

Even if the capping layer could be designed to be effective, long-term tenure of the above ground capping layer cannot be guaranteed in most coastal situations. Future land uses in the area may penetrate the capping layer through disturbances such as swimming pools, underground infrastructure, road or rail construction and/or maintenance, or even tree roots.

The engineering requirements needed for effective above-ground capping would be much like those required for toxic regulated waste landfill sites. This would generally make the proposal economically unviable. Furthermore, the issue of which organisation looks after the cap in the long-term, and who is responsible for the associated risks, would need to be resolved.

**ASS Tip 34: Asphalt surfaces as caps**

Proposals for above-ground capping which involve using asphalt surfaces (e.g. roads, car parks, netball fields) to block oxygen and water from reaching ASS are unacceptable. Asphalt surfaces are typically permeable and will not maintain anaerobic conditions in the material below, so their use as caps is not supported.

Asphalt surfaces can degrade if they are placed on top of untreated or poorly treated ASS. Capillary rise of acidic water and collection of acid salts where the soil meets the asphalt can cause the surface to blister (Figure 16). Caution should also be exercised when considering road construction on treated ASS. Neutralisation of ASS with aglime will result in the formation of gypsum ($CaSO_4 \cdot 2H_2O$) which, when combined with excess water in the presence of aluminium in clay, may create expansive products such as ettringite, leading to heave problems that may damage the asphalt surfacing.

**Figure 16: Acidic salts and minerals on asphalt surfaces**

*Photo credit: Steve Lawrence*

## 11.2 Hastened oxidation

Hastened oxidation of ASS without appropriate neutralisation is a high-risk management measure and use of this procedure is not supported. Soils with high concentrations of sulfidic material may take decades to fully oxidise under natural conditions. Specific techniques can accelerate this process. The oxidation rate is influenced by the permeability of the material, the sulfide content, temperature, moisture content and bacterial activity.

### 11.2.1 Environmental risk

Significant time delays are associated with using this technique, particularly with marine clays and sediments containing high concentrations of sulfidic material.

A large body of soil and leachate containing acid, heavy metals, iron and aluminium by-products of oxidation pose a risk to the environment unless it can be guaranteed that the system is fully contained (especially during flood events), and that all the leachate is able to be collected and suitably treated. It can be difficult to remove potentially soluble heavy metals from solution, and the leachate needs complex monitoring and management. As such, an effective leachate and collection system is critical to the performance of this management procedure. This increases the complexity of the site management, puts a greater reliance on site supervision and technology, and may be costly. The risks to the environment are large if the leachate treatment and collection system fails to contain leachate during storms and flooding events. Leachate releases would constitute a significant breach of Section 440ZG of the *Environmental Protection Act 1994*.

## 11.3 Seawater and groundwater neutralisation

Seawater and/or groundwater neutralisation of ASS and/or water discharging from these soils is unacceptable as a primary management tool. Seawater is naturally alkaline, with a moderate acid buffering capacity from dissolved bicarbonate (and some carbonate). Up to two moles of protons may be neutralised by each cubic metre (1000 L) of sea water, but the potential downstream risks preclude its use. The alkalinity of groundwater is varied. The long-term impacts of using seawater and/or groundwater solely to neutralise large quantities of acidity are largely unknown. It may result in modification of the geochemistry of the receiving water column, which may stress near-shore marine, estuarine and groundwater organisms and may lead to unacceptable and possibly irreversible changes to tidal, marine and/or groundwater ecosystems, particularly those already under stress.

A possible exception to this principle may be for remediation of a site where significant disturbance of ASS occurred before the recognition of the environmental impacts of ASS; there already is an acid and/or metal load impacting on the receiving environment; and there are no other viable choices (e.g. broadscale acidity associated with agricultural production). In such situations, some of the strategies with higher risk may be allowed if there is no practical alternative and it can be shown that existing risk to the environment can be lowered by these means. Before its use in remediation, there should be a detailed hydrogeochemical study of the site waters and the receiving environment. The system should be rigorously monitored before, during and after the treatment.

### 11.3.1 Environmental risk

Where acidic waters are discharged to marine waters (e.g. marine embayments, tidal channels and marine estuaries) the carbonate-bicarbonate within seawater may be consumed during the neutralisation process and the equilibrium may change (particularly if the replenishment of carbonate-bicarbonate is exceeded by the volume of acidity for extended and repeated periods). These changes may be more pronounced in closed and partially closed estuarine environments. At present, the effect of depletion of carbonate in these waters on aquatic ecosystems is not fully understood. There is particular concern for invertebrates such as crustaceans and molluscs that are dependent on carbonate-bicarbonate for shell and exoskeleton growth.

Bicarbonate naturally present in seawater is available to neutralise acidity generated after natural processes lower the watertable (e.g. during tidal fluctuations or drought) in estuarine systems. There is an ethical debate as to whether it is proper to use the natural receiving environment to treat acidity generated from artificial drainage works. Development costs are likely to be much lower if neutralisation of leachate (using hydrated lime or other agents) can be avoided. However, there may be significant environmental costs to the receiving environment, particularly in closed or partially closed estuarine ecosystems. It is suspected that the cumulative impacts of a series of sites depleting the carbonate levels in the estuary could result in significant impacts, although individual contributions may be small.

Iron hydroxide and oxyhydroxide precipitates (and other metal compounds) may cause problems with sediment quality, water quality at the sediment interface, and dissolved oxygen concentration. This may affect the health or even the survival of gilled organisms, filter feeders, benthic species and associated communities. Additionally, iron in dissolved form and/or iron complexed with organic matter can increase the frequency and severity of cyanobacterial algal blooms.

## 11.4 Offshore disposal of ASS

Proposals for offshore disposal of ASS may carry high risk to the receiving environment. Any offshore disposal of dredged materials must follow the Australian Government's *Environment Protection (Sea Dumping) Act 1981*. This act is supported by the National Assessment Guidelines for Dredging 2009 (Commonwealth of Australia 2009).

### 11.4.1 Environmental risk

Risks associated with offshore disposal of ASS include smothering of marine organisms with sulfidic sediments, acidification of the marine environment and contamination of the marine environment with heavy metals or other toxicants.

## 11.5 Unconfined groundwater dewatering

Unconfined groundwater dewatering without appropriate management strategies to limit drawdown and oxidation of *in situ ASS*—either temporarily or permanently—is unacceptable.

### 11.5.1 Environmental risk

The risk associated with exposure of ASS to oxidising conditions has been stated in numerous sections of these guidelines. Within an oxidised cone of depression, a large body of soil and leachate containing acid, heavy metals, iron and aluminium by-products of oxidation may be produced. This poses a risk to the environment and to any adjacent infrastructure unless it can be identified that the system is fully contained, and soils and leachate can be effectively treated. This is exceptionally difficult to achieve.

Such impacts may present after a short period or may take years to be expressed in the environment and may also persist over a long timeframe, or they may peak seasonally following periods of rainfall. The subsequent risks will be high during periods of rainfall when the leachate may flow within palaeochannels and along preferred pathways to the receiving environment. The models on which cone of depression characterisation and preferred flow path prediction are made are complicated and rarely accurate enough to sufficiently safeguard environmental protection in the long term, due to the number of uncertainties involved. Once oxidised, the soils within the cone of depression are extremely difficult if not impossible to treat or reverse, and there will be unacceptably high costs associated with continuous long-term treatment and disposal of the discharge waters, the potential for degradation of aquatic ecosystems, remediation costs and damage to infrastructure. The potential long-term management and monitoring needs will outweigh the benefits of a cheaper drainage system in the short-term.

Soil shrinkage can also be a problem for surface and in-ground infrastructure. For example, at East Trinity in Far North Queensland, the surface elevation at parts of the site dropped by 1.2 m following drainage (compared to the elevations that were recorded 20 years earlier) (Hicks *et al.* 1999). Such extremes may not be common in urbanised areas; however, this example does highlight that soil shrinkage is a significant risk for permanent unconfined groundwater dewatering.

# 12. Closure reporting

Once an area containing ASS has been disturbed or otherwise modified, an assessment is necessary to demonstrate that the management has complied with these guidelines and the approved ASS EM plan. This process minimises future risks to the environment, stakeholders and land users, and mitigates the probability of subsequent litigation. Closure reports discuss the eventual management that was undertaken on site and certify a project's compliance with best practice environmental management.

A closure report can accomplish the above by demonstrating that the residual risks are low. For the 'very high' treatment category defined in Section 3.4.4, a simple closure report is adequate. For 'extra high' category defined in Section 3.4.5, a detailed closure report is necessary. Closure reporting is not required for the 'low', 'medium', and 'high' categories defined in Section 3.4, but it is still advantageous to document ASS management strategies, details of environmental performance and retain photographic evidence. These may need to be provided to the regulatory decision maker upon request. When conditioning development approvals, the regulatory decision makers will consider all factors that pose a risk to the environment and specify the requirements for closure reporting accordingly. Additional information on EM plans is included in Appendix 2. Additional information on water quality parameters is included in Appendix 3 and Appendix 4.

The closure report must be filled out for all developments/activities conditioned for an ASS management closure report under the relevant provisions of the *Planning Act 2016*, the *Environmental Protection Act 1994*, and/or the *State Development and Public Works Organisation Act 1971*. Closure reports can be required as a component of an ASS EM plan.

The closure report must be completed and submitted to the regulatory decision maker to demonstrate that site management has complied with the requirements of the latest version of the:

- *Queensland ASS Sampling Guidelines*
- *National and Queensland Laboratory Methods Guideline*
- *Soil Management Guidelines* (this guideline)
- *Guidance for the dewatering of ASS in shallow groundwater environments*,
- *National guidance material for dredging ASS* (if dredging was undertaken)
- *MBO National Guidance material* (if MBOs were disturbed) and
- approved ASS EM plan for the activity in question.

Completing the closure report enables the regulatory decision maker to maintain an accurate and consistent record for the site and expedites the assessment and compliance process. The assessing authority may request further information in situations where there are concerns over risk to the environment, neighbouring infrastructure or human health.

## 12.1 Components of a closure report

Closure reports should include the following information:

- total volumes and dimensions of disturbed ASS
- details of soil management strategies undertaken at the site (including evidence of specific management measures such as waste tracking, photographic evidence of neutralisation of bunded treatment pads, liming rates and tonnes of neutralising agent used). Include a discussion of the effectiveness of management strategies employed at the site
- where dewatering was involved, final location, extent and duration of dewatering. Include details of groundwater management strategies applied to ensure that the rate and

duration of dewatering variables were optimised to minimise risk to water quality, the receiving environment and neighbouring infrastructure

- photographic evidence of management and monitoring undertaken at the site
- details of surface water management strategies undertaken at the site
- summary of monitoring results for surface water and groundwater (with an emphasis on trends in water quality)
- location of any offsite treatment and/or disposal of ASS and evidence of treatment offsite
- summary of verification testing results for material treated either on- or offsite
- location and maps of areas used for burial of fines from hydro-sluicing (if relevant) or treatment of fines from maintenance dredging (if relevant)
- location and maps of areas used for strategic burial of PASS, depth below finished surface and details of safety margin below the permanent watertable (if relevant)
- details of any incidence of nonconformity with the EM plan and corrective actions taken
- a discussion of any potential risks to the water quality, the receiving environment, neighbouring infrastructure or human health
- proposed future monitoring and/or reporting programs
- proposed remediation measures if required
- a statement that the suitably skilled and experienced person in ASS science (see Section 3.2) considers the subject site to have been adequately managed, suitable for the proposed final uses, with minimal impact on water quality, the receiving environment, neighbouring infrastructure and/or human health
- a statement that the suitably qualified engineer considers the site to be geotechnically suitable for its intended end purpose.

The closure report will be completed by the suitably skilled and experienced person in ASS science (see Section 3.2) who was responsible for the ASS management during site works. Regulatory decision makers have the option of requiring independent third-party review (see ASS Tip 7) of all management undertaken on site (as is the case for Contaminated Land assessments).

Participation in closure reporting should be a key deliverable in works contracts. Where there are indications of inadequate ASS management, risks to water quality, the receiving environment, neighbouring infrastructure or human health, the regulatory decision maker and the Department of Environment, Science and Innovation must have been notified at the time of detection—the closure report is not a tool to notify authorities about these risks.

In the case of systematic failure of ASS management, or where environmental harm has occurred, or where there is potential for environmental harm, further action may be taken under the *Environmental Protection Act 1994.*

*Note: Version 4 of the Soil Management Guidelines (Dear et al. 2014) included a section on Handover Testing. Handover testing is an independent round of soil sampling and laboratory testing to demonstrate that disturbed ASS have been adequately managed. If a site has been managed by a suitably skilled and experienced person in ASS science and has passed verification testing, the requirement for handover testing is considered onerous and mostly unnecessary. However, there may be situations where handover testing is justified, especially when the risks to the environment are considered to outweigh the cost of the additional round of testing and there are questions of the appropriateness of the site management. In this instance, it is recommended that reference is made to section 13 of version 4 of the Soil Management Guidelines for careful consideration. Independent third-party review is also an option in this scenario (see ASS Tip 7).*

# Glossary

**%S**: A measure of reduced inorganic sulfur (using the $S_{CR}$ or $S_{POS}$ methods) expressed as a percentage of the weight of dry soil analysed. Can also be used as an 'equivalent sulfur unit' when comparing the results of tests expressed in other units, or when doing acid base accounting.

**Acid base account (ABA):** A simple equation used to combine the results of several laboratory soil tests to produce a consistent and comparable measure of soil Net Acidity. The accounting system includes measures of freely available (Actual) acidity, acidity released from low solubility chemical compounds (Retained Acidity) and sulfides vulnerable to oxidation (Potential Acidity), balanced against any Acid Neutralising Capacity (ANC) if corroborated.

**Acid mine drainage (AMD):** An environmental problem related to acidic leachate and metal releases from mine tailings, overburden and rocks containing sulfides, particularly pyrite. The underlying chemistry of acidification is similar to coastal ASS, but management techniques differ substantially. Also referred to as acid and metalliferous drainage or acid rock drainage (ARD).

**Acid neutralising capacity (ANC):** The ability of a soil to counteract acidity and resist the lowering of the soil pH. In an ASS context, ANC is considered negligible if the soil's $pH_{KCl}$ after processing is less than 6.5. Above pH 6.5, ANC is measured according to the latest *Laboratory Methods Guideline*, Australian Standard 4969, and Sullivan *et al*. (2018b). For ANC to be incorporated into the quantification of Net Acidity in the ABA, it must be corroborated by other data that demonstrates the soil material does not experience acidification during complete oxidation under field conditions.

**Acid rock drainage (ARD):** See acid mine drainage

**Acid sulfate soils (ASS):** Soils, sediments or other materials containing iron sulfides and/or acidity generated by their oxidation. These materials are environmentally benign when left undisturbed in an aqueous anoxic environment, but when exposed to oxygen the iron sulfides oxidise, releasing large quantities of sulfuric acid and soluble iron. Both substances have considerable ability to degrade the natural and built environment, and the acid can additionally mobilise other pollutants (e.g. aluminium, lead, zinc).

**Actual acidity:** Soluble and exchangeable acidity readily available for reaction, including pore waters containing metal species capable of hydrolysis (e.g. $Fe^{2+}$, $Fe^{3+}$ or $Al^{3+}$ ions). Operationally defined by the Titratable Actual Acidity (TAA) test.

**Actual ASS (AASS):** Soils containing highly acidic soil horizons resulting from the aeration of soil materials that are rich in iron sulfides, primarily pyrite. This oxidation produces hydrogen ions in excess of the sediment's capacity to neutralise the acidity, resulting in soils of pH 4 or less. These soils can usually be identified by the presence of jarosite.

**Action criteria:** For ASS, the measured level of Net Acidity beyond which management action is required if a soil or sediment is to be disturbed. The trigger levels vary for texture categories and the amount of disturbance.

**Advection:** The transport of a substance or of energy by a fluid. In the context of this guideline, this term commonly refers to the transport of dissolved oxygen through water.

**Aglime:** An alkaline calcium carbonate ($CaCO_3$) based neutralising agent used to treat acidic soils. By composition high quality aglime may be 98% calcium carbonate and hence has a neutralising value of 98%. It is mildly soluble in pure water, with a pH of ~8.3. Application rates will depend on the purity and fineness of the product. Some commercially available aglimes have much lower neutralising values.

**Alkaline:** Description of a substance with a pH greater than 7 when dissolved in or mixed with water.

**Alluvium:** An extensive stream-laid deposit of unconsolidated material, including gravel, sand, silt and clay. It typically forms floodplains that develop into alluvial soils (Houghton and Charman 1986).

**Aluminium:** A metallic element (atomic number 13, symbol Al). The most common metal in the Earth's crust, and a major component of soil minerals. Aluminium can be released into solution within the soil at either very low or very high pH. Some aqueous aluminium bearing compounds are significantly toxic to fish and other aquatic species at pH 5.0–5.5.

**Amorphous:** Lacking a clear shape; when referring to ionic solids, it describes a lack of long-range ordered crystalline structure.

**Anaerobic**: In soil science, describes soil conditions in which free oxygen is deficient and chemically reducing conditions prevail. Such conditions are usually found in waterlogged or poorly drained soils in which water has replaced soil air.

**Anion:** An ion with a negative charge.

**Anoxic:** An environment where oxygen is intrinsically rare or absent.

**Aqueous:** Composed of or pertaining to water.

**Aquifer:** Layers of rock, sand or gravel that can contain free water and allow it to flow. An aquifer acts as a groundwater reservoir when the underlying rock is impermeable.

**Arsenic:** A metalloid element (atomic number 33, symbol As). Arsenic is sometimes contained in soil or rock material, commonly bound up in minerals with the composition MAsS or MAs2, where M = iron, nickel or cobalt. Significantly toxic to life, and associated with a variety of cancers in humans, it is released into solution within the soil under various pH and redox conditions. While arsenic can co-precipitate with iron or aluminium as pH is raised, an excess of arsenic can remain in solution and may require further management before contaminated waters can be released.

**Assessment manager:** Per section 48 of the *Planning Act 2016*, the entity prescribed under regulation as having responsibility for administering and deciding a development application; and assessing all or part of the application. This is usually local government.

**Australian height datum (AHD):** The datum used for the determination of elevations in Australia. The determination uses a national network of benchmarks and tide gauges and sets mean sea level as zero elevation.

**Batter:** The sloping sides of an excavation (e.g. a pit or drain), generally described as a ratio of its vertical and horizontal dimensions.

**Benthic:** Refers to the environment at the base of waters, and to the animals and plants that live in that environment.

**Best practice environmental management (BPEM):** The management of an activity to achieve a continuing minimisation of the activity's environmental harm, through cost-effective measures, assessed against the measures now used nationally and internationally for the activity. See Section 21 of the *Environmental Protection Act 1994*.

**Bicarbonate:** A compound containing the $–HCO_3$ functional group, or the $HCO^{3-}$ anion itself.

**Black water:** Natural water systems in which the water carries little sediment but large amounts of dissolved organic matter. The waters are acidic and low in nutrients, and the surrounding catchment soils are generally sandy and are often Podosols (Reeve and Fergus 1982).

**Bottom shear:** The resuspension or entrainment of bottom sediments by moving water.

**Buffering capacity:** The ability of a mixture or solution to resist pH change—in an ASS context, this may refer to surface or groundwaters, the soil solution, or to the soil itself.

**Bulk density (BD):** With regard to soils, the mass of an oven-dry sample per unit of soil as found in the field. In an ASS risk assessment context, planned disturbance volumes can be converted to tonnage using the bulk density (volume x BD = tonnage). Expressed in units of $g/cm^3$ or $t/m^3$, which are numerically equivalent i.e.1.5 $g/cm^3$ is the same as 1.5 $t/m^3$.

**Bunding/bund:** An elongated earth mound used to direct and/or contain the flow of water.

**Calcareous:** With regard to soils, containing appreciable amounts of calcium carbonate, usually in the form of carbonate segregations, chalk or limestone particles.

**Calcium carbonate:** A compound with the formula $CaCO_3$. Forms a number of minerals with distinct crystalline structure (e.g. calcite, aragonite) and is the principal component of agricultural lime and the shells of many marine organisms. Calcium carbonate has several industrial uses, particularly in construction and fabrication, and is generally produced by quarrying.

**Calcium hydroxide:** A compound with the formula $Ca(OH)_2$, also known as hydrated lime. It is created by adding calcium oxide to water and is used in several industrial processes, including water treatment.

**Calcium oxide:** A compound with the formula CaO, also known as quicklime. Calcium oxide is created by burning limestone at high temperature. Once produced, CaO slowly reverts back to $CaCO_3$, as it reacts with $CO_2$ in the air. Calcium oxide is a lightweight, strong neutralising agent with a high pH (~12.5) but reacts violently with water so is difficult to handle safely.

**Calcium sulfate:** A compound with the formula $CaSO_4$, also known as anhydrite. Calcium sulfate is a primary product of the neutralisation reaction of aglime with sulfuric acid. In the presence of moisture, it commonly crystallises to form gypsum $CaSO_4{\bullet}2H_2O$.

**Capital dredging:** Dredging to create a new harbour, marina or shipping lane.

**Carbon dioxide:** A gas with the formula $CO_2$. A by-product of cellular respiration and of the neutralisation reaction of aglime with sulfuric acid.

**Carbonate:** A compound containing the $–CO_3$ functional group, or the $CO_3^{2-}$ anion itself.

**Catchment:** The area of land contributing water to a given watercourse and its tributaries.

**Cation:** An ion with a positive charge.

**Certified professional soil scientist (CPSS):** A professional accreditation scheme for soil scientists, administered by Soil Science Australia.

**Chromium Reducible Sulfur ($S_{CR}$):** A laboratory test to measure reduced inorganic sulfides i.e. the potential acidity component of the Net Acidity calculations.

**Clean fill:** In a general sense, clean fill is earthen material free of large rocks (>10 cm) and any contaminants. The concept is defined in the legislation of some jurisdictions, for instance Western Australia, but is not clearly defined in Queensland except in the context of determining whether and how the *Environmental Protection Regulation 2009* applies to a waste disposal facility. In the context of this guideline, clean fill is non-ASS material.

**Coffee rock:** A common term for indurated sandy horizons that can form within mature Podosols. The sand is cemented together by iron- and aluminium-rich organic compounds washed out of surface horizons and concentrated at depth, generally at the top of the watertable. Its appearance at the land surface along stretches of eroded sandy coastline has led to it being referred to as 'beach rock'.

**Complex:** In chemistry, a molecular structure comprising a central atom (usually a metal) surrounded by a number of binding molecules or ions, referred to as ligands. Can also describe the association (through covalent bonding or otherwise) between metals and organic matter.

**Compliance depth:** In ASS management, describes the depth to which ASS have been fully treated with a neutralising material on site, and independently verified as such. The concept is primarily applied to areas of filled or made land and helps to ensure that ASS management problems are not passed on to those purchasing or developing land made from treated ASS. Within construction sites geotechnical advice on structural stability will need to be addressed as well.

**Composite samples:** In soil sampling, the practice of combining a number of subsamples together (or sampling across a large depth range in a soil core) to produce a sample which represents an average across a given spatial extent or depth range. The practice is useful in some circumstances (e.g. during verification testing) but can be misused or the results misinterpreted. When samples are composited across natural soil horizon boundaries or across soil types, results are unlikely to be representative of any useful parameter.

**Cone of depression:** In hydrology, the three-dimensional volume of soil or sediment dewatered around an extraction point. The slow movement of water through sediments means that dewatering an area also lowers the local watertable, with the effect attenuating with distance. Despite its name, the cone of depression is rarely a regular shape, since it is strongly influenced by the permeability and porosity of the sediments involved. These parameters are highly spatially variable.

**Cumecs:** a cubic metre per second, as a unit of flow of water.

**Declared fish habitat area**: An area declared under the Queensland *Fisheries Act 1994* to be a fish habitat area. Under the Act, fish habitat includes land, water and plants associated with the life cycle of fish, and includes land and waters not presently occupied by fisheries resources. Disturbance of declared fish habitat areas is regulated under the Act, with the Queensland Department of Agriculture and Fisheries charged with their protection.

**Deep soil mixing (DSM):** An engineering technique by which soil or sediment is mixed *in situ* with a setting agent (usually cement), forming an impermeable barrier.

**DESI:** Queensland Department of Environment, Science and Innovation.

**Diffusion:** The process by which a substance moves from an area of high concentration to an area of low concentration.

**Dissolution:** In chemistry, the process by which a solid material forms a homogenous mixture with a solvent.

**Disturbance:** In terms of this guideline, disturbance consists of (a) excavating or removing the soil; or (b) exposing the soil to air; or (c) changing the level of the groundwater.

**Dolomite:** A mineral and rock composed of crystals of calcium magnesium carbonate, $CaMg(CO_3)_2$. The mineral can precipitate under anaerobic, saline conditions and, when ground, may be used as an alternative neutralising material to aglime. However, magnesium-based compounds can produce magnesium sulfate (Epsom salts) during neutralisation, which can be an environmental contaminant. Commercially available dolomite may also have quite a variable composition. Legally in Queensland, dolomite or dolomitic limestone must contain at least 80 g of magnesium in the form of magnesium carbonate for each kilogram of the total product (Agricultural Standards Regulation 1997, s16). Thus cheap dolomite sources may have relatively low magnesium carbonate content and therefore low neutralising values. Extremely large quantities of such materials would be needed to effectively treat ASS.

**Drop board:** A simple floodgate structure used to regulate flow in small drains and canals.

**Environmental management plan (EM plan):** A document detailing the management procedures for a development with the goal of meeting the *general environmental duty* under the *Environmental Protection Act 1994*. While non-statutory, these may be requested by an assessment manager as a condition of development approval.

**Environmental management program (EM program):** A statutory tool under Part 3 of the *Environmental Protection Act 1994*, approved or refused by DES.

**Environmental harm:** is defined under the Section 14 of the *Environmental Protection Act 1994*, as any adverse effect, or potential adverse effect (whether temporary or permanent and of whatever magnitude, duration or frequency) on an environmental value, and includes environmental nuisance as defined in Section 15 of the same Act.

**Ettringite:** A crystalline compound with the formula $Ca_6Al_2(SO_4)_3(OH)_{12}•26H_2O$ that occurs in nature and as part of the system of reactions associated with Portland cement. In initial concrete-setting reactions the mineral is vital as it controls the rate of concrete setting. However, 'delayed' or secondary ettringite formation in concrete can occur in the presence of sulfate and acid, causing considerable damage. The large, needle-shaped crystals invade set concrete and cause it to expand and crack. Ettringite formation in soil can also cause substantial heaving.

**Evapotranspiration:** A term referring to the evaporation of water from the land surface as well as the uptake of water by plants and its gaseous release from their leaves.

**Existing acidity:** A term previously used in acid base accounting, a collective term that includes Actual Acidity and Retained Acidity.

**Ferric hydroxide:** A compound with the nominal formula $Fe(OH)_3$. Ferric hydroxides precipitate from acidic, iron-rich waters as the pH rises above 4, and may form a variety of different minerals, including goethite, lepidocrocite and ferrihydrite.

**Ferrihydrite:** A compound with the nominal formula $5Fe_2O_3•9H_2O$. Its water content varies and it only exists as a nanomaterial, being unable to form larger crystals. Ferrihydrite is a common soil mineral and is considered a precursor for the formation of minerals like goethite and haematite. It has an extremely high surface area and demonstrates the ability to bind other chemical compounds, including many environmental toxins. For this reason, it is sometimes used in water purification systems.

**Fetch:** In limnology, the length of water over which wind blows. This property of surface water bodies can affect their wave-generating potential and thus the depth of mixing within the water body.

**Fineness:** Regarding a solid substance, its particle size. Fine particles of a substance have a larger surface area and are therefore more chemically reactive than larger particles of the same substance.

**Fines:** A term to describe concentrated sulfidic material that is generated after fine-textured material has been hydraulically separated from coarse-textured material during dredging or hydrocycloning operations. Fines are initially supersaturated and take some time to settle completely. Alternative terms: dredge fines, sulfidic fines, slimes.

**Floc:** In chemistry, flocculation is the process by which a substance causes fine particles of material suspended in water to group together (or aggregate), forming larger particles that may settle out of the water, float on top or otherwise become easily filterable. The larger particles are known as floccules, or floc.

**Foraminifera:** Microscopic marine protozoa whose shells contain varying amounts of calcite. When present in large numbers in the soil, these tiny shells (<1 mm) can contribute to the neutralising capacity of soils. Foraminifera have been found in some soils along the Queensland coast in varying concentrations, sometimes rendering a soil horizon partially or fully self-neutralising.

**Fulvic acid:** A subgroup of compounds found in humic solutions, operationally defined as those compounds that do not precipitate when a humic solution is lowered to pH 1 using hydrochloric acid.

**General environmental duty (GED):** Under Section 319 of the *Environmental Protection Act 1994*, a person must not carry out any activity that causes, or is likely to cause, environmental harm unless the person takes all reasonable and practicable measures to prevent or minimise the harm.

**Goethite:** An iron oxyhydroxide mineral with the formula $FeO(OH)$, which can precipitate from iron-rich waters or form from other iron-bearing minerals.

**Global positioning system (GPS):** A network of linked satellites capable of accurately locating a point on the Earth's surface with the use of an appropriate receiver.

**Greigite:** A magnetic iron sulfide mineral with the formula $Fe_3S_4$. Greigite forms microcrystals in sulfide-rich sediments, much like pyrite.

**Groundwater:** Water permeating rocks or sediments underground (Wilmott 2010).

**Groundwater dewatering:** The process of extracting water from a saturated soil or sediment that results in alteration of the watertable level. See Shand *et al. 2018.* Groundwater dewatering does not include short-term pumping (< 1 day duration) of saturated soils or sediments from small volume excavations.

**Guard layer:** A layer of neutralising agent applied to the surface of the treatment pad before ASS are spread for treatment. It reduces risk by neutralising acidic leachate generated in the treatment pile and not neutralised during the treatment process. The guard layer helps protect groundwater quality.

**Gypsum:** A mineral composed of hydrated calcium sulfate $CaSO_4 \bullet 2H_2O$ crystals, common in arid soils but also detectable in some coastal ASS, particularly after its disturbance and/or treatment. Gypsum has swelling properties.

**Haematite:** An iron oxide mineral with the formula $Fe_2O_3$. Haematite can precipitate from iron-rich waters or form during volcanic activity and comprises a major iron ore. Small haematite crystals also form during soil weathering processes.

**Humic acid:** A group of acids rather than a single compound, this term refers to several complex acids formed as organic matter breaks down. Humic acids can form complexes with ions and are soluble in water only at pH >2.

**Hydraulic conductivity:** In soil science, the rate at which water moves through a given volume of soil, usually expressed in units of metres per day.

**Hydraulic separation:** The partitioning of sediment, soil fragments or minerals using natural or accelerated differential settling into fractions, based on differences in particle size and density.

**Hydrated lime:** See calcium hydroxide.

**Hydrogen:** A gaseous element (atomic number 1, symbol H). Hydrogen is the lightest element and third most abundant in soil and rock.

**Hydrogen sulfide:** A gas with the formula $H_2S$. Commonly known as 'rotten egg gas' due to its smell, $H_2S$ is released from anaerobic systems as a metabolic by-product. The gas is heavier than air and potentially fatally toxic if allowed to accumulate in confined spaces.

**Hydrology:** The characteristics of water and the study thereof.

**Hydrolysis:** In chemistry, a reaction that splits water into hydrogen cations and hydroxide anions.

**Hydroxide:** A compound containing the –OH functional group, or the OH- anion itself.

**Hydroxy-sulfate:** A compound containing both the –OH and $–SO_4$ functional groups. In ASS, a common hydroxy-sulfate is jarosite $KFe_3(SO_4)_2(OH)_6$.

**Hypersulfidic material:** is capable of the most severe acidification as a result of sulfide oxidation. Hypersulfidic material has a field pH of 4 or more and is identified by experiencing a substantial[21] drop in pH to 4 below 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: a) until the soil pH changes by at least 0.5 pH unit to below 4, or b) until a stable[22] pH is reached after at least 8 weeks of incubation (Isbell & NCST 2021).

**Hyposulfidic material:** is intermediate to weak in its degree of acidification as a result of sulfide oxidation. Hyposulfidic material: (i) has a field pH of 4 or more and (ii) does not experience a substantial[17] drop in pH to below 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[18] pH is reached after at least 8 weeks of incubation (Isbell & NCST 2021).

***In situ***: From the Latin; literally, ‘in the place’. In this guideline, the term refers to undisturbed soils or sediment, and often those soils or sediments directly adjacent to or affected by a disturbance.

**Indurated:** In soil science, soils or sediments that have become physically compacted or chemically cemented.

**Infrastructure:** The basic facilities and support systems underpinning urban areas, for instance water, power, sewerage and transport networks.

**Iron:** A metallic element (atomic number 26, symbol Fe) common in the Earth's crust. In an ASS context, iron is important as its ionic form $Fe^{2+}$ is released by the breakdown of pyrite and goes on to become involved in a complex series of environmentally relevant reactions, including oxidation and hydrolysis, which release acid.

**Jarosite:** An acidic, pale yellow (straw- or butter-coloured) iron hydroxy-sulfate mineral: $KFe_3(SO_4)_2(OH)_6$. Jarosite forms upon the hydrolysis of ferric sulfate if the pH is between 3.5–4.0 and conditions are oxidising enough for the $Fe^{3+}$ to be stable. It is commonly found precipitated on the

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[21] A substantial drop in pH arising from incubation is regarded as an overall decrease of at least 0.5 pH unit

[22] 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.

surfaces of soil peds and along root channels exposed to air (Fanning 1993). It is an environmentally important store of acidity as it can slowly break down to release acid and iron without needing a supply of oxygen.

**Landfill:** land used as a waste disposal site for lawfully putting solid waste on the land. Landfills in Queensland are operated under an environmental authority, which may be conditional on particular management and containment strategies being employed.

**Laser-levelling:** In agriculture, a method of levelling (or otherwise contouring) the ground using machinery guided by laser.

**Leachate:** In an ASS context, water from treatment pad areas or from stockpiles of acid sulfate soils. These waters include surface runoff, and may contain acidity, iron, aluminium and other metals, as well as particles of soil and neutralising material.

**Lime:** A generalised term that may refer to a wide range of calcium and magnesium carbonates, oxides and hydroxides, depending on context. In this guideline, use of the term is avoided in favour of ‘neutralising materials’, aglime’, or specific names for substances.

**Limnology:** The study of lakes, and by extension, constructed water bodies, with limited inflows or outflows.

**Linear disturbance:** In an ASS context, a disturbance substantially longer than it is wide (normally more than five times longer) and no wider than 100 metres.

**Mackinawite:** A mineral with the formula $Fe1^{+x}S$, where x = 0-0.11. Mackinawite crystals can form in sedimentary reducing environments and their formation is possibly bacterially mediated.

**Macropores:** In soil, larger pores formed chiefly by biological activity such as root holes or earthworm holes, as well as structural cracks and fissures. A minimum size of ~50 micrometres is sometimes applied to the concept. In ASS, particularly actual ASS, macropore presence can create a wide spatial variability in hydraulic conductivity (Johnston *et al*. 2009b).

**Magnesium carbonate:** A compound with the formula $MgCO_3$, also known as magnesite. The compound can be used as a soil neutralising agent.

**Magnesium sulfate**: A compound with the formula $MgSO_4$. Its hydrated form, $MgSO_4 \bullet 7H_2O$, is commonly known as Epsom salts. Magnesium sulfate is common in marine environments and may form as a by-product of the reaction of magnesium-bearing neutralising agents with sulfuric acid. High concentrations of magnesium sulfate in drinking water can have a strong laxative effect on animals and humans.

**Maintenance dredging:** Dredging to maintain or re-establish the depth and breadth of shipping channels, canals, harbours and similar structures.

**Marine Park:** An area of Queensland waters declared under the *Marine Parks Act 2004*. Section 8 of the Act describes in detail the areas of the state that may be declared a marine park under the Act.

**mol $H^+$/t:** A measure of acidity, expressed as the number of moles of hydrogen cations per tonne of oven-dry soil material. A mole is $6.022 \times 10^{23}$ atoms of a given substance. The term can also be used as an 'equivalent acidity unit' when comparing the results of tests expressed in other units.

**Monosulfidic black ooze (MBO):** Amorphous gels that form in the base of low-flow surface water bodies in acid sulfate soil-influenced environments (Sullivan *et al*. 2002). MBOs contain high concentrations of iron monosulfide minerals (general formula FeS). These minerals are highly reactive in the presence of oxygen, breaking down in minutes to produce free iron and acidity. The reactions are controlled by the presence of oxygen in the water, and their disturbance can cause significant deoxygenation events in natural waters, killing aquatic life. Monosulfidic black oozes may sometimes be referred to as iron monosulfides, monosulfides or acid volatile sulfides. MBO formation is often a precursor to biogenic pyrite formation, and thus formation of ASS.

**Monosulfidic materials**: the sulfidic material described in the Australian Soil Classification that contains high concentrations of detectable monosulfides (≥ 0.01% acid volatile sulfide). Monosulfidic material is conceptually similar to MBOs (Sullivan *et al*. 2002). However, it differs from MBO in that monosulfidic material encompasses a wider array of soil textures and consistencies. For example, monosulfidic material includes sands with >0.01% acid volatile sulfide, which are excluded (based on soil consistence) from being MBOs (Isbell & NCST 2021).

**Munsell colour chart:** A proprietary system of colour description based on three properties—hue, value and chroma. Munsell products are used in a variety of industrial and commercial applications. In soil science, Munsell colour charts are used to formalise soil colour description as the system is considerably more refined and robust than using a list of subjective colour names.

**Natrojarosite:** A variant of the mineral jarosite, in which potassium is replaced by sodium. The chemical formula is $NaFe_3(SO_4)_2(OH)_6$ and it forms under similar conditions to jarosite but in areas where potassium is not available. Does not have the same distinctive colour as jarosite and is more commonly encountered in mining situations.

**Net Acidity:** the quantitative measure of the acidity hazard of ASS materials. See Section 3.1 of this guideline and Sullivan *et al.* (2018b).

**Neutralisation:** In chemistry, the process in which an acid and a base react to produce a salt. In an acid sulfate soils context, neutralisation refers to the addition of a base (generally aglime, $CaCO_3$) to soil containing or releasing an acid (sulfuric acid, $H_2SO_4$). The salt produced is calcium sulfate ($CaSO_4$), along with carbon dioxide ($CO_2$) as a by-product. This neutralisation reaction raises the pH of the soil back to environmentally acceptable levels (in the range 6.5 to 8.5). Soil neutralisation is rather more complicated than the general 'acid + base = salt' formula implies, owing to further release of acid from pyrite breakdown and the reaction kinetics of an acid solution interacting with a solid base in the presence of many interfering substances.

**Nutrients of concern:** In water quality management and in the context of this guideline, these are nutrients that contribute to increased algal growth in coastal waters i.e. phosphorus, iron, nitrogen and organic matter (dissolved organic carbon). Land-based development and management activities that disturb soils and sediments or alter the natural hydrological regime (including groundwater levels and composition and surface water runoff), can mobilise and transport increased loads of nutrients into coastal waters (Queensland Government 2011a). Such releases are to be prevented or controlled under various instruments.

**Organic acidity:** Acidity sourced from organic material in the soil, including some free acidity ($H^+$) as well as a wide variety of humic and fulvic acids.

**Oxidation:** Describes the loss of electrons or hydrogen and the gain of oxygen by a molecule, atom or ion, or the increase in oxidation state of an element. The most familiar example of chemical oxidation is rusting iron. In an ASS context, the term is commonly used to refer to the process of pyrite or iron sulfides reacting with oxygen and releasing acid and iron products. Another important reaction in ASS chemistry is the oxidation of ferrous ion $Fe^{2+}$ to ferric ion $Fe^{3+}$, which also releases acidity.

**Oxide:** A compound containing the –O functional group, or the $O_2^-$ anion itself.

**Oxygen:** A gaseous element (atomic number 8, symbol O). Its diatomic form $O_2$ comprises ~21% of the Earth's atmosphere and is vital for life.

**Oxyhydroxide:** A compound containing at least one oxide ($–O^-$) and at least one hydroxide (–OH) functional group.

**Oven-dried basis:** When referring to acid sulfate soils analysed according to Sullivan *et al*. (2018), the *Laboratory Methods Guideline* or AS 4969, this means that the soil sample has been placed in a fan-forced oven at 85°C for 48 hours, minimising sample oxidation during drying. Other analytical protocols (for instance, those used when measuring soil nutrients) may specify different temperatures and drying periods.

**Palaeochannel:** In geomorphology, deposits of sediment left behind by a river system as it moves across a floodplain. Palaeochannels are often coarser in texture than the surrounding sediment deposits, since they were deposited under higher-energy conditions, by faster-flowing water. Thus, they can form preferential flow paths for groundwater.

**Particle size distribution (PSD):** The relative amount of soil particles in a sample that fall into various size fractions, usually expressed as a series of percentages by weight. Soil textures are partly defined using PSD categories.

**Peat:** Soil material with little mineral particle content, dominated by organic matter in varying stages of decomposition and saturated with water for part or all of the year.

**Perched watertable**: A small, local watertable that exists above the larger surrounding watertable, created where a layer of impermeable material (usually rock) prevents water moving downward. Where such impermeable layers are near the surface in topographical depressions, perched lakes can form.

**Permeability:** In soil science, the ease with which water can move through a soil material. This property is independent of climate and drainage and is related to porosity, texture and structure. It is properly defined across an entire soil profile, with the least permeable horizon controlling the property (NCST 2009).

**pH:** A measure of the acidity or alkalinity of a soil or water body on a logarithmic scale of 0 to 14; pH <7 is acidic, pH = 7 is neutral, and pH >7 is alkaline. Note that one unit change in pH denotes a ten-fold change in acidity.

**Piles:** An engineering term encompassing a variety of techniques for installing walls or support structures in the ground prior to excavation. Piles may be sheets of interlocking metal or plastic with or without a sealant applied at joints. They may also be constructed by boring holes in the ground and filling the holes with concrete, or by mixing the concrete with *in situ* soil or sediment using specialised equipment. Precast concrete, metal or timber piles can also be driven into the soil without excavation. Some piles are suitable for bearing the load of overlying structures, while some cannot support significant weight and only act as a containment structure. Sheet and driven piles can be placed either temporarily or permanently.

**Podosol:** In the Australian Soils Classification (Isbell & NCST 2021), a Podosol is 'a soil with B Horizons dominated by the accumulation of compounds of organic matter, aluminium or iron'. These soils are primarily coastal, forming in sandy areas with relatively high rainfall and enough vegetation cover to provide a source of organic matter. The soil profile commonly exhibits a relatively thin surface horizon, followed by a pale, sandy, heavily leached horizon and then a layer or layers of dark brown to black organic sandy material, which may be indurated. This pattern may repeat itself within the profile in locations where newer sand deposits have overlain older ones. The dark layers are commonly known as coffee rock.

**Porosity:** A measure of the relative proportion of void space in a solid material, usually expressed as a percentage. This measure makes no assessment of the degree of connectivity between void spaces.

**Potential acidity:** Acidity associated with the complete oxidation of sulfides (mainly pyrite)—that is, the maximum theoretical amount of acidity that could be produced if all the pyrite in the soil oxidised. In an acid sulfate soils context, potential acidity is operationally defined by either the $S_{CR}$ or $S_{POS}$ method.

**Potential ASS (PASS):** Soils that contain iron sulfides or sulfidic material, which have not been exposed to air and so have not oxidised. The field pH of these soils in their undisturbed state is pH 4 or more and may be neutral or slightly alkaline. PASS pose a considerable environmental risk if disturbed, as they will generate iron and sulfuric acid when exposed to air.

**Preloading:** The practice of placing a thick layer of fill ('preload', usually >2 m depth) on land temporarily, to compress soil or sediment and make it more stable for supporting buildings. The process may take up to several years before the land is sufficiently stable, particularly if the soil and surrounding landscape contains significant water and/or is heavy textured.

**Putrescible material:** Material subject to putrefaction, which is the decomposition of animal proteins. Essentially refers to wastes containing some fraction of animal protein and can be used in a more general sense to refer to garbage.

**Pyrite:** Pale-bronze or brass-yellow mineral with the formula $FeS_2$; the most widespread and abundant of the sulfide minerals. In ASS, pyrite usually occurs as very small crystals, often within a framboidal or euhedral structure. The large surface area of these small particles makes them highly reactive; much more so than the larger crystals commonly encountered in mining situations.

**Redox potential:** A measure of the availability of free oxygen (oxidising conditions) or the demand for oxygen (generally indicated by the availability of free $H_2S$, reducing conditions) in a particular soil environment at a particular time. This is a complex issue but in general, reducing conditions prevail in the absence of oxygen, the presence of organic matter and/or sulfate reducing bacteria. Oxidising conditions prevail when the material is in direct contact with air, or where significant diffusion of oxygen into soil masses can occur.

**Reduced Inorganic Sulfur:** Inorganic sulfur compounds containing sulfur in a reduced state, that is, sulfur with an oxidation state of less than +6. In ASS materials this includes a wide variety of compounds, such as pyrite, marcasite, greigite, mackinawite, aqueous FeS, $HS^-$ (Sullivan *et al.* 2018a).

**Reducing conditions:** An environment where chemical species can exist at their lowest oxidation state or are being converted to such a state (by gaining electrons). Usually requires at least a local absence of oxygen.

**Retained acidity:** Acidity retained from sparingly soluble and insoluble sulfur compounds (other than sulfides) that slowly produce acid (e.g. jarosite, natrojarosite and schwertmannite). Retained Acidity is estimated using calculations from either the $S_{NAS}$ or $S_{RAS}$ laboratory methods.

**Safety factor:** A factor applied to the calculated liming rate to account for incomplete mixing of neutralising material with soil. A minimum safety factor of 1.5 is applicable to all liming rate calculations in Queensland.

**Schwertmannite:** An iron oxyhydroxy-sulfate mineral with the formula $Fe_8O_8(OH)_6SO_4$ that forms in low-pH, iron-rich waters. Schwertmannite is the major component of iron floc in such waters and may act to keep the pH of ASS-affected surface waters low, complicating their management.

**Scouring:** In geomorphology, the process by which rock or sediment is worn away by water or wind movement. Coastal ASS deposits are commonly scoured out by watercourses as they migrate across the floodplain and may be replaced with other sediments that may or may not develop into ASS as well. In an ASS management context, scouring via water movement is a potential process of concern when carrying out strategic reburial.

**Sediment:** Broken down particles of rock, produced by various weathering processes; a major component of soil.

**Self-neutralising soil:** Acid sulfate soils that contain an abundance of naturally occurring calcium and/or magnesium carbonates with a high surface area, such as crushed shells, skeletons, coral, foraminifera, etc. The carbonates in these soils may be able to partially or completely neutralise the acidity generated from the oxidation of the sulfides within the soil, if their particle size is sufficiently small (<0.5 mm). The ANC of this material needs to be corroborated for use in the Net Acidity equation.

**Sluicing:** The process whereby sulfidic fines are hydraulically separated from sands at the discharge point during a dredging operation. The heavier sands are then commonly used as fill.

**Sodium:** A metallic element (atomic number 11, symbol Na) common to soil; a component of table salt.

**Sodium bicarbonate or sodium hydrogen carbonate:** A compound with the formula $NaHCO_3$, commonly known as baking soda. A mild, highly soluble neutralising agent that may be appropriate for use in areas where the addition of sodium to the soil and water system will not cause environmental impacts (i.e. marine, estuarine or brackish environments).

**Soil horizon:** A soil layer that differs from the layers above and below it in physical, chemical or biological properties such as colour, texture, structure, consistency, pH, etc.

**Soil profile:** A vertical section of a soil from the soil surface through all its horizons down to parent material, other consolidated substrate material or selected depth in unconsolidated material (NCST 2009, p. 147).

**Soil solution:** The water in a soil containing ions dissociated from the surface of soil particles, and other soluble substances (Charman & Murphy 2007).

**Soil structure:** Refers to the distinctness, size and shape of peds. A ped is an individual natural soil aggregate consisting of a number of primary particles. Peds are separated from other peds by surfaces of weakness (NCST 2009, p. 171). PASS is generally unstructured, as it is saturated and little affected by soil-forming processes beyond those which caused a build-up of pyrite. Actual ASS can develop a blocky structure as it loses water and reacts with oxygen.

**Soil texture:** Soil texture is determined by the size distribution of mineral particles smaller than 2 mm. In Australia, this is determined in the field and has only an approximate relationship with particle size distribution (PSD), while other jurisdictions rely only on PSD. Texture can be affected by a range of soil properties, including clay content, clay mineral type(s), presence of silt, organic matter, oxide minerals, calcium and magnesium carbonates, cation composition, and presence of fine, strong structure (NCST 2009, pp. 161–70).

**Solubility:** In chemistry, how easily a substance will dissolve into a homogeneous solution, and how much of a substance can dissolve into a solvent before saturation is reached. Solubility in water is the most common measurement, and the most relevant to ASS management.

**Spatial tracking:** The accurate tracking of large volumes of ASS (e.g. during the neutralisation process) to make sure that initial soil testing results can be correlated with prescribed treatment and any required verification testing. The ASS must be tracked appropriately (e.g. survey with GNSS, RTK, differential GPS, and conventional survey etc.) depending on the level of accuracy needed.

**SPOCAS:** The ‘suspension peroxide oxidation combined acidity and sulfur’ (SPOCAS) method, a peroxide-based method of measuring the acid-generating potential of an acid sulfate soil. The SPOCAS suite is a set of analytical results and derived calculations from the method that allow calculation of Net Acidity. See the *Laboratory Methods Guideline* or AS 4969 for more information.

**Strategic reburial:** The placement of PASS in a void in anoxic, preferably anaerobic conditions where sulfide oxidation and hence acid generation is permanently precluded. The void may be deep e.g. within the base of a lake, canal or artificial wetland; and covered by surface waters. Alternatively the void may be a safe distance beneath the permanent watertable, and hence also below non-ASS.

**Statutory planning instrument:** Any set of planning rules or policies in Queensland declared to have powers under the *Statutory Instruments Act 1992*. Examples include regional plans, state planning policies, and state planning regulatory provisions made under the *Planning Act 2016*.

**Store-release cover:** A method of stockpile capping primarily used in mining contexts. The cover is designed to absorb rain events without allowing transmission of water to the material beneath, thus preventing leachate from being generated within the stockpile. Such designs are heavily dependent on the nature of vegetation planted in the cover material, as the vegetation’s transpirative capacity assists in removing added moisture. Also known as ‘supersponge’ covers.

**Stratigraphy:** In geology and geomorphology, the arrangement of rock and/or soil layers in space, and the study thereof.

**Sulfate:** A compound containing the $–SO_4$ functional group, or the $SO_4^{2-}$ anion itself.

**Sulfide:** A compound containing the –S functional group, or the $S^{2-}$ anion itself. The terms ‘sulfides’ and ‘sulfidic’ are used more generally throughout this guideline to refer to all the inorganic sulfur-containing minerals and precipitates involved in acid sulfate soils chemistry.

**Sulfidic materials:** Soil material that contains detectable inorganic sulfides (≥0.01% sulfidic sulfur) that can exist as horizons or layers at least 30 mm thick or as surface features. Sulfidic materials accommodate: (i) a diverse range of seasonally or permanently waterlogged soil materials, and (ii) materials that are almost entirely formed under anaerobic conditions. Three kinds of sulfidic materials are distinguished, based essentially on the specific nature and amounts of the various oxidisable sulfur minerals present and the neutralising capacity of the material. The three kinds (defined in this glossary) are: (i) hypersulfidic material, (ii) hyposulfidic material, and (iii) monosulfidic material (Isbell & NCST 2021).

**Sulfidisation:** Set of processes by which sulfide minerals (mainly iron sulfides) form and accumulate in anaerobic soil materials (Fanning *et al.* 2017).

**Sulfur:** A non-metallic element (atomic number 16, symbol S), commonly found in volcanic areas and salt deposits.

**Sulfuric materials:** Soil material that has a pH less than 4 (1:1 by weight in water, or in a minimum of water to permit measurement) when measured in dry season conditions as a result of the oxidation of sulfidic materials (defined above). This material has commonly been called actual acid sulfate soil. When low pH is caused by the oxidation of iron sulfides, there will be evidence of:

- mottles and coatings with accumulations of jarosite (hue of 2.5Y or yellower and chroma of about 6 or more) or other iron and aluminium sulfate or hydroxy-sulfate minerals such as natrojarosite, schwertmannite, sideronatrite, tamarugite, etc.
- $S_{CR}$ greater than or equal to 0.01 %S
- soluble sulfate (e.g. $S_{KCl}$ >0.03%)
- underlying sulfidic material (Sullivan *et al*. 2010; Isbell & NCST 2021).

*Note: Jarosite may have chromas of 4 in some situations observed in ASS in dredged materials in Baltimore, Maryland. Chroma of 6 or more has consequentially been removed from the definition of the sulfuric horizon in Soil Taxonomy (Fanning and Witty 1993).*

**Sulfuric acid:** A compound with the formula $H_2SO_4$. A strong mineral acid that is highly soluble in water, it is a principal breakdown product of the oxidation of pyrite.

**Sulfuricisation:** Overall process by which sulfide-bearing soil materials are oxidized (and $Fe^{3+}$ hydrolysed), minerals are weathered by sulfuric acid produced, and new minerals formed from dissolution products (Fanning *et al*. 2017).

**Sump:** A reservoir for the collection of leachate or wastewater, usually located at the lowest point in a process stream.

**Tamarugite:** A sulfate salt with the formula $NaAl(SO_4)_2 \cdot 6H_2O$. Tamarugite is one of many compounds that can be generated during acid sulfate soils oxidation and is also commonly found in acid mine drainage situations.

**Titratable Actual Acidity (TAA):** The acidity measured by titration to pH 6.5 with dilute sodium hydroxide (NaOH) following extraction from the soil with potassium chloride (KCl) solution. In an ASS context, this test is the operational definition of Actual Acidity. See Sullivan *et al*. (2018b), the *Laboratory Methods Guideline* and AS 4969 for more information.

**Toxicity:** The degree to which a substance can damage the health of an organism.

**Treatment pad:** Area where ASS are treated during neutralisation. See Section 7.4.

**Unconfined groundwater dewatering:** Groundwater dewatering without appropriate management strategies to limit drawdown and oxidation of *in situ ASS*—either temporarily or permanently.

**Vacuum settlement:** A modification of or alternative to preloading, intended to speed up the process of preparing saturated land to bear weight without introducing oxygen. Involves installing a network of wick drains in the target soil or sediment before sealing the surface with an impermeable membrane and using a pumping system to hasten the extraction of groundwater. Preload may be placed on top of the membrane to further hasten water removal.

**Verification testing:** Laboratory testing to confirm compliance with performance criteria.

**Void:** A hole or empty space; in strategic reburial, the final location of the soil or sediment which is to be reburied.

**Watertable:** The level at which atmospheric and groundwater pressure are equal, below which soil or sediment is water-saturated. May vary with season, climate, topography, vegetation and soil and rock characteristics.

**Weathering:** The physical and chemical disintegration, alteration, and decomposition of rocks and minerals at or near the Earth's surface by atmospheric and biological agents (Charman & Murphy 2007).

**Wick drain:** Wick drains are essentially artificial drainage paths that can be installed in soft, saturated sediments to enhance dewatering.  They are generally composed of a thin corrugated sheet of plastic surrounded by a thin geotextile sleeve.  They usually measure ~10 cm wide, less than a centimetre thick, and can be many meters long.  Wick drains are installed by specialised equipment in densities and patterns determined by industry knowledge and local sediment characteristics.

**Wombat sanctuaries:**  The short-legged muscular quadruped Australian marsupial commonly known as a wombat will dig extensive burrow systems.  Although not commonly found in ASS, the protection of sanctuaries for wombats is thought to be a suitable mechanism to implement the avoidance principle.

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# Appendix 1: Recommended components of an ASS Investigation Report

Table A1-1 is a checklist for an ASS investigation report. This table has been compiled by Soil Science Australia as part of the *Registered Soil Practitioner – Acid Sulfate Soils* accreditation program for soil professionals (see ASS Tip 6). This checklist should be used as a guide for consultants and assessing authorities when completing/reviewing an ASS investigation.

**Table A1-1: Checklist for an Acid Sulfate Soil Investigation Report**

| Report Section | Information to include |
|---|---|
| Executive summary | • Background<br>• Objectives of the investigation<br>• Scope of work<br>• Summary of analytical results (where applicable)<br>• Summary of conclusions and recommendations |
| Objectives | • Clear statement of the objectives |
| Scope of work | • Clear statement of the scope of work |
| Site identification | • Lot and plan details<br>• Street number, street name and suburb<br>• Common title/name of site (for example Sparkling Waters Residential Estate)<br>• Coordinates of site boundaries (Northings/Eastings—specify datum set)<br>• Local government authority<br>• Locality map<br>• Current site plan showing any existing infrastructure, scale bar, north arrow, local environmentally significant features, 'stages' of development<br>• Surrounding land uses |
| Details of development | • Full description of proposed development<br>• Full description of proposed ground disturbing activities (including soil and water disturbance, anticipated timelines)<br>• The nature of the planned disturbance (e.g. filling, basement, trenching, canal estate)<br>• Provide the following information about all proposed excavation or filling activities that will or may disturb soil or sediment below 5 m AHD:<br>➢ the total volume of soil to be disturbed<br>➢ the volume of each soil disturbance below 5 m AHD<br>➢ the method of disturbance (e.g. dry excavation following groundwater extraction)<br>➢ the maximum time envisaged for disturbance activity (e.g. 2 months)<br>➢ the dimensions (length, width and depth) of each disturbance<br>➢ whether the disturbance(s) may intercept or otherwise disturb the permanent watertable<br>➢ the lowest elevation (in metres AHD) of material to be sourced as fill<br>• Clearly define the location of each disturbance on site maps, plan diagrams and/or colour aerial photographs that are of an appropriate scale for the development<br>Note: Where disturbance dimensions or locations are not finalised, ensure that this is made clear in the ASS investigation report and provide approximate locations and provide conservative volume and dimension figures. Should the nature, location or dimensions of the disturbance change, then the associated ASS Investigation Report may need to be revised. |

| Report Section | Information to include |
|---|---|
| Site history | • Land use—previous, present and proposed, focusing on history of ground disturbance on site or in vicinity of site (for example importation of fill material, mineral sand or peat mining, previous dewatering, drainage or deep excavation)<br>• Local usage of ground/surface waters, and location of groundwater bores |
| Site conditions and surrounding environments | • Locate the site on an existing ASS map (if available), and describe the map name, date, version, scale and mapping units that the development site is on, and mapping units adjacent to the proposed development site. Note if ASS are known to be present on any adjacent properties<br>• Describe the landscape pattern, soils, geology, topography, hydrology and surface elevation of the proposed site. Note if any of the descriptions indicate that ASS may be present<br>• Note if any visual indicators of Actual ASS (AASS) and/or Potential ASS (PASS) (e.g. soil, water, vegetation) are present on the site<br>• Identify the proximity of the areas to be disturbed and/or the site to environmentally sensitive areas. These areas include but are not limited to National Parks, Conservation Parks, Declared Fish Habitat Areas, Marine Parks, Wetlands of State or Regional Significance<br>• Identify any surface water bodies (e.g. channels, drains, ponds, creeks) on site or near to the site<br>• Identify any contaminated sites in the vicinity<br>• Identify onsite and offsite conservation values including flora and fauna that may be affected by changes to soil or water pH, groundwater table levels, or potentially toxic effects of any mobilised metals<br>• Identify the location and use of groundwater bores within a 1 km radius of the site and assess the likely presence of aquifers<br>• Provide photographs of site and surrounds |
| Sampling and analysis plan and sampling methodology | • Provide a brief description of the sampling equipment used to retrieve the samples, methods used to undertake field tests ($pH_F$, $pH_{FOX}$), health and safety measures and protocols to retrieve, transport and store all soil samples<br>• Include an appropriately scaled site plan showing all sample locations and sample identification numbers<br>• Provide the following details regarding the investigation:<br>  ➢ the number of boreholes<br>  ➢ field pH test frequencies<br>  ➢ the number of samples collected at each borehole<br>  ➢ the number of samples submitted for laboratory analysis<br>  ➢ the laboratory methods used for analysis of samples, and<br>• Provide justification if the ASS investigation does not comply with the *National Acid Sulfate Soils guidance: National acid sulfate soils sampling and identification methods manual* in regard to the above |
| Field quality assurance and quality control (QA/QC) | • Decontamination procedures carried out between sampling events<br>• QA/QC sampling (i.e. duplicates)<br>• Description of field tests performed<br>• Chain-of-custody documentation identifying (for each sample), the sampler, nature of the sample, collection date and time, analyses to be performed, sample preservation method, departure time from the site<br>• Field instrument calibrations |
| Laboratory QA/QC | • Provide a copy of signed chain-of-custody forms acknowledging receipt date and time, identity of samples included in shipments, description of condition of samples received (e.g. cold, on ice, frozen) |

| Report Section | Information to include |
|---|---|
| | • Record of holding times and a comparison with methods specification<br>• Description of analytical methods used<br>• Laboratory accreditation for analytical methods used<br>• Sample splitting techniques<br>• Laboratory duplicate results<br>• Extent of uncertainty and limit of detection for each method used |
| Results (Soil) | • Provide borelog or soil profile descriptions for each borehole or investigation pit. Ensure that the following information is presented in a manner that enables cross-referencing or correlation of soil profile descriptions with pH field test results and laboratory analysis results:<br>➢ spatial co-ordinates for each borehole or soil investigation pit using Australian Metric Grid<br>➢ detailed descriptions of soil in accordance with the latest version of the *Australian Soil and Land Survey Field Handbook* (NCST 2009) or *Australian Standard 1726* (*Geotechnical site investigations)* (Standards Australia 2017) (including, but not limited to: field texture, horizon differentiation, depths, colour, mottles, organic matter, moisture content, watertable level and other diagnostic features (for example jarosite, shell))<br>➢ sampling depths (include sample numbers for cross-referencing and duplicate samples)<br>• Photographs of the soil profile, identifying examples of the soil stratum intercepted, including depth of soil shown in the photographs<br>• Summary of all soil results in a table with observations and data, including:<br>➢ summary borehole descriptions<br>➢ results from field soil $pH_F$ and $pH_{FOX}$ tests, highlighting those that are likely to be PASS or AASS<br>➢ tabulated summary of results of laboratory analyses in mol $H^+$/t and/or %S<br>➢ all results exceeding the ASS 'Texture-Based Action Criteria'<br>Note: It is preferred that soil description information, field pH results and laboratory results (or a summary of this information for each sample) are presented side-by-side on the same page.<br>Note: Provide a copy of the raw laboratory data in an appendix to the ASS investigation.<br>• Discussion of the soil $pH_F$ and $pH_{FOX}$ test results<br>• Discussion of the laboratory analyses results for each material type encountered (e.g. fill, alluvium) including identification of trends in the data (vertical or lateral)<br>• Discussion of discrepancies between $pH_F$ and $pH_{FOX}$ tests results and laboratory analyses results<br>• For complex and/or very large or intense disturbances (typically greater than 10 000 $m^3$ or in the extra high treatment category) prepare cross-section/s of ASS occurrence/absence at the site, including soil type and Net Acidity by depth |
| Results (Groundwater and Receiving Water) | • Detailed description of the location, design and construction of onsite groundwater bores including a description of the vertical dimensions of monitoring wells relative to existing surface height in both metres below ground level (m BGL) and metres above AHD (m AHD)<br>• Depth to the groundwater table in both m BGL and m AHD<br>• Permeability of strata on the site<br>• Direction and rate (average linear velocity) of groundwater flow |

| Report Section | Information to include |
|---|---|
|  | • Preferential migratory pathways<br>• Groundwater discharge location/s<br>• If applicable, cone of depression modelling (as per Shand *et al*. 2018)<br>• Groundwater/surface water/receiving water interactions<br>• Groundwater conditions (for example unconfined, confined, ephemeral or perched)<br>• Beneficial use of groundwater in the vicinity such as public drinking water supply and source areas, domestic irrigation, aquatic ecosystems, and the potential impacts on these uses<br>• Site plan showing groundwater quality results<br>• Summary of all water quality results in a table that shows essential details such as sampling locations and depths, assessment criteria, highlights all results exceeding the adopted assessment criteria, baseline water quality data<br>• Discussion of groundwater and receiving water quality results |
| Risk assessment | • Receptor identification<br>• Assessment of receiving environment's sensitivity<br>• Exposure assessment<br>• Discussion of the potential risk of harm to human health and/or the environment associated with disturbance of the site<br>• Discussion of assumptions<br>• Risk management decisions based on outcome of the assessment |
| Conclusion and recommendations | • Brief summary of all findings, including<br>➢ Assumptions used in reaching the conclusions<br>➢ Extent of uncertainties in the results<br>➢ Recommendations for further sampling or assessment (e.g. for groundwater dewatering assessment)<br>➢ Recommendations for the need for an ASS Management Plan |

*Note: while this checklist provides the recommended minimum information to be considered during an ASS investigation, not all items may be applicable at all sites.*

This checklist was compiled based on Dear *et al.* (2014), Queensland Government (2002), Shand *et al.* (2018) and Sullivan *et al.* (2018b).

# Appendix 2: Recommended components of an ASS EM plan

The offsite environmental impacts associated with disturbing ASS can often be mitigated when appropriate environmental management measures are implemented. All earthworks which are performed on-site should ensure that the potential short and long-term environmental impacts of any soil disturbance are mitigated using the most cost-effective and environmentally sustainable management measures. Once disturbance, drainage or excavation of ASS is proposed, the management of the material being disturbed, that remaining *in situ*, and contaminated waters associated with ASS disturbance must be adequately addressed. These issues should be addressed in an environmental management plan (EM plan).

An ASS EM plan is often included as a condition of approval for a development application and helps ensure that commitments given at a project's assessment stage can be identified and implemented during the construction and operation phases. The environmental management strategies to be employed in any ASS EM plan must be consistent with the intent of the nine management principles listed in Section 2 of these guidelines, and in particular the primary objective of avoiding the disturbance of ASS wherever possible.

The ASS EM plan must be completed by a suitably skilled and experienced person in ASS science (see Section 3.2). The following information can be used to assist with the preparation of such a plan and is based on DLGP and DNRM (2002) and Department of Environment (2014).

## Background

An ASS EM plan describes how an ASS management strategy might impact on the environment in which it occurs. It outlines concise commitments from the operator on how the environmental impacts will be avoided, minimised and managed, so they are environmentally acceptable. An EM plan specifies environmental impacts, performance criteria, and mitigation strategies together with relevant monitoring, reporting, auditing and, in the case of unforeseen impacts, appropriate corrective actions.

EM plans for ASS may comprise a standalone document or be part of a larger EM plan for a project. An EM plan is most effective when it is clearly structured and easy to implement on site. It provides the regulatory decisionmaker a framework within which to confirm compliance with policies and conditions and is often used by project management staff.

An EM plan may require periodic review and refinement as management practices evolve, or as the success or failure of management methods become apparent well before a project is complete. This is especially true when trialling new management and mitigation technologies—a certain amount of learning on the job is sometimes inevitable, and unexpected issues should be documented and evaluated for future benefit. It is recommended that strategies be built in to detect and act upon breaches of performance criteria and contingency plans included in case things go wrong. EM plans should be auditable and contain clear reporting arrangements. They should identify any issues where there is a lack of relevant information or a significant amount of uncertainty. Any change or amendment of an EM plan for ASS should be carried out in consultation with the assessment manager.

It is important that the plan is concise and written in a manner that is understood by all relevant operators/contractors. Conceptual landscape diagrams and CSMs can also be used to explain and to derive management measures that are to be used on site (see Figure 1 and Appendix A6-1, A6-2 and Northern Territory EPA for examples). All operators/contractors must be able to understand what is required of them, be easily identified, and must take full responsibility for the content and commitments contained in the EM plan. It should not be a document that is written to achieve a development approval only, and then sit on a shelf and not get implemented. The EM plan for ASS needs to interface with other environmental management plans, construction management plans, sediment and erosion control plans etc.  Training of personnel is also important.

Regulatory decision makers have the option of requiring (or commissioning their own) independent third-party review (see ASS Tip 7), prior to any final approvals, during the on-site management phase, or at the completion of the project, or as a component of the closure reporting.

Finally, an EM plan requires a system ensuring appropriate version control so that all changes to the document over time are appropriately recorded, including the details of any timing, persons responsible and reasons for the changes.

## Specifics for ASS

Any EM plan for ASS needs to be specific enough to address the management issues and accommodate the features of each development site.  An EM plan for ASS is implemented prior to soil drainage or disturbance and includes the following:

- A spatial representation of the distribution of ASS on site, maps, cross-sections and 3D representations and a CSM (showing various ASS layers with corresponding soil analysis indicated may be useful), especially with planned disturbances superimposed.  The maps should identify separate areas of both AASS and PASS according to the upper depth of occurrence e.g. 0-0.5 m, 0.5-1 m, 1-1.5 m etc.  *It is assumed knowledge of the baseline ASS, surface water and groundwater conditions on site will have informed the project design process.*
- Discussion of the nature of the planned disturbance (e.g. lake, basement excavation, infrastructure trench) to provide context for the plan, volumes to be disturbed (including soils and groundwater), and the treatment category (see Section 3.4).
- Details of potential onsite and offsite impacts of the disturbance of the soil and/or the groundwater levels, and strategies to prevent the oxidation of iron sulfides consistent with these guidelines (e.g. avoiding the disturbance of ASS by redesigning the layout of the excavations).
- A discussion of any higher risk management strategies proposed on site, and measures to reduce the risks to acceptable levels.
- Proposed management strategies and measures to mitigate any risks associated with the disturbance:
  - if neutralisation is proposed, the EM plan will account for issues such as neutralising application rates, treatment pad design and location, the use of guard layers etc as per Section 7
  - if hydraulic separation is proposed, the EM plan will account for issues such as reducing oxygen exposure of the fines, guard layers, and management of the process waters and sulfidic fines as per Section 8
  - if strategic reburial is proposed, the EM plan will account for risks such as ensuring long-term reducing conditions for the buried material as per Section 9
  - If any short-term groundwater dewatering or drainage is proposed, the EM plan will account for risks and include measures to mitigate impacts; and details of long-term contingency planning and monitoring as per Shand *et al.* (2018)
- Details of any ASS to be removed offsite, including the location of any licenced offsite treatment facilities, liming rates, monitoring and verification that occurs offsite, and the agencies responsible for the management.  Landfill sites must be licensed to accept ASS materials.

- All commitments in the EM plan must be specific and auditable with measurable outcomes and clear timeframes. Performance criteria (as outlined in these guidelines) to be used to assess the effectiveness of the ASS management and monitoring measures.
- Where groundwater disturbance is not avoidable, the results of the groundwater investigation and cone of depression modelling are used to formulate management strategies for watertable management, including measures to contain the size of dewatered areas and measures to minimise the duration of dewatering. For example, basements below the watertable need to be engineered to be fully tanked to ensure there is limited groundwater ingress (that may lead to lowering of the watertable) during all phases of the development. Treatment strategies should be developed and detailed for all drained areas.
- Monitoring schedules for soil, including any field $pH_F$, $pH_{FOX}$ and laboratory procedures.
- Location (including manual, automated, and laboratory procedures) methodology, frequency and duration of surface water and groundwater monitoring for key parameters such as pH, electrical conductivity, dissolved oxygen, chloride, sulfate, total iron, dissolved iron, aluminium, bicarbonate, and calcium need to be specified, including appropriate trigger values or conditions under which corrective actions are required to be undertaken. Monitoring biological indicators may be required in some cases.
- Details of verification testing (see Section 7.2) including sampling rates and performance criteria that are required to establish:
  - whether sufficient neutralising material has been added to the batch of soil on the treatment pad and whether it has been sufficiently mixed (for neutralised soils)
  - whether sluiced/washed soil has been effectively separated (for hydraulic separation)
  - whether ASS will be maintained in a permanent state of reduction (for strategic reburial)
- Details of the handling and storage of neutralising agents.
- Containment and treatment strategies (including bunding, diversion drains, lime dosing, use of silt curtains etc) to ensure that contaminated stormwater, acid and leachate associated with the oxidation of ASS is prevented from entering the receiving environment.
- Description of contingency procedures to be implemented on and off the site if the management procedures prove to be unsuccessful, acid is generated, leachate problems occur, and/or if performance criteria are breached, including designated personnel responsible for the contingency plans. Consideration should be given to the financial impost of contingency procedures at the time of the risk assessment and decision making. It is recommended contingency plans identify whether problems are related to ineffective operation of the EM plan and/or ineffective management strategies.
- An independent third-party review/auditing and reporting system to demonstrate compliance and non-compliance reporting with the performance criteria. It is recommended monitoring results are retained for auditing purposes.
- Closure reporting (see Section 12).

If environmental harm has occurred, then the Department of Environment, Science and Innovation will need to be informed and will provide further guidance or action.

Table A2-1 is a checklist for an ASS EM plan. This table has been compiled by Soil Science Australia as part of the Registered Soil Practitioner – ASS accreditation program for soil professionals (see ASS Tip 6). This checklist should be used as a guide for consultants and assessing authorities when compiling/reviewing an ASS EM plan.

**Table A2-1: Checklist for an Acid Sulfate Soil Management Plan**

| Report Section | Information to Include |
|---|---|
| Executive summary | • Background<br>• Objectives of the Acid Sulfate Soil Management Plan (ASS EM plan)<br>• Scope of work<br>• Summary of ASS investigations<br>• Summary of ASS EM plan |
| Scope of work | • Clear statement of the scope of work |
| Objectives | • Clear statement of the objectives |
| Details of development | • Include information from ASS Investigation Report, however include more specific details around bulk excavation volumes |
| Management strategies | • Discussion of management options and how risk will be reduced<br>• Rationale for the selection of recommended management strategy/ies |
| Environmental management | • Details of responsibilities of site personnel (names of responsible positions or persons) |
| Performance criteria | • Provide performance criteria for soils, surface water, receiving water and groundwater to enable the assessment of the effectiveness of the ASS management measures<br>• Baseline water quality results are to be used in determining appropriate water quality performance criteria |
| Implementation of management strategies | • For each type of disturbance as identified in the ASS Investigation Report, detail prevention, minimisation and mitigation strategies (including design details) for controlling environmental impacts to soil and water:<br>➢ if neutralisation is proposed, include soil and water treatment application rates (in text and on a site plan), treatment pad design and location, application rates and location of guard layers, details of storage and handling of neutralisation agent, soil treatment verification program and health and safety requirements for the neutralising agent<br>➢ if hydraulic separation is proposed, include measures to reduce oxygen exposure of the fines, details on guard layers, and management of the process waters and sulfidic fines<br>➢ if strategic reburial is proposed, include measures to ensure long-term reducing conditions for the buried material<br>➢ if filling is proposed, include measures to manage groundwater impacts, including design of lime slot trenches and details of guard layers<br>➢ if any short-term groundwater dewatering or drainage is proposed, measures to mitigate impacts; and details of long-term contingency planning and monitoring<br>• Also provide the following details:<br>➢ staging of earthworks program and ASS disturbance<br>➢ decommissioning of soil and/or water treatment areas<br>➢ identification of regulatory compliance requirements such as licences and approvals (local and state level)<br>➢ containment strategies (including bunding, diversion drains, lime dosing, use of silt curtains etc) to ensure that contaminated stormwater, acid and leachate associated with the oxidation of ASS is prevented from entering the receiving environment<br>• For any soil that is to be removed offsite, describe the volume of soil to be removed, protocols that will apply for its selection and transport, the |

| Report Section | Information to Include |
|---|---|
| | location to which it will be removed (including the location of any licenced offsite treatment facilities), proposed management measures that will be utilised offsite (e.g. liming rates, monitoring and verification that occurs offsite), and the agencies responsible for managing the ASS after it is moved offsite |
| Monitoring | • Provide details of the proposed monitoring of the effectiveness of management measures against the agreed performance criteria<br>• Provide the location, methodology, frequency and duration of surface water and groundwater monitoring and the field parameters and/or analytes that are required to be monitored<br>• Provide details on water sample handling and storage<br>• Provide monitoring schedule for inspecting remedial measures e.g. guard layers and check dams<br>• Provide monitoring schedules for soil, including any field $pH_F$, $pH_{FOX}$ and laboratory procedures |
| Reporting / Auditing | • Provide details on reporting and auditing requirements to demonstrate compliance with the specifications of the ASS EM plan<br>• Provide details/results of independent third-party review<br>• Provide closure reporting details |
| Contingency actions | • Provide description of contingency actions to be implemented on and off the site if the management procedures prove to be unsuccessful, acid is generated, leachate problems occur, and/or if performance criteria are breached, including designated personnel responsible for the contingency plans. It is recommended contingency plans identify whether problems are related to ineffective operation of the ASS EM plan and/or ineffective management strategies. |

*Note: while this checklist provides the recommended minimum information to be included in an ASS Management Plan, not all items may be applicable at all sites.*

This checklist was compiled based on Dear *et al.* (2014), DER (2015) and Queensland Government (2002).

# Appendix 3: Water quality parameters for monitoring groundwater

The following tables have been modified from the *Guidance for the dewatering of ASS in shallow groundwater environments* (Shand *et al.* 2018). For further information about groundwater monitoring, refer to Shand *et al.* 2018.

**Table A3-1: Suggested pumped groundwater parameters for baseline characterisation and monitoring during dewatering of ASS**

| Suite | Key determinands | Comments |
|---|---|---|
| Physical parameters | Water level, discharge rate | Monitored daily or continuously in highly sensitive sites. Discharge rate if removing water by pumping to quantify how much water is removed |
| Field parameters | pH, EC, Eh, alkalinity/acidity, temperature, dissolved oxygen, smell of noxious gases | Monitored daily during discharge, reducing over time. Care should be taken in enclosed spaces where gases may accumulate |
| Major and minor elements | Na, K, Ca, Mg, $HCO_3$, Cl, $SO_4$, alkalinity, ionic balance, pH, TDS, EC, $NO_3$, $NH_4$, SRP, total P | Monitored monthly initially to characterise groundwater facies (types), and if field parameters indicate a risk, for example decreasing pH |
| Metal and metalloids | Al, Cd, Co, Cr, Cu, Mn, Ni, U, Zn, total (unfiltered) Al, Fe (total and dissolved), ferric iron, Mn | Monitored monthly initially and if field parameters indicate a risk, for example decreasing pH. Some, for example U may be mobile at high pH. Note that soluble metals and pH are needed to calculate acidity (see Shand *et al.* 2018) |
| Metal and metalloids | Pb, As, Se, Sb | Often mobile at low and high pH, the latter due to the formation of oxyanions; these may also be mobilised as pH increases if sorbed to/ incorporated in iron minerals |
| Soil materials | Net Acidity, peroxide pH | This may be useful if acidic conditions are formed to assess the loss and continued existing hazard in the area of dewatering, which may improve the conceptual model and understanding of the site. May or may not be necessary depending on degree of risk |
| Soil materials | Visual observations | The formation of easily identifiable minerals such as straw-yellow jarosite occurs at an advanced stage of acidification. Once formed, these sparingly soluble minerals are difficult to remove and may prolong remediation efforts |

**Table A3-2: Management levels suggested for different duration and extent of drawdown**

| Management level | Scope of works or scale of impact |
|---|---|
| 1 | Dewatering confined to <50 m radius cone of depression and/or duration of dewatering less than 7 days |
| 2 | Dewatering duration >7 days with a radial extent of the cone of groundwater depression >50 m |
| 3 | Regional scale dewatering where multi-stakeholders are involved and/or external processes are responsible. Responsibility typically comes under the auspices of state and territory jurisdictions, but may require multilateral or multi-jurisdictional agreement |

The management levels required for dewatering levels 1, 2 and 3 are contained within Appendix G of Shand *et al.* 2018.

*Note: The extent of drawdown at any site largely depends on soil type and permeability. Not all aquifers are confined so the radius may easily extend beyond 50 m even during short duration dewatering. It is important to define rebound criteria as part of demonstrating the impacts are not permanent. For instance, 'after cessation of pumping, groundwater recovery is expected to return to within 10% of pre-pumping levels after 24 hours and 5% within 48 hours, and the ASS sediment within the dewatered zone remains within its field capacity'.*

**Table A3-3: Aspects of monitoring that should be covered in any monitoring program**

| | Monitoring component |
|---|---|
| 1 | Baseline groundwater data to be collected prior to commencement of any dewatering activity, or any activity which may impact the baseline. More than one monitoring event should be completed to ensure that the data are representative and to cover the range of seasonal variations |
| 2 | Watertable monitoring – ensure that watertable decline is minimal away from the cone of depression |
| 3 | Water level, pH, EC, acidity/alkalinity monitored at short intervals (to be agreed with relevant local authority) and continued, at longer intervals, until groundwater rebound is complete and water quality not impacted—the latter will typically be for a period of at least six months |
| 4 | Samples to be collected at agreed intervals during the dewatering operation |
| 5 | Analysis to include relevant parameters (see Shand *et al.* 2018) |
| 6 | Water quality and other measurements to be assessed for trends during and after operation for duration of monitoring |
| 7 | All results to be collated and reported within an initial closure report at the end of any works period |
| 8 | Results from the post works period to be collated and reported within a post-works monitoring closure report along with a discussion of any environmental impacts observed (potential requirements for continued monitoring and/or remediation may be required by responsible authority) |

**Table A3-4: Strategy for developing a contingency plan for groundwater contamination**

| **Exceedance detected** |
|---|
| Inform relevant authority |
| Carry out additional testing to confirm |
| **If they still exceed trigger values** |
| Install additional piezometers to assess the extent and severity of contamination |
| Undertake additional studies to determine the fate and transport of contaminants in groundwater |
| **Remediation measures considered** |
| Groundwater recharge barriers to divert flow |
| Permeable reactive barriers |
| Monitored natural attenuation |

**Table A3-5: Key actions for monitoring potentially impacted water bodies caused by dewatering**

| **Key actions** |
|---|
| Monitor pH, EC, DO, acidity/alkalinity every second day during dewatering |
| Laboratory data to be collected at a longer timescale, for example 2 weeks |
| Laboratory analytical suite as in Table A3-1 |
| Measurement of water levels to ensure that levels are not reduced as a result of groundwater dewatering |
| Measurement and monitoring of groundwater levels adjacent to the water body |
| Dewatering to cease upon any deterioration in water quality or significant decrease in groundwater water levels adjacent to the water body related to dewatering |
| Results of water quality and water level monitoring program for the surface water body must be reported within an Initial Closure Report for the project along with a discussion of any environmental impacts observed |
| Laboratory water quality data to be collected from the surface water body at intervals for a period of 6 to 12 months (depending upon the magnitude of the dewatering operation) following completion of the dewatering operation |
| Remedial actions to be undertaken to restore the water quality of the surface water body if needed |

Source: Modified from DER (2015a).

# Appendix 4: Management of surface and drainage waters

This information has been adapted from *State Planning Policy 2/02 Guideline: Planning and Managing Development Involving Acid Sulfate Soils* (DLGP and DNRM 2002) and the *Treatment and Management of Soils and Water in Acid Sulfate Soil Landscapes* (DER 2015). For specific information on techniques, methods and standards for sample collection, handling, quality assurance and control, custodianship and data management, refer to the *Monitoring and Sampling Manual, Environmental Protection (Water) Policy 2009* (DES 2018).

## A4-1 Introduction

It is recommended that surface and groundwater flows (including flows to any water storages) coming from disturbed ASS are treated and managed to prevent the leaching of acid and metal contaminants into the environment. The preferred management approach is to prevent the generation of acid leachate during disturbance. This is particularly important for groundwaters, as *in situ* neutralisation of groundwater is difficult (refer to Shand *et al.* 2018).

While the treatment of relatively small quantities of water may be quite straightforward, experience has shown that qualified professional assistance is required as water treatment chemistry can be complex. Note that the requirements for monitoring and treatment of surface and drainage waters increase with higher levels of treatment (see Section 3). In cases where excessive iron, aluminium and other salts are present, particularly in large volumes, or acidophilic ecosystems are close by, sophisticated treatments may be required.

## A4-2 Monitoring

Monitoring is an important component of water management planning. Monitoring may be necessary to audit compliance with environmental requirements, to assess whether management is functioning properly, and because of the risk and likely consequences of management failure. Issues that need to be addressed in establishing monitoring programs include:

- Determining appropriate monitoring locations to provide operational data for management of discharges and impact assessment of receiving waters. Monitoring of intake waters may also be appropriate to assist in management decisions in some cases.
- Deciding which indicators to monitor, and what the results will mean to operators on the site. For example, operational monitoring of on-site collection ponds may be necessary to manage on site risk. Operational objectives may trigger management actions to ensure risk is minimised and objectives are met. Monitoring of discharge to audit compliance limits might be considered higher level monitoring due to the consequences of non-compliance. Management plans should be clear about how and when results will be interpreted and what actions these results will trigger to ensure the protection of environmental values.
- Determining the frequency of monitoring that is necessary to minimise risk, prevent environmental harm, provide effective on-site management, for auditing purposes, demonstrate compliance with objectives or release limits, and demonstrate the level of impact on the receiving environment.
- The variability of wastewater released from the activity. For example process related variations or climate related variations.

## A4-3 Water quality parameters

Under the *Environmental Protection (Water and Wetland Biodiversity) Policy* 2019, Environmental Values (EVs) and Water Quality Objective (WQOs) have been formulated for many major Queensland Catchments. EVs define the uses of the water by aquatic ecosystems and for human uses and WQOs define objectives for the physical, chemical and biological characteristics of the water, including pH, Dissolved Oxygen (DO), Electrical Conductivity (EC), and some metals.  As EVs and WQOs are established for Queensland waters in accordance with the *EPP Water and Wetland Biodiversity*, they are included in Schedule 1 after approval.  For waters not included in Schedule 1, the EVs and WQOs are respectively determined in accordance with section 6 and section 11 of the *EPP Water and Wetland Biodiversity*.  The *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* (ANZG 2018) includes a management framework that has been adopted in the *EPP Water and Wetland Biodiversity.*  For further information, see *Environmental Protection (Water and Wetland Biodiversity) Policy 2019*.

Key parameters for monitoring the quality of water affected by ASS include: pH, EC, DO, Aluminium (Al), and Total and Dissolved Iron (Fe).  Additional parameters that are recommended for groundwater monitoring are included in Table A3-1 of Appendix 3.  See DES (2018) for more information.

## A4-4 Monitoring versus treatment

The monitoring parameters discussed above are necessary for determining whether waters are affected by ASS disturbance, and necessary for determining whether water is suitable for release.  However, they aren’t very useful when calculating application rates for water treatment.  It is recommended that treatment application rates be calculated based on laboratory determinations of total acidity and/or alkalinity.  Automated titration procedures are available for this purpose.

## A4-5 Neutralising acid leachate and drainage water

There are a range of neutralisation products available that can be used to treat acidic waters with the more soluble neutralising agents usually being more effective.  The optimum water pH level is usually 6.5–8.5.  Extra precautionary measures may be required when acidophilic ecosystems are in proximity to a proposed development that will involve disturbance of ASS.

The application rate of these products should be carefully calculated to avoid the possibility of ‘overshooting’ optimal pH.  Overdosing natural waterways results in alkaline conditions and can impose environmental risks similar to acid conditions, with the potential to damage estuarine ecosystems.  Overshooting can occur quite easily if strongly alkaline neutralising agents such as hydrated lime $Ca(OH)_2$ (pH 12) and quick lime CaO are used.  Strict protocols are established for their safe use, storage, handling, monitoring and to manage their effects on the receiving environment.  Sodium bicarbonate $NaHCO_3$ is quick to act and not subject to pH overshoot.

It is recommended that pH monitoring be carried out regularly during neutralisation procedures and for a suitable period after treatment to verify the appropriate pH has been achieved and maintained.  It should be noted that when neutralising acid water, no safety factor is used.  The monitoring of pH should be carried out regularly (preferably automated) during neutralisation procedures.

Agricultural lime, $CaCO_3$ is the most used neutralising agent for ASS.  It equilibrates around a pH of 8.2 and is not generally harmful to plants, stock or humans and most aquatic ecology species (except for acidophilic ecosystems).  The main shortcoming associated with the use of agricultural lime is its insolubility in water (though it is more soluble in strongly acidic water).  As a result, trying to raise the pH of water with agricultural lime can be slow and result in wastage of lime.

*Note: Where freshwater ecosystems are acidic because of naturally occurring organic acids and are in vicinity of any ASS disturbance, additional management considerations and water quality objectives will be required to ensure the protection of these ecosystems.  This will be required to prevent any increases in the concentrations and/or toxicities of dissolved metals that may impact on the complex habitat requirements of these species.  Avoiding the disturbance of ASS that may impact these acidophilic ecosystems is always the most preferred management strategy, and expert advice should be sought.*

## A4-6 Calculating application rates

It is recommended that application rates for water treatment be calculated by suitably skilled personnel and based on laboratory determination of total acidity/total alkalinity. Knowledge of the solubility and purity of the neutralising agent to be applied is also a key factor in determining application rates.

In an emergency, an estimate of the moles of alkalinity required can be calculated from the difference between the current pH and target pH of a water body. The result can be converted into a mass of treatment chemical using simple stoichiometry. However, it should be noted that this will not account for acidity from non-$H^+$ sources (e.g. $Fe^{2+}$, $Al^{3+}$), nor will it make allowances for the solubility or purity of the available neutralising agent. As a result, this simple calculation method will almost always be an underestimate. As ASS drainage normally contains many acidic ions other than $H^+$ (e.g. Fe, Al), samples should always be taken for laboratory analysis of titratable acidity to determine lime requirements more accurately.

**Table A4-1: Quantity of pure neutralising agent required to raise from existing pH to pH 7 for 1 megalitre of low salinity acid water**

| Current Water pH | $[H^+]$ (mol/L) | $H^+$ in 1 Megalitre (mol) | Aglime to neutralise 1 Megalitre (kg pure $CaCO_3$) | Hydrated lime to neutralise 1 Megalitre (kg pure $Ca(OH)_2$) | Sodium bicarbonate to neutralise 1 Megalitre (kg pure $NaHCO_3$) |
|---|---|---|---|---|---|
| 0.5 | 0.316 | 316 228 | 15 824 | 11 716 | 26 563 |
| 1.0 | 0.1 | 100 000 | 5004 | 3705 | 8390 |
| 1.5 | 0.032 | 32 000 | 1600 | 1185 | 2686 |
| 2.0 | 0.01 | 10 000 | 500 | 370 | 839 |
| 2.5 | 0.0032 | 3200 | 160 | 118 | 269 |
| 3.0 | 0.001 | 1000 | 50 | 37 | 84 |
| 3.5 | 0.00032 | 320 | 16 | 12 | 27 |
| 4.0 | 0.0001 | 100 | 5 | 4 | 8.4 |
| 4.5 | 0.000032 | 32 | 1.6 | 1.18 | 2.69 |
| 5.0 | 0.00001 | 10 | 0.5 | 0.37 | 0.84 |
| 5.5 | 0.0000032 | 3.2 | 0.16 | 0.12 | 0.27 |
| 6.0 | 0.000001 | 1 | 0.05 | 0.037 | 0.08 |
| 6.5 | 0.00000032 | 0.32 | 0.016 | 0.012 | 0.027 |

***Notes on Table A4-1:***

- *1 $m^3$ = 1000 litre = 1 kilolitre = 0.001 Megalitre*
- *Correlations between current water pH and [H+] (mol/L) do not account for titratable acidity. The titratable acidity component should be included in any calculations of neutralising agent requirements.*
- *Agricultural lime has a very low solubility and may take considerable time to react even partially. While aglime has a theoretical neutralising value of 2 mol of acidity ($H^+$), this tends to be only fully available when there is excess acid. This, together with it's very low solubility, means that much more aglime beyond the theoretical calculation will generally be required.*
- *Hydrated lime is more soluble than aglime and hence more suited to water treatment. However, as $Ca(OH)_2$ has a high water pH, incremental addition and thorough mixing is needed to prevent overshooting the desired pH. The water pH should be checked regularly after thorough mixing and allowing sufficient time for equilibration before further addition of neutralising product.*
- *Weights of material given in the table above are based on theoretical pure material and hence use of such amounts of commercial product will generally result in under treatment.*
- *To more accurately calculate the amount of commercial product required, the weight of neutralising agent from the table should be multiplied by a purity factor (100/ Neutralising Value for aglime) or (148/ Neutralising Value for hydrated lime).*

- *If neutralising substantial quantities of ASS leachate, full laboratory analysis of the water will be necessary to adequately estimate the amount of neutralising material required.*
- *Neutralising agents such as hydrated lime $Ca(OH)_2$, quick lime CaO, and magnesium oxide MgO neutralise 2 mol of acidity ($H^+$), while sodium bicarbonate $NaHCO_3$ and sodium hydroxide NaOH neutralise only 1 mol of acidity.*

Issues to consider include:

- the quality and purity of the neutralising agent being used
- the effectiveness of the application technique (e.g. mixing, surface spraying, distribution)
- the particle size of the neutralising agent and any iron and aluminium coatings that develop
- the existence of additional sources of acid leaching into the water body further acidifying the water; and
- the neutralising agent has become lumpy and sinks to the bottom of the water body, rendering it ineffective.

Neutralisation may be faster if higher rates are used, but this is not recommended as it is expensive, wasteful and may result in overdosing. However, this is less of a concern with aglime.

To increase the efficiency, the neutralising agent should be mixed into a slurry before adding. A slurry can be prepared in a concrete truck, cement mixer or large vat with an agitator. Methods of application of the slurry include:

- spraying the slurry over the water with a dispersion pump
- pumping the slurry into the water body with air sparging (compressed air delivered through pipes) to improve mixing once added to water
- pouring the slurry out behind a small motorboat and letting the motor mix it in
- incorporating the slurry into the dredge line (when pumping dredge material)
- using mobile water treatment equipment such as the ‘Neutra-mill’, ‘Aqua Fix’ or calibrated reagent application blender to dispense neutralising agents to large water bodies, or
- containerised purpose built, water treatment plants etc.

When the pH of ASS leachate has been below 4.5, it usually contains soluble iron and aluminium salts. When the pH is raised above 4.5, the iron precipitates as a red-brown stain/scum/solid which can coat plants, monitoring equipment, the base or walls of dams, drains, pipes, piezometers and creeks. In addition, the soluble aluminium is a good flocculent and may cause other minerals to precipitate or for suspended clay particles to flocculate. Where the water contains considerable soluble iron, large quantities of acid can be generated as the pH is raised and iron hydroxides are precipitated. It is important to let any sludge settle before using treated water (otherwise it will block pipes and pumps) or before discharging treated water (to avoid adverse aesthetic and ecological effects). Chemicals can be used to reduce the settlement time if it does not settle quickly enough for the staging of the works, however care should be taken in choosing flocculating agents as these can also alter pH or cause other management problems.

The large-scale dosing of waters to alter their chemical characteristics is a specialised and highly technical task that requires considerable expertise and experience. It is recommended that professional guidance be obtained in these situations.

The water quality should be monitored in accordance with Appendix 3. Automatic monitoring is strongly recommended and considered best practice.

# Appendix 5: Limnological assessments

Limnology is the study of lakes, and by extension, constructed water bodies with limited inflows or outflows, but the focus here is on physical aspects of water movement in lakes and water bodies (physical limnology). Limnological investigations can help decide whether anaerobic or near-anoxic conditions can be maintained at the depth to which PASS are to be reburied. Similar principles are applied to assessing risks from proposed reburial of PASS under flowing waters. Limnology has been applied as part of environmental management strategies in lakes around the world. It has been used to manage burial of pyritic fines from mining and minimise interactions between anoxic bottom waters and oxygenated upper waters in many dams (Catalan *et al*. 2000; Atkins *et al*. 1997; Li *et al*. 1997).

## A5-1 Oxygen transport and sulfide oxidation rates

A risk assessment may need to be conducted before strategic reburial of sulfidic materials in a large water body. It will need to assess the risk of acid generation in the long-term, under both ‘steady-state’ or normal conditions, and also under ‘extreme’ or infrequent weather conditions (such as flooding and cyclonic winds). The factors that need to be considered should include the depth of water cover, sulfide concentration, texture and dispersive nature of the materials proposed for reinterment, and the degree to which the materials may interact with the overlying (oxygenated) water, as a result of all potential processes. As risk of oxidation increases, it may be necessary to undertake a limnological study to quantify the various oxygen transport processes.

*Note: The re-suspension of sediments is a very real risk in some instances, but is not a universal risk with all uses of strategic reburial.*

**Case Study A5-1: Limnological modelling**

A risk assessment of sulfidic fines previously reburied in a canal showed that fines in the uppermost layer of the interred material (at the base of the water column), contained %S in the range 1 to 1.5%.

The average surface area of these sulfides was calculated, enabling geochemical and limnological modelling to quantify the likely acid generation rates for various wind-driven mixing scenarios. The study showed that there was some risk of acidification of the water body from protracted 1-in-40-year wind events that would cause re-suspension and oxidation of the bottom fines.

The risk assessment also found extra risks associated with the further placement of sulfidic fines with higher sulfide concentrations in this location.

Dosing these fines with fine aglime was selected to mitigate these risks.

The fine aglime grain size range selected was too small to sink through the fines, and hence stayed with the surface sulfide grains, acting to neutralise any *in situ* acidity that may develop in future events.

The risk assessment may also include the prediction of likely chemical reaction rates in the case of episodic or event-driven oxygenation of sulfidic materials. This must allow for competing oxygen demand from intrinsic organic matter and must account for the neutralising capacity of natural carbonate minerals or shell fragments, if present. The need for, and scope of, the risk assessment (and any limnological study) should be discussed with regulatory authorities.

Reburial voids at the base of water bodies need to be deep enough to both accommodate the reburied material and ensure that there is insignificant dissolved oxygen transport through the water to the PASS.  Many lakes have low levels of dissolved oxygen at depth.  Wind and wave action and seasonal turnover may increase the dissolved oxygen content at depth.

*Note: Care must be exercised in applying the results of papers written about mining situations to situations involving coastal ASS dredge or hydrocyclone fines, as there may be major differences in milled ‘mineral’ pyrite versus ASS pyrite grain size, reaction rates and effective grain density.*

The risks increase when the oxygen transport mechanism is not limited to diffusion (e.g. where dissolved oxygen levels in water become high enough to cause significant oxidation of the submerged sulfidic sediments).  The risks are a function of several variables.  For example, if the sulfidic fines are buried under shallow water in a large freshwater lake, with a long fetch in a high wind area and where there is a lot of boat traffic, the lake waters will experience considerable wave action and have a high probability of mixing, causing resuspension, oxygenation and finally acidification of the overlying water.  The applicant should expect to provide an appropriately detailed limnological investigation when reburial of sulfidic fines is proposed.

### A5-1.1 Water column depth

The water column above the PASS must be deep enough to minimise oxidation.  Based on modelling of some sites in South East Queensland, the depth of a water column over sulfidic fines needs to be at least four metres, but this may vary in some circumstances.  Greater depths may be needed in North Queensland, due to the prevalence of cyclonic winds and other extreme weather.  In general, the deeper the water above the PASS is, the lower the risk of oxygenation.  In shallow waters, there is a greater risk of bottom shear and sediment resuspension resulting from surface wave action.

Stratification is a process by which water in a confined space may separate into layers, distinguished by temperature, biological activity and water chemistry.  The process can lead to stable or non-mixing bottom layers where oxygen transport is considerably reduced or even halted if the bottom layer is totally anoxic.  However, stratification of the water body may be stable only during part of the year as it may break down because of seasonal changes in temperature through the water column or high sustained winds.  The breakdown of water stratification may restart oxygen transport to sulfidic bottom fines resulting in acid production, and this is especially relevant if monosulfides have been formed under anaerobic conditions.  So, different types of stratification and destratification over normal variations and extremes in annual climatic conditions should be considered when assessing the risk of the proposal.

### A5-1.2 Mixing in the water body

Reinterred PASS may be at risk of exposure to oxidising conditions from thermally driven seasonal and diurnal water mixing.  This is an efficient oxygen transport mechanism, but the velocities involved will generally not resuspend reinterred material.  A higher risk may result from wind-driven mixing because of the potential for resuspension of reinterred material.  This process depends primarily upon wind velocity and duration, and is further affected by the water body shape, orientation, depth, surface elevation and other site-specific geographic and constructed features.

If significant quantities of fines are to be reinterred under water, calculations or modelling may be necessary to predict the likely mixing of waters (and hence oxygen transport), potential resuspension of sulfidic fines, and likely overall sulfide oxidation rates.

### A5-1.4 Maintenance dredging

Over time, silt may build up on the bottoms or beds of lakes or canals and may need removal for navigation or other purposes.  Maintenance dredging or similar operations may disturb interred PASS.  This is particularly important if monosulfides (which oxidise readily once exposed to oxygen) have formed in the interred material.

Compliance with strict management requirements during such dredging or silt removal operations are essential to ensure that any PASS perpetually remain under anoxic conditions. The PASS must not be exposed to oxygenated waters or be placed in an aerobic environment, for example, on a beach on the side of the canal.

Water bodies that will need regular maintenance dredging or silt removal are unsuitable reinterment locations unless the PASS can be maintained under anoxic conditions at all times.

**ASS Tip 35: Maintenance dredging equipment**

A suction dredge using precise depth control is preferred for maintenance dredging as it is less likely to stir up reinterred PASS. A cutter suction dredge is more likely to penetrate and stir any buried material. If PASS is disturbed, it should be managed as per Sections 7, 8 and/or 9.

**Case Study A5-2: Hydrosluiced fines and destratification devices**

A deep lake in South East Queensland was considered unsuitable to use for reinterment of sulfidic fines, as it could not support a capping layer. During lake ‘operation’, destratification (mixing) devices were needed to prevent thermal stratification (to address other water quality concerns). There was concern that the mixing devices would resuspend fines and oxygenate them at the base of the water column.

Some PASS clays were found to be suitable for reinterment in the lake because they had the geotechnical stability to support a capping layer to protect them from oxidising conditions that might develop. As a result, most soils on the site were treated by neutralising techniques (rather than hydraulic separation) and only PASS clays were strategically reburied.

*Note: This site was previously an extractive industry site, and it was likely that sulfidic fines were buried at the site from earlier operations. This complicated the management requirements for the site.*

### A5-1.5 Scouring and resuspension

The risk of scouring and resuspension of PASS on the floor of a water body is increased by stormwater inflows, tidal flushing and flood flows. Such scouring or resuspension might occur regularly (e.g. under normal tides) or infrequently (e.g. king tides). A water body is not suitable for use as a reinterment location if its design or form means that sulfidic material (including monosulfides) is likely to be scoured or resuspended.

Measures that can be used to protect against scouring or resuspension include redesigning the water body to achieve flow rates that will not cause scouring, or redirection of stormwater inflows that may result in resuspension.

### A5-1.6 Disturbance by boats

The risk of disturbance of the water−sediment interface by boats (and similar engine-driven watercraft like jet skis) is generally controlled by the depth of the water column and the turbulence left in the wake of the boat. Risk may increase with the frequency of boat traffic but should decrease if speed restrictions are obeyed. Water bodies often used by owners of such equipment may not be suitable reinterment locations.

# Appendix 6:  Remediation case studies of ASS

Remediation is the remedying of a deficiency or adverse effect.  In this case it is the rectification or mitigation of environmental harm, or the threat thereof, caused by a failure to appropriately manage ASS.  The essential principles of ASS remediation have been documented to encompass a series of containment, neutralisation and dilution strategies (Tulau 2007).  Methods of ASS remediation can also be based around the manipulation of the watertable, and hence the re-establishment of reducing conditions—this method requires soils which have sufficient quantities of available organic matter present to drive reducing conditions.  Neutralisation of the Actual and/or Retained Acidity that has already been generated may also be required, along with strategies that stabilise the area with vegetation.

Most of the time, more than one strategy will be required for successful remediation.  For example, a site that is to be reflooded will also require neutralisation of the surface soil and revegetation.  Achieving remediation of degraded areas can require complex site management that is cost effective.  Often there are no simple solutions to the problem, and the landscape can take decades to restore.

## A6-1 East Trinity

*Section A6-1 was compiled by Michelle Martens, Doug Smith and Steven Wilbraham from Queensland Department of Environment, Science and Innovation*

The East Trinity site in Far North Queensland (Figure A61-1) has opted to use three strategies of containment, neutralisation and dilution (Powell and Martens 2005).  It is considered a reference point for best practice remediation and management of broadacre ASS and is an exemplar conversion site linked to the Australian National Standards for Ecological Restoration (Luke 2016).

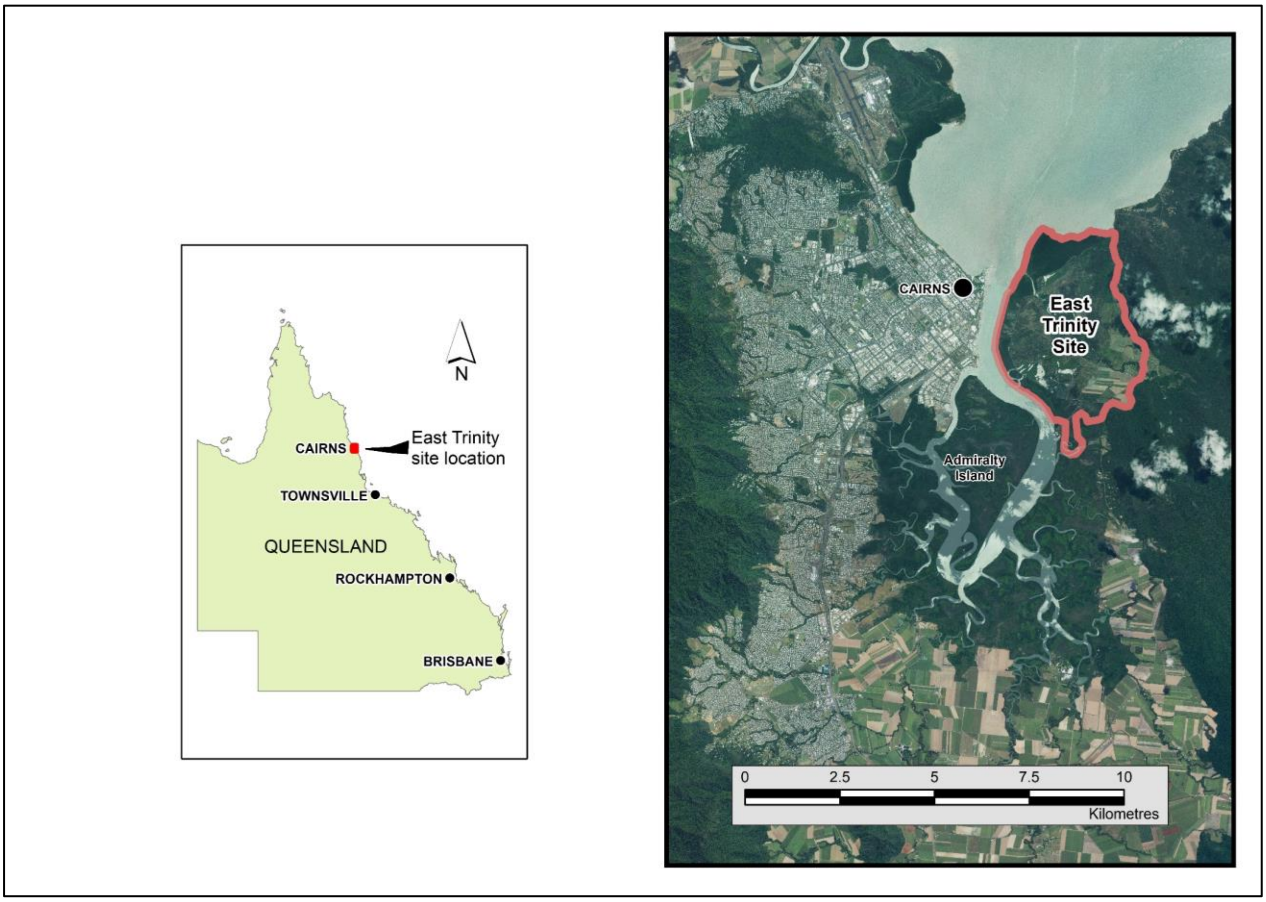

**Figure A61-1:   Location of the East Trinity site**

### A6-1.1 Rationale

A 750 ha tidal wetland on Trinity Inlet near Cairns was drained and bunded to exclude tidal influence in the 1970s to grow sugar cane. Floodgates were installed to intercept two major creek systems. The sugar cane project ultimately failed, and the site drainage caused the release of more than 3000 tonnes of sulfuric acid per year, over a thirty-year period. This occurred because the tidal wetlands were underlain by sands and muds containing iron sulfides which became unstable and formed AASS once they were drained. There were documented fish kill events, large-scale loss of mangrove and other tidal wetland vegetation, and acid (and toxic metal) release into Trinity Inlet. In 2000, the Queensland State Government purchased the land and funded a project to remediate the environmental hazard.

Rehabilitation of the East Trinity land by conventional lime treatment of soil was considered prohibitively costly and impractical. At the same time, there was no guarantee that the area could be brought to a stabilised condition.

Knowledge of ASS remediation in 2000 was not extensive but predictions were that remediation, if successful could take many decades. However, the remediation method adopted brought about early and tangible improvements—the acidity of soil and drainage water declined much earlier than predicted. This prompted the need for a research program to understand the mechanisms involved in what was suspected to include both chemical and biological processes in the soil. This led to radical changes in the understanding of broadacre ASS remediation processes.

### A6-1.2 Controlled daily tidal exchange

The remediation at East Trinity involved the controlled re-introduction of daily tidal exchange, with the strategic addition of hydrated lime to enhance the natural acid buffering capacity of sea water. Lime-assisted tidal exchange (LATE) kept the soil wet and neutralised some of the acidity, which stimulated the proliferation of naturally occurring sulfate and iron reducing bacteria. Microbial metabolism generated *in situ* alkalinity which was shown to be responsible for the majority (58–74%) of the acid neutralisation at the East Trinity site (Johnston *et al.* 2012). Hydrated lime additions were calculated to neutralise just 1% of the acidity. However, the early and strategic application of hydrated lime was responsible for both kick-starting the microbial remediation processes, and for dropping mobilised iron, aluminium and other co-associated trace elements such as arsenic from ebb tide waters before they exited the site.

The site has undergone a dramatic transformation since 2000 with stark changes in water quality, soil condition, aquatic life and vegetation. After the site was drained in the 1970s and then acidified, vegetation drastically changed. Ti-trees (*Melaleucas*) grew in extremely acidic soils and the mangrove communities died out. The latter have since returned and are proliferating in soils that have lost virtually all of their acidity, while seagrass meadows are establishing in the newly-created sub-aqueous areas. The acidity of water leaving the site and drainage water within the site has also decreased with water quality parameters now similar to pre-drainage conditions in many areas. Fish and other aquatic species have returned to what is now approaching a functional tidal wetland habitat. Globally, such habitats support 80% of total fish catch.

### A6-1.3 The path to remediation

Research has shown that the processes underpinning the East Trinity ASS remediation are a series of complex biogeochemical loops. The following diagrams depict the original conditions (Figure A61-2), the landscape response to development for sugar cane production (Figure A61-3) and then the changes due to LATE at the East Trinity site (Figures A61-4 and A61-5).

### East Trinity prior to bunding and development

Figure A61-2 represents the East Trinity site as the tidal wetland before development for sugar cane production. Here, the ~3 m natural tidal range largely kept the (grey coloured) surface sediments containing pyrite saturated, hence the PASS on site were stable.

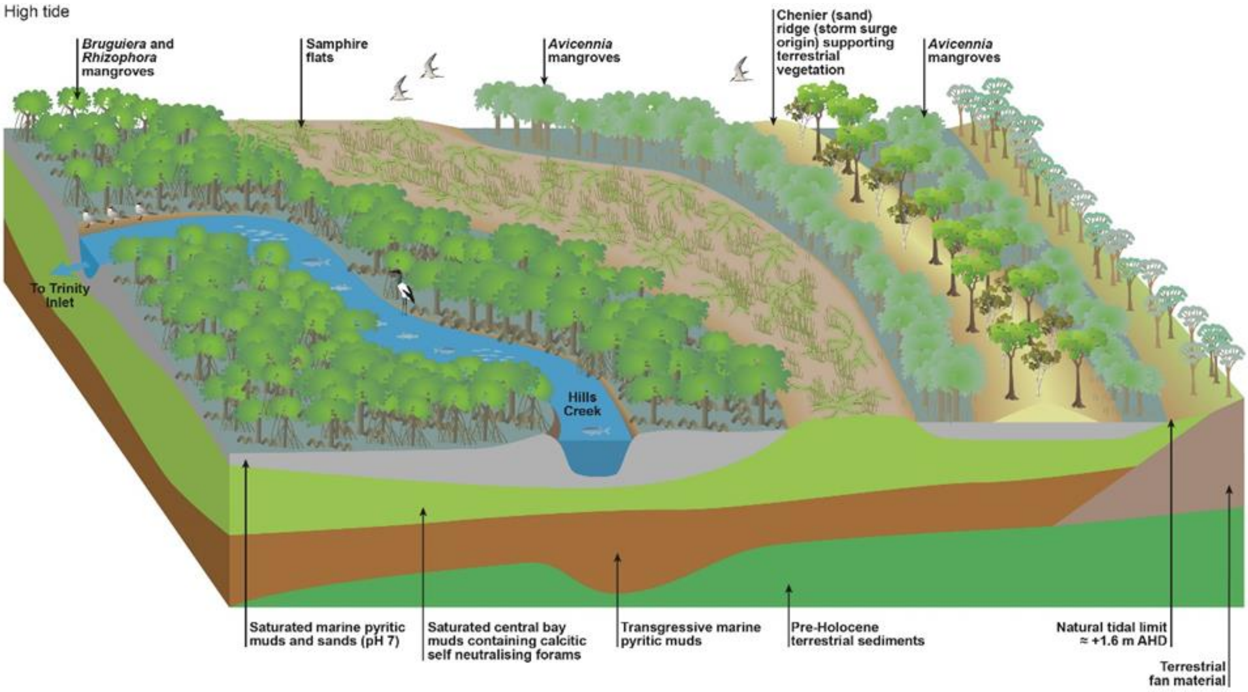

**Figure A61-2: East Trinity prior to bunding and drainage**

### *Development for sugar cane production*

A large seawall (bund wall) around the seaward perimeter, 27 km of drains and active pumping of water from the East Trinity site were required to lower the watertable and facilitate agricultural production. Figure A61-3 highlights the changes that occurred when the PASS were drained causing the iron sulfides in the soil to be exposed to oxygen. This led to the formation of AASS (shown in red) that contain iron sulfate minerals (i.e. jarosite and schwertmannite), and the release of sulfuric acid and soluble iron in the creek systems. The site transitioned from a tidal wetland to an acidified freshwater environment.

The soil and water baseline characteristics were extensively studied (Hicks *et al*. 1999; Smith *et al*. 2003) prior to remediation. An additional soil survey was completed to quantify changes in soil properties brought about the LATE (Smith *et al*. 2016). Water monitoring systems were installed, and there were significant challenges to be met before LATE could commence. For example:

- a need for all weather access to a range of key locations to facilitate water monitoring and treatment, and to have those locations made safe (in a heavily constrained site)
- the removal of sediment that had clogged Hills Creek thus preventing tidal flow
- devising a means of adding hydrated lime to approximately 400 cumecs of tidal flow
- the establishment of up to 12 water quality monitoring stations able to gather real time data on pH, EC, oxygen level, temperature and depth
- a means of tide control to restrict inundation to 0.5 m AHD, and sourcing/designing tidal floodgates that could withstand the high energy environment
- establishment of deep and shallow groundwater monitoring bores; and
- protection from saline encroachment into neighbouring banana and cane land.

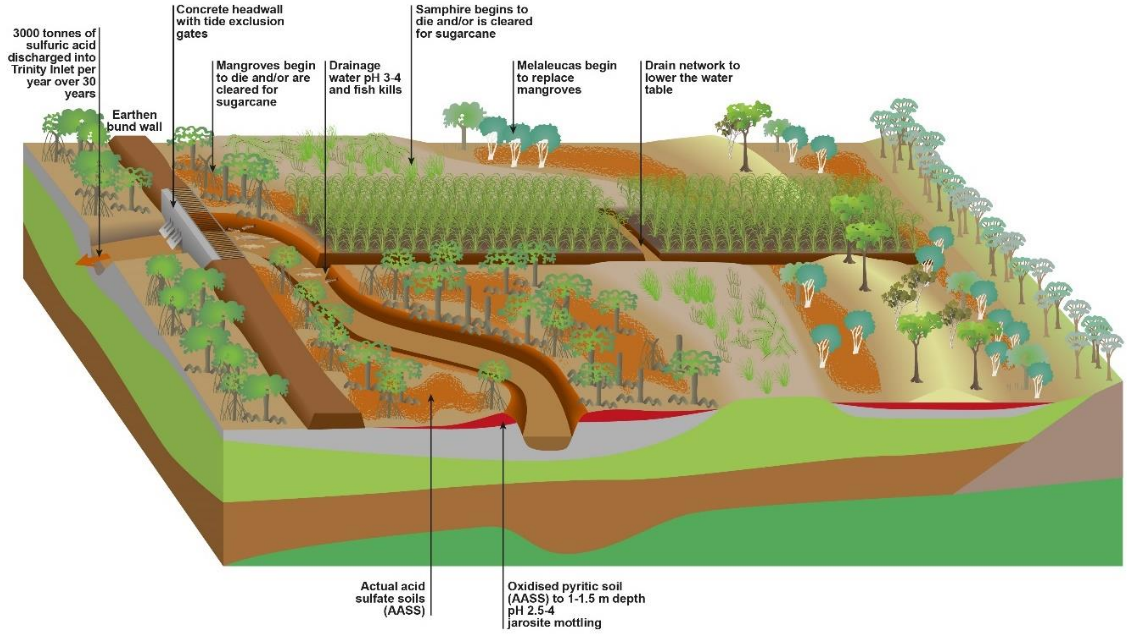

**Figure A61-3: East Trinity after bunding and drainage**

***Commencement of tidal exchange***

Tidal exchange was returned to the Hills Creek catchment in one event—from nothing to controlled lime-assisted tidal exchange to an elevation of 0.5 m AHD on day 1. A significant store of acidity was mobilised all at once which complicated manual water treatment. In contrast, Firewood Creek catchment had leaky and missing gates, which were subsequently replaced with the ideal gates that were tested and developed in Hills Creek. The incremental increases in tidal exchange up to the 0.5 m AHD limit in Firewood Creek were comfortably managed with bulk water treatment equipment despite this being the more acidic catchment.

The timing and locations for the addition of hydrated lime during active LATE were designed to allow the iron oxidation and hydrolysis reactions to occur as high in the catchment as possible to allow the iron to 'floc' out within the site rather than being transported offsite with the exiting water. With an increased tidal inundation level now consistently covering low-lying, acidified areas, many of the post-development colonising *Melaleucas* were inundated and died (Figure A61-4).

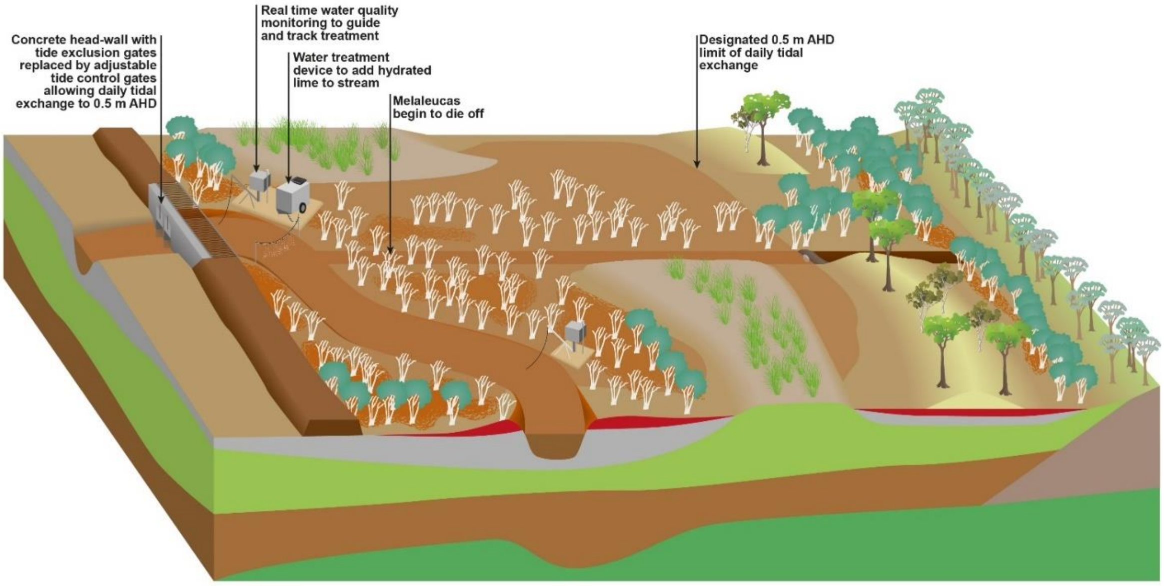

**Figure A61-4: East Trinity at commencement of active lime-assisted tidal exchange in 2001**

## A6-1.4 The transition from active to passive management

The East Trinity site now has high ecological function and has transitioned from active to passive management, even with the continued acidity and metal generation from untreated acidified areas beyond the tidal inundation limit. Under passive management, the addition of hydrated lime to the waterways ceased, and regular tidal inundation has remained in place to ensure that ASS remain protected from further oxidation. Maintaining the current hydrology will ensure that the site does not revert to acid-producing conditions. Real-time water monitoring is used to confirm that the system is stable under passive management, with targeted interventions occurring if this is not the case. Ongoing monitoring and research into the geochemical pathways that operate over the longer term are required to verify predictions of future system stability.

### *East Trinity 2021*

After more than a decade of LATE at East Trinity, from 2017, the entire site is now managed by passive LATE alone (Figure A61-5). Telemetered water monitoring continues to check for acid events and add value to a unique and valuable dataset. Seasonal soil and water sampling for laboratory analysis also continue to a lesser extent, as the site has stabilised in terms of acidity export but has not yet reached a final equilibrium.

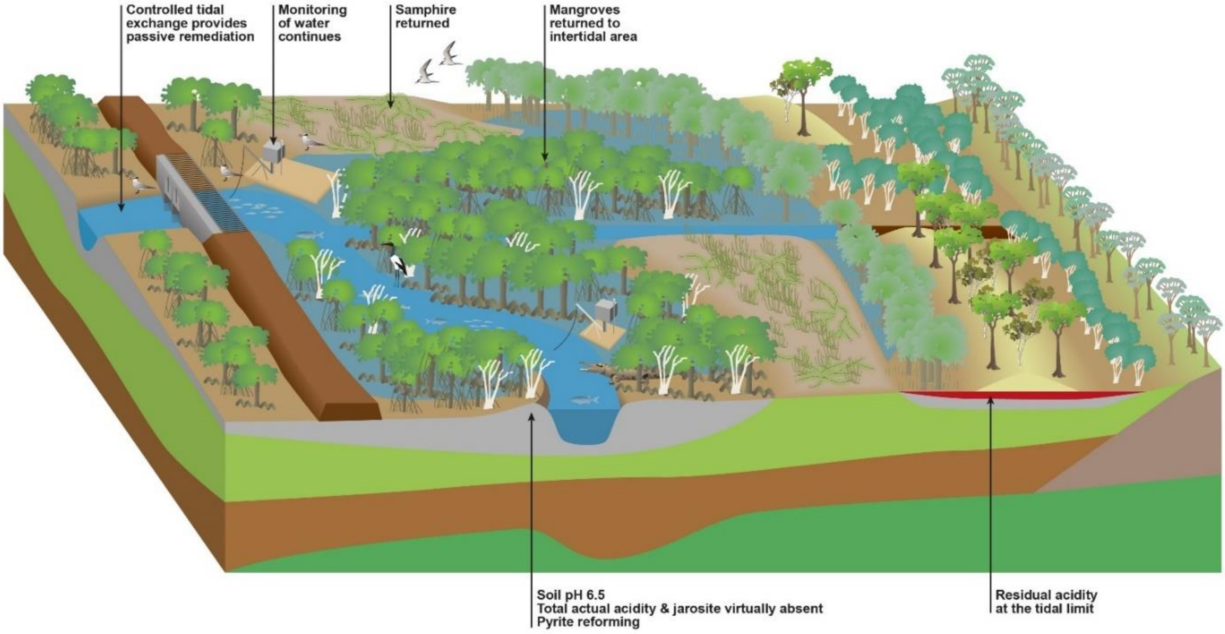

**Figure A61-5: East Trinity after 20 years of remediation**

### *Drivers of LATE remediation*

The drivers for the *in situ* remediation of the deeply acidified soil profiles are depicted in Figure A61-6, where twice daily entry and retreat of tidal water (augmented initially with hydrated lime) into the highly permeable acidified sulfuric layers of AASS created a cyclic pushing of lime-treated seawater into the permeable soils and drawing of ferrous iron up and out of the soil.

The critical discovery at East Trinity is that the addition of organic carbon plus seawater (and hydrated lime) initiated bioremediation that facilitated and pre-conditioned the ferrous iron catalysed weathering of jarosite. This process was largely responsible for the remarkable rates of dissolution/weathering of jarosite and schwertmannite, setting the site on a pathway toward rapid recovery. Microbial mineralisation of organic carbon and dissolution of iron minerals produces bicarbonate as a by-product. This provided further *in situ* acid neutralisation and increased the pH which enhanced the sorption of ferrous iron to jarosite and amplified the catalytic effect. There was an ecosystem shift when jarosite dissolved as iron reducing bacteria produce bicarbonate as a by-product.

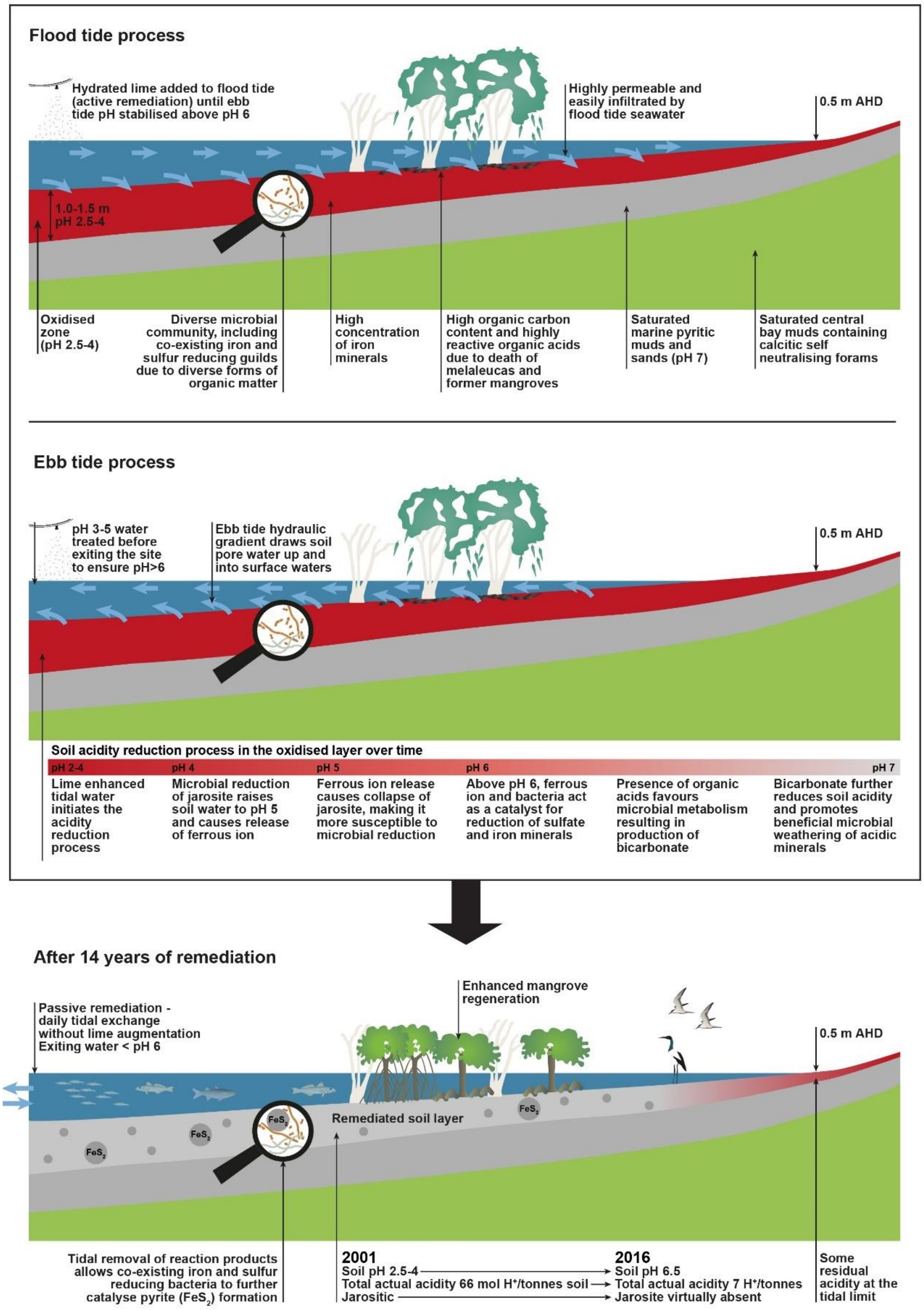

**Figure A61-6: Drivers for remediation of ASS using LATE**

## Acknowledgements

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Helen Walter from Department of Resources created Figure A61-1.  Kate Hodge of Hodge Environmental created all other figures in this section.

For more information, refer to the Queensland Government Website.

**ASS Tip 36: The Society of the Phriends of Phragmites**

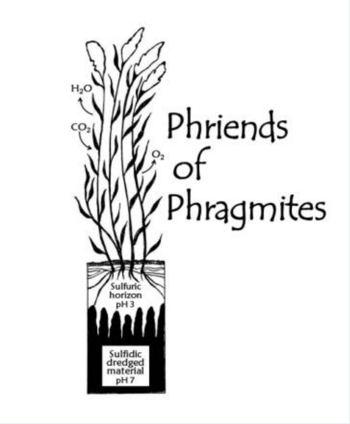
Phriends of Phragmites is not yet an official society, but *Phragmites* (and their Phriends) have been officially promoted as far back as the year 2000 as a reclamation strategy for dredged ASS materials where the rapid rate of soil ripening has been termed the ‘big bang’ of soil genesis (Fanning and Burch 2000; Fanning *et al.* 2016) due to its rapid rate of oxidation. Professor Leen Pons (considered the Father of the International ASS Conferences) was also supportive of this approach. The yet to be official society was formed to promote the understanding, use and control of *Phragmites* for such uses. At the first meeting in Maryland in 2015, almost everyone who signed up for the organisation agreed to purchase a Phriends of Phragmites T-Shirt.

*Phragmites australis* (the Common Reed) will out compete nearly all other species and can form a totally dominant stand on dredged materials which can have sulfuric horizons at or close to the surface. Following the deposition of the dredged materials, these soils are unvegetated, and consequently *Phragmites* are not displacing other plant species because other species are not present—particularly after the oxidation of sulfides has occurred and extreme acidity (pH often <3.5) has resulted. *Phragmites* is essentially the only plant that will grow on these soils, until the sulfides in the upper horizons of the soil have to a large extent been oxidized, which can take several decades.

*Phragmites* will often invade and colonize these acidic soils with rhizomes running out from the edges of the dredged material deposition areas, where part of the root systems of the plants are in parts of soils with less extreme chemical conditions. Once these plants start to grow in the sulfuric horizons, healthy roots of *Phragmites* have been observed in these soils, supporting above ground portions of the plants 2–3 metres tall—at one society gathering, healthy roots were observed to be growing in the sulfuric horizons of soils with pH as low as 2.85.

The not yet official society does acknowledge that *Phragmites* can also be responsible for outcompeting more desirable species (albeit not in sulfuric ASS landscapes), however they are considered a special plant for utilisation during the ripening and initial development of the soils. The large biomass produced by *Phragmites* benefits the soil in terms of additions of organic matter and in removing $CO_2$ from the atmosphere. With $O_2$ coming out of the roots, it hastens the oxidation processes and the physical ripening of the soils and accelerates the drying of the soils by evapotranspiration.

All of these benefits and others (e.g. the beauty of *Phragmites* with benefits to many forms of wildlife) are reasons why the not yet official society encourages people in all walks of life to be Phriends of Phragmites.



*Society logo drawn by Kate Hearing, Dept of Crop and Soil Environmental Sciences at Virginia Tech.* (Modified from Fanning 2015; Fanning 2016).

## A6-2 Acidification in the Lower Lakes of South Australia due to severe drought

*Section A6-2 was compiled by Emily Leyden, Luke Mosley and Rob Fitzpatrick from the University of Adelaide*

The Lower Lakes area in South Australia is characterised by a series of interconnected lakes and lagoons, including Lake Alexandrina, Lake Albert, and the Coorong (CLLMM). The CLLMM was designated in 1985 as a Wetland of International Importance under the Ramsar Convention on Wetlands, reflecting the region's ecological significance (Muller *et al.* 2018).

### A6-2.1 Formation of ASS in the CLLMM region

Since the 1940s, water levels in the Murray River, adjacent wetlands and Lower Lakes have been maintained and managed using locks, barrages and levee banks along the river channel. The construction of locks, barrages and levee banks have excluded seawater from entering the system and allowed artificially stable water conditions in the Lower Murray regions to be maintained for over 80 years (Fitzpatrick *et al*. 2018b). The stable water conditions in the Lower Murray over this time, along with plentiful supply of organic matter (from *Phragmites australis* reed beds, algal productivity and farming activities) and the evaporative concentration of sulfate from river and groundwater sources resulted in the large-scale accumulation of acid sulfate soil materials in the sediments in the Lower Murray and Lakes (Fitzpatrick *et al.* 2018b).

### A6-2.2 The Millennium drought and exposure of ASS in the CLLMM region

From the early 2000s to mid-2010, Eastern Australia experienced one of the worst droughts in European history. Known as the Millennium drought, it was caused by a combination of factors, including a decrease in rainfall, higher temperatures, and increased evaporation rates (Fitzpatrick *et al.* 2018b). During the Millennium drought water levels fell over 1.5 m (to -1 m AHD) in Lake Alexandrina and 1.3 m in Lake Albert (to -0.8 m AHD) (Mosley *et al.* 2014b) (Figure A62-1). The reduction in water level was exacerbated by the over-extraction and over-allocation of water from the river system for irrigation and other uses.

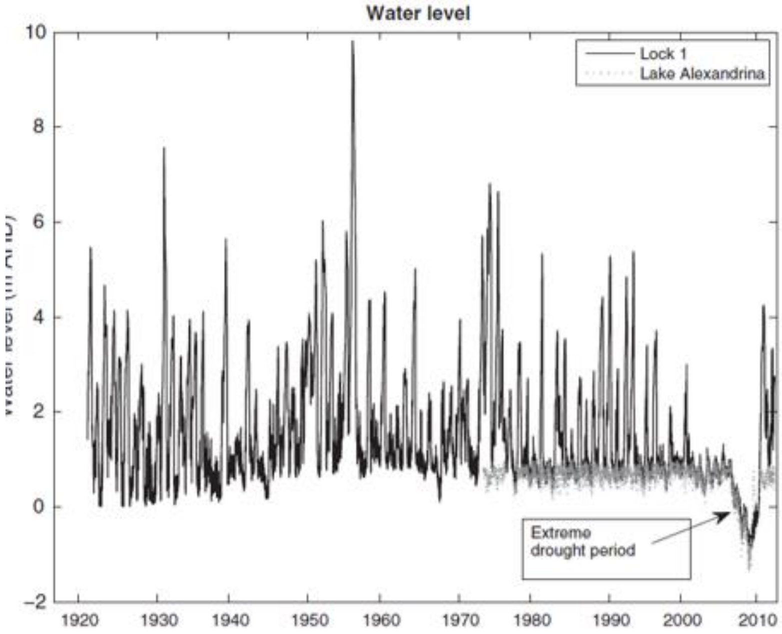


**Figure A62-1: Water level (m AHD) in Lower Lakes from 1920 to 2020 showing the drought period**

*Reproduced from (Mosley et al. 2014b)*

As the drought progressed and the watertable fell, previously saturated ASS material was exposed to oxygen and oxidised, leading to large acidification events in adjacent waters. Figure A62-2 illustrates the major areas of lake margin acidification realised in 2009.

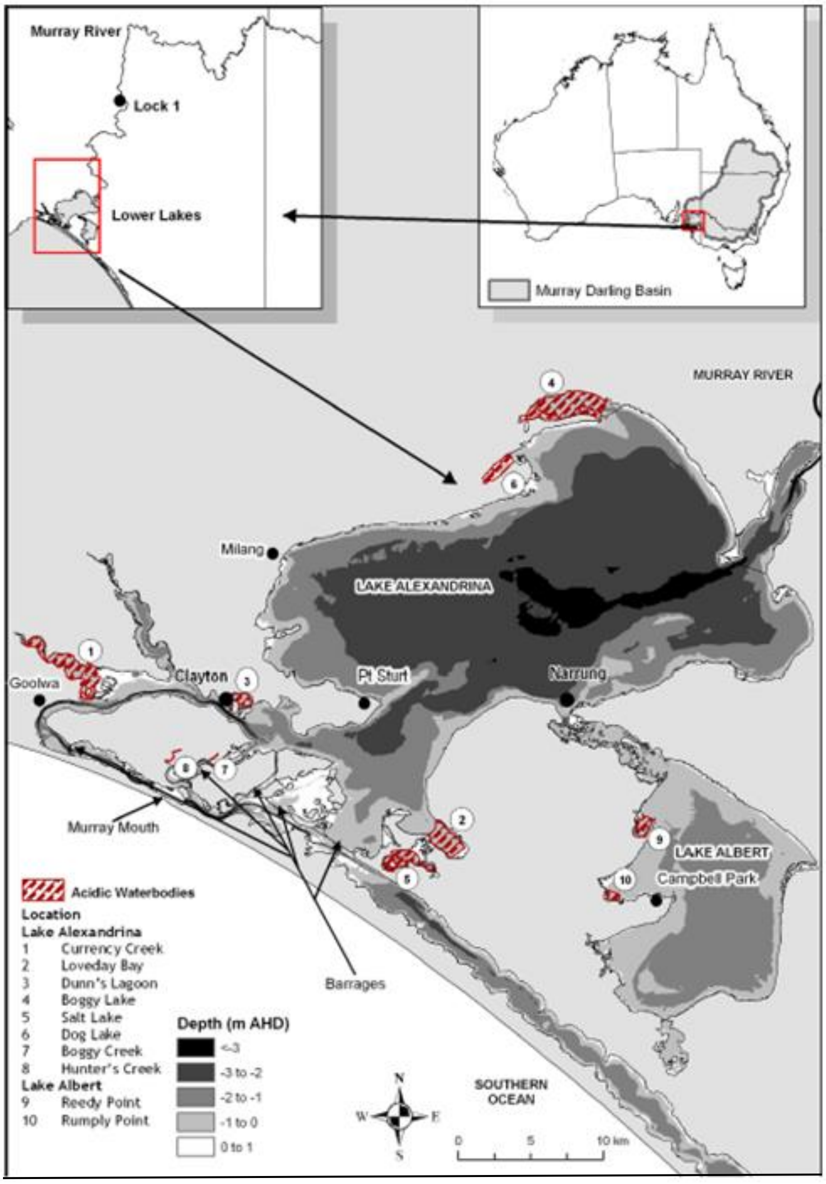


**Figure A62-2: Map of the CLLMM region, illustrating key acidification areas in red around the lake margins in late 2009**

*Reproduced from (Mosley et al. 2014b)*

Computer projections (Figure A62-3), based on data from extensive soil surveys, were prepared to plot the incremental spread of oxidation of ASS with sulfuric materials from normal pool level of +0.5 m to the predicted drought level of -1.5 m AHD. These projections showed the potential for 32 699 ha of shoreline and lakebed to convert from subaqueous sulfidic soils to sulfidic soils and sulfuric soils (Fitzpatrick *et al*. 2008a, 2008b, 2009a, 2009b, 2010b). These predictions gave rise to grave concerns that without significant new river inflows to the Lakes, the ASS oxidation trajectories could eventually be realised, along with the associated severe environmental degradation.

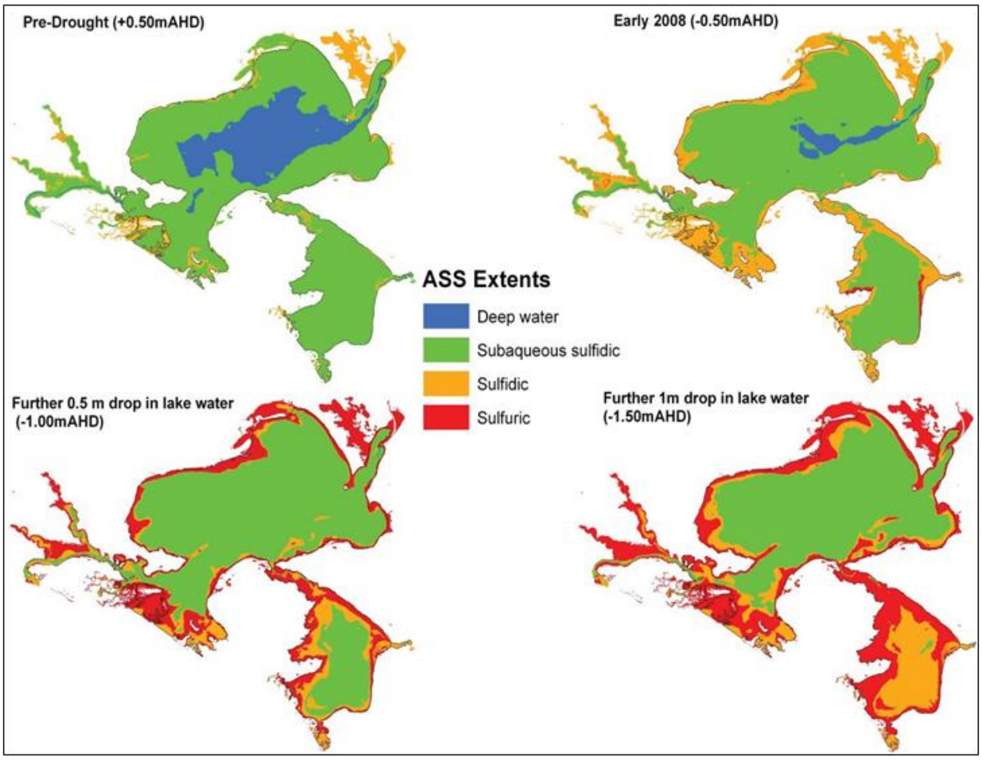


**Figure A62-3:** **Predictive scenario maps depicting changes in ASS materials at different water levels in the Lower Lakes (+0.5 m AHD, -0.5 m AHD and -1.5 m AHD)**

*Based on regional soil investigations and bathymetry (modified from Fitzpatrick et al. 2008a, 2008b, 2009a, 2009b, 2010b)). Finniss River, Currency Creek and Goolwa Channel are the three extensions occurring on the left side of Lake Alexandrina.*

About 85% of the lake surface soil/sediment had a positive Net Acidity (i.e. total acidity minus soil-neutralising capacity), with highest net acidities (>500 mol $H^+$/t) occurring in clay-rich sediments in the middle of Lakes Albert and Alexandrina. About 82% (67 087 ha) of the total lake area (82 219 ha) had potential for developing sulfuric (pH <4) materials in the soils/sediments if water levels continued to decline (Fitzpatrick *et al.* 2018b). The median Net Acidity measured (10 mol $H^+$/t) was below guideline action criteria trigger levels (18 mol $H^+$/t) for when management of ASS is recommended. However, a large area of the inundated soil/sediments of both Lakes and tributaries, particularly Lake Albert, contained very high levels of Net Acidity (>250 mol $H^+$/t). The southern and north-eastern regions of Lake Alexandrina and some marginal areas around both Lakes were a lower hazard.

The Net Acidity (Figure A62-4) and ASS classification (Figure A62-5) maps showed that sulfuric soils were especially prevalent in tributary regions with poor connection to the main lake bodies, such as Currency Creek, Finniss River, Loveday Bay, Boggy Creek and the bodies of water at Tolderol and Boggy Lake (Fitzpatrick *et al.* 2018b). In August 2009, the pool level had dropped to -1 m AHD in Lake Alexandrina and -0.8 m AHD in Lake Albert, and the predictions of lake margin acidification were realised based on extensive field investigations and laboratory analyses across the Lower Lakes region.

The rewetting of these materials via rainfall and tributary inflow resulted in widespread surface water acidification (pH 2–5) in the Currency and Finniss tributary areas and other shallow embayments around the lake margins in 2009–2010. The metal and metalloid contaminants that were released from the sediment matrix by extreme acidification (e.g. pH <2) posed risks to the public and the environment (Simpson *et al.* 2010; Mosley *et al*. 2014b). Other hazards included noxious (hydrogen sulfide) gas release as well as mobilisation of dust from exposed ASS areas, which led to community concern.

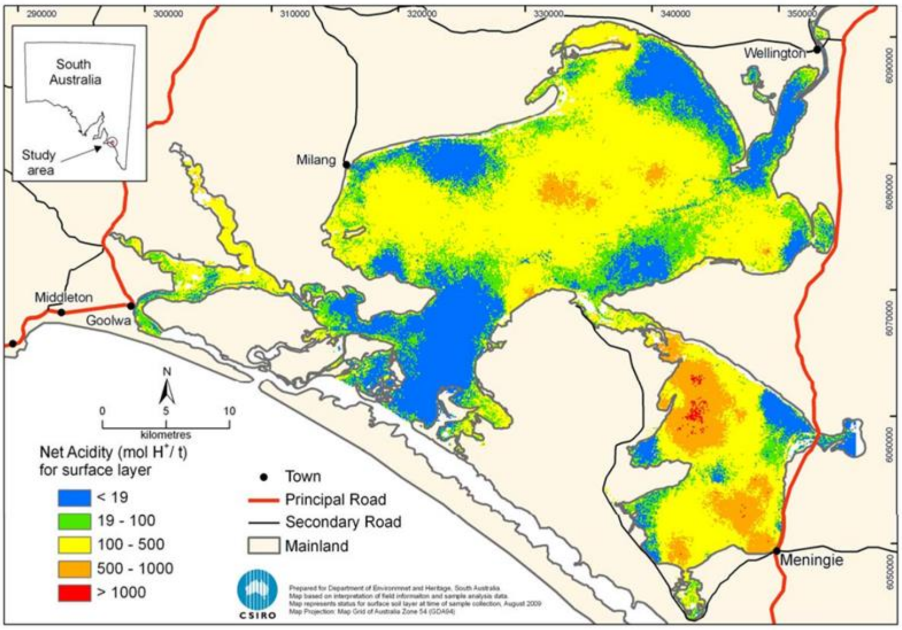


**Figure A62-4:** **Net Acidity map with data grouped into five classes for upper soil layer (0 to 10 cm)**

*Modified from (Fitzpatrick et al. 2010a)*

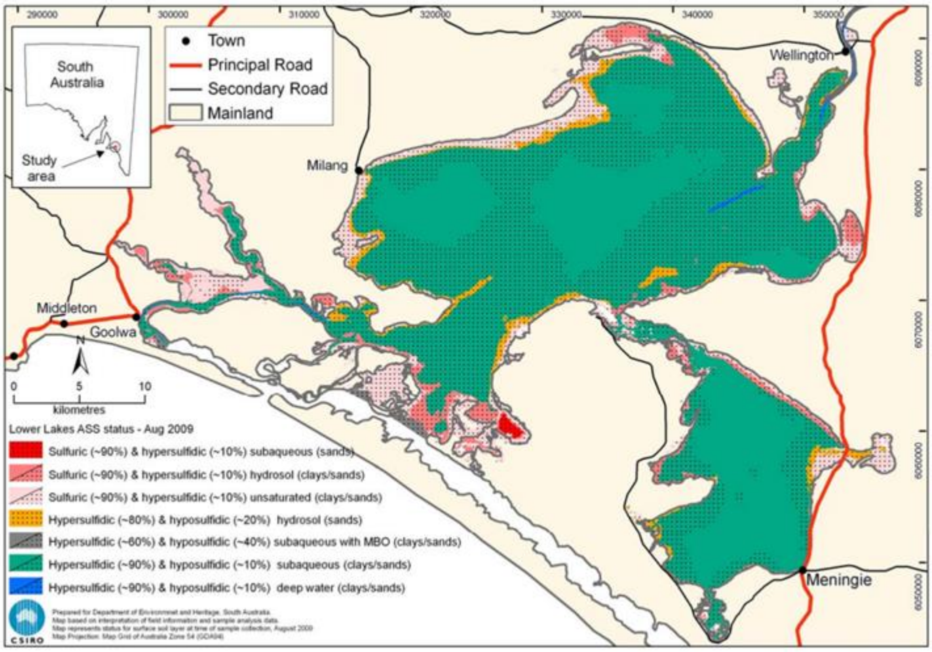


**Figure A62-5:** **Soil classification map showing the distribution of ASS, saturation status and soil texture**

*Modified from (Fitzpatrick et al. 2010a)*

### A6.2.3 Management response, implications and strategies

The management response in the region was two-fold; to keep as much hypersulfidic soils saturated as possible with the very limited water available, and to treat the area with lime where acid and metal mobilisation were the highest. Reliable ASS hazard maps, at appropriate scales, such as those in Figures A62-3, Figure A62-4 and Figure A62-5 were critical to understanding soil properties, the rates of pyrite oxidation and identifying areas of highest risk. This allowed the appropriate selection of management options for each area.

### *Clayton and Narrung Narrows embankments, regulators and water pumping*

As a consequence of the widespread occurrence of sulfuric material and acidic waters in the Goolwa Channel, Finniss River and Currency Creek areas, the Australian Government, in response to a Referral under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Reference Number 2009/4833), gave approval for the South Australia Government to undertake a set of emergency actions to undertake management measures to mitigate ASS (Natural Resources SA Murray-Darling Basin 2009). First, a temporary flow regulator across the Goolwa Channel at Clayton was constructed (Figure A52-8) to allow water levels in the Goolwa Channel, Finniss River and Currency Creek to be raised. This strategy aimed to saturate the exposed sulfuric and hypersulfidic materials to minimise further sulfide oxidation and to allow the early season flows (which would have mobilised acid and heavy metals) to be held back whilst also allowing natural *in situ* bioremediation to proceed. The constructed height of the regulator was c.+2.5 m AHD (to allow sufficient freeboard), but the water level was managed to a maximum level of +0.7 m AHD. The pool level was initially raised to +0.7 m AHD by pumping water from Lake Alexandrina. This action required ~20 GL of water. In addition to this regulator, a large bund was constructed across the Narrung Narrows (between Lake Albert and Lake Alexandrina) and water was pumped from Lake Alexandrina into Lake Albert to maintain water levels and soil saturation. This regulator successfully prevented more hypersulfidic material in Lake Albert oxidising to form sulfuric material. A low-level regulator (0 m AHD) was also constructed across the mouth of Currency Creek to permit continued saturation of sulfidic, hypersulfidic and sulfuric materials.

### *Limestone application at Wally's Landing, Currency Creek and Boggy Lake*

Applications of fine limestone ($CaCO_3$) were applied to the upper Finniss River in the form of a barrier across the river below Wally's Landing jetty, as shown in Figure A62-6, to neutralise potential acidic waters from the wetland and channel (Fitzpatrick *et al*. 2018b). Larger areas of exposed ASS with sulfuric (pH <4) materials and associated acid water bodies in two key 'hotspots' (Currency Creek and Boggy Lake) were managed via aerial dosing of limestone (Figure A62-7). This option involved precision application of limestone into the water body using a crop-dusting plane. The amount and location of limestone dosed was informed by measurements of acidity already present in the water body (Mosley *et al*. 2014a, 2014b).

**Figure A62-6: Applications of fine limestone in the Finniss River below Wally's Landing jetty to acidic waters flowing from the wetland and channel in May 2009**

*Reproduced from Fitzpatrick et al. (2011)*

**Figure A62-7:** **Aerial application of limestone in Boggy Lake, SA**

*Right: photos showing mechanism used to upload fine agricultural limestone into the aircraft in a nearby paddock (reproduced from Fitzpatrick et al. 2011d).*

Goolwa Channel Water Level Management Project

All of the wetland complexes around the Lower Lakes have been adversely impacted by falling water levels and increasing salinity in the lake water bodies. Urgent action is required to protect critical areas as falling water levels cause almost all of these areas to become dry or cut-off from the main body of the lakes. Failure to protect at least some of these wetlands will result in important plant and animals becoming locally extinct, and would severely limit the potential for these communities to re - establish and re-colonise the region when conditions improve.

The Currency Creek and Finniss River wetlands are generally regarded as the most important and valuable remaining in the Lower Lakes region. These wetland complexes have already been severely impacted through desiccation (drying out), salinisation and acidification. There is already clear evidence of these impacts at many of the sites with loss of vegetation and the appearance of acidification 'hot spots'.

To protect these important ecological sites, water levels in the wetlands must be raised and maintained at new levels. This will be achieved by the Goolwa Channel Water Level Management Project, which will include the construction of three environmental flow regulators.

The main regulator in the Goolwa Channel near Clayton will be about 400m long and 40m wide. It will be constructed as an earth-fill embankment with appropriate rock protection. The Finniss River and Currency Creek regulators will be about 900m long and 10m wide, and 320m long and 10m wide, respectively. They will be constructed as low-level rock fill embankments.

The structures will be temporary, and will be removed when River Murray flows improve and the Lower Lakes recover.

Acid sulfate soils

Acid sulfate soils naturally occur in some coastal and fresh water areas.
As long as the soils are covered by water they are harmless to the environment,
but if water levels drop and the soils are exposed to the air they react
with oxygen to form sulfuric acid (the same acid in a car battery)
and can release heavy metals from the soil.
If too much acid is created by soils being exposed to the air,
then soil and water can become very acidic, which can impact on
the environment, agriculture and infrastructure.
The acid can also cause toxic metals to be released.
If detected and managed appropriately, serious problems can be avoided.
Keeping acid sulfate soils wet is a proven and effective management technique.

Government of South Australia
Department of Water, Land and Biodiversity Conservation

DROUGHT RESPONSE

Further information about the project is available through the Department of Water, Land and Biodiversity Conservation.
Website http://www.dwlbc.sa.gov.au/murray/drought/gcll.html
Contact Officer (08) 8204 8605

**Figure A62-8:** **The main temporary flow regulator across the Goolwa Channel**

*Note: This was completed in early August 2009, allowing water levels in the Goolwa Channel, Finniss River and Currency Creek to be raised and to saturate the existing exposed sulfuric material shown in the soil map. The regulator was about 400 m long and 40 m wide and was constructed as an earth-fill embankment. Photo credit: Rob Fitzpatrick*

### *Other management options*

Additional management options were also scoped, including the opening of the barrages to let seawater in and bioremediation and revegetation. Research conducted at the time suggested that allowing seawater to enter the Lakes risked the severe mobilisation of metals and acidity through cation exchange pressure.  In addition, computer modelling of electrical conductivity (EC) post seawater ingress estimated a rapid increase in salinity, reaching estuarine concentrations (~ 20 g L-1, or 31 000 EC) in the first year, before increasing to marine and then hypersaline concentrations (up to 100 g L-1 or 157 000 EC) in following years (Muller *et al.* 2018).  It was predicted that this scenario would lead to serial losses of all freshwater and any colonising estuarine taxa, so it was deemed necessary to use seawater to keep soils inundated only if water levels fell beneath severe acidification trigger levels (which were not reached in 2009 before water returned in 2010).  Bioremediation aimed to stimulate microbial activity (specifically sulfate-reducing bacterial activity) to convert dissolved sulfate to sulfide minerals, essentially reversing the oxidation reactions that generate acidity in exposed ASS (Muller *et al*. 2018).  Bioremediation was successful, not just in effectively treating the exposed ASS, but also in providing social benefits to the local communities and Indigenous contractors, who were making a tangible difference by growing plants to revegetate these problem sediments (Muller *et al.* 2018).

#### ***Community volunteer groups / citizen science projects***

Sampling protocols for monitoring changes in ASS conditions in the Lower Lakes region were also specifically developed for community volunteers by Thomas and Fitzpatrick (2011).  Seminars and field days were held to build the capacity of 85 community group volunteers to effectively monitor acid sulfate soils during 2009 and 2010.  This resulted in a total of 486 soil profiles and 1458 soil layers being sampled and tested for pH in the field by community groups, and in the laboratory by CSIRO.  The engagement of citizen scientists greatly raised awareness of ASS in the Lower Lakes, and in turn helped inform more detailed follow-up work and management in some areas.

#### ***Costs and future predictions***

The acidification events in the Lower Lakes region imposed significant management challenges and costs.  The direct acidification management interventions were estimated to cost greater than $50 million Australian dollars (AUD), with overall costs of the drought event in the Lower Murray and dependent region estimated at over US/AUD $2 billion (Kingsford *et al.* 2011; Mosley *et al.* 2014b).

The decline in water levels and acidification in the Lower Lakes could have been prevented with a different water management regime across the Murray Darling Basin.  Currently, the Basin has high water extraction levels, diverting around 50% of available water annually for irrigated agriculture (CSIRO 2008).  To avoid the huge cost of large-scale acidification events and the associated management interventions in the Lower Murray and Lakes region’s future, it is crucial that water is allocated to ensure appropriate environmental flows, particularly in years of drought and as climate change alters water flow down Australia’s largest river system.  A new Murray-Darling Basin water management plan has been implemented over the last decade, which is recovering water for the environment, leading to positive environmental outcomes for the local and regional environment.

## Acknowledgements

We especially thank other members past and present of the Acid Sulfate Soil team in CSIRO Land and Water (Dr Gerard Grealish, Richard Merry, Mark Raven, Steve Marvanek, Warren Hicks, Stuart McClure, Dr Mark Thomas, Dr Nathan Creeper, Dr Andrew Baker, Dr Stuart Simpson, Dr Peter Self, Dr Nilmini Jayalath and Sonia Grocke), EPA (David Palmer, Ben Zammit, Jarrod Eaton, Dr Emily Leyden and Andrew Beal), University of Adelaide (Dr Patrick Michael) and University of WA (Dr Matt Hipsey) for assistance, and Greg Rinder for drafting the figures.

## A6-3 Former Sun Sun Prawn Farm ASS remediation

*Section A6-3 was compiled by Steve Lawrence from GHD*

The former Sun Sun Aquaculture site in Far North Queensland covered an area of approximately 50 ha, and operated as a prawn farm between 1986 to 1993. After failure of the venture, the site was abandoned for more than 15 years and in a highly disturbed state. The former prawn farm consisted of 15 holding ponds separated and surrounded by external and internal bund walls, constructed using soil materials from the site (later identified as ASS). Between 1993 and 2008 the soils on site were subject to irregular tidal inundation, erosion and significant recreational off-road traffic. The site was heavily degraded and illegal dumping was also occurring.

In 2008 the land was returned to the Port of Townsville for development of the new port access road, with the balance reserved for conservation purposes. As part of the planning process, the Port Authority commissioned further investigations, which led to development and instigation of a remediation plan for the site. The primary objective of the remediation works was to focus on treating surface and disturbed soils (both PASS and AASS) while minimising disturbance to natural soils and, secondly, to return the site to its former landform, promote tidal inundation and re-establish the natural marine environment.

Researching site history, undertaking a site assessment and developing a well-informed understanding of the site was important in supporting the development of an effective and appropriate site-specific remediation strategy. Liaising with stakeholders allowed a collaborative approach in developing appropriate remediation goals and meeting client, regulatory and community requirements and expectations.

The site was broken up into functional and structural areas such as upper and lower bund walls, natural material, spoil, pond floors etc to enable separation and classification of material for remediation works. Approximately 350 $m^3$ of former site infrastructure, rubbish and debris material (including 15 car bodies, concrete, pump wells, tanks, weir boxes and pipes) required removal to landfill. Several large sections of stormwater pipe located in the banks of Stuart Creek were also removed during the excavation works.

The primary remediation strategy involved the mixing of pure fine aglime to both fill and natural soils and ultimately placing the material in a stable and non-erodible landform that would be subjected to occasional tidal inundation. This also included, preferentially, to cut and treat the more benign surface ASS material and stockpile for later use as the final capping layer. ASS were found to be variable at the site with over 35 000 $m^3$ of soil being treated (at 5–10 kg ag/lime/t), reprofiled (using laser levelling) and compacted over an area of approximately 25 ha, with low strength soil and saturated areas having to also be managed throughout the project.

The contouring of the final site landform was designed to ultimately maintain a stable free draining non-erodible surface. This final landform was designed to a finished maximum height of 1.95 m AHD to maximise the wetted area of the site during regular tidal events. Tidal inundation was enhanced by the installation of swale lines to provide a preferential flow path for tidal waters to access the central locations of the site. These sag and swale lines were established with suitable bed and batter gradients to minimise erosion and provide various environmental zones (in respect to the frequency and duration of inundation) to which different marine plant species may preferentially colonise.

During the remediation, performance was monitored by frequently validating the effectiveness of lime amelioration by verification testing and regular supervision and support to the contractor undertaking the works.

Fill imported to the site during the remediation works was utilised primarily for creek bank stabilisation and at swale discharge points to reduce flow velocity (rock fill), to act as stabilised cut off walls within the filled drainage lines to minimise piping within treated soils (bentonite) and as road base fill imported to site, to provide a trafficable area along the proposed corridor alignment, located within the remediation footprint.

At the completion of the project, the area was handed back to the state as part of a proposed natural corridor associated with the Townsville Southern Port Access Corridor.  The remediation of the site cost approximately $1.8M.

**Figure A63-1:  Aerial view of the site**

**Figure A63-2:  Rotary hoe mixing in surface applied aglime within excavated fill material**

**Figure A63-3: Tidal inundation of the site**

*Photo credits: Steve Lawrence*

# Appendix 7: Liming Rate Calculations for Small Disturbances

This is a summary of the steps and statistical analysis undertaken to generate the liming rates in Table 4. For more detail, please contact soil.enquiry@resources.qld.gov.au

1. Extract all ASS data from the Queensland Government SALI database (using only the observation 1 data from the East Trinity project—the remainder of observations were excluded due to the number of samples in the dataset that may bias that results).

2. Only samples with SPOCAS and/or $S_{CR}$ analytes were retained. Some filtering of data was carried out (e.g. any negative lab results and samples with no laboratory data were removed).

3. Allocate field textures to the three categories in the ASS Texture-Based Action Criteria, with peats separated as a fourth category. Clay percentages have been modified from Table 2 to ensure more conservative liming rates.

4. Calculate Retained Acidity, with all results converted into equivalent %S units.

5. Perform Net Acidity calculations as per pH rules (i.e. if pH is less than 6.5, Actual Acidity must be measured and if pH is less than 4.5, Retained Acidity must be measured).

   *Note: Actual Acidity and Retained Acidity (both required to calculate Net Acidity) are missing from some earlier samples as laboratory methods developed over time. However, these samples were included in the analysis as exclusion would have underestimated the liming rate results.*

6. Any Net Acidity results less than 0.03 %S are removed.

7. The Net Acidity calculations for the three texture categories, plus peats, are as follows:

| Texture Category | Mean | Median | Maximum | 95 %ile | 99 %ile | Count |
|---|---|---|---|---|---|---|
| Coarse | 137 mol $H^+$/t<br>0.22 %S | 75 mol $H^+$/t<br>0.12 %S | 2676 mol $H^+$/t<br>4.29 %S | 449 mol $H^+$/t<br>0.72 %S | 848 mol $H^+$/t<br>1.36 %S | 2317 |
| Medium | 281 mol $H^+$/t<br>0.45 %S | 131 mol $H^+$/t<br>0.21 %S | 4185 mol $H^+$/t<br>6.71 %S | 1067 mol $H^+$/t<br>1.71 %S | 1827 mol $H^+$/t<br>2.93 %S | 1130 |
| Fine | 586 mol $H^+$/t<br>0.94 %S | 449 mol $H^+$/t<br>0.72 %S | 10 353 mol $H^+$/t<br>16.6 %S | 1634 mol $H^+$/t<br>2.62 %S | 3268 mol $H^+$/t<br>5.24 %S | 5574 |
| Peats | 356 mol $H^+$/t<br>0.57 %S | 162 mol $H^+$/t<br>0.26 %S | 2838 mol $H^+$/t<br>4.55 %S | 1478 mol $H^+$/t<br>2.37 %S | 2089 mol $H^+$/t<br>3.35 %S | 117 |

8. Calculate liming rates based on the 95th percentile using a safety factor of 1.5, a bulk density of 1.7 t/m$^3$ and 98% pure aglime. *Note: Bulk density of peat is typically 0.5–0.7 t/m$^3$.*

| **Type of material** | | **95th percentile** | **Kilograms of aglime / m$^3$ of soil** |
|---|---|---|---|
| *Texture range* | *Approx. clay content (%)* | Equivalent acidity (mol H$^+$/t)<br>Equivalent sulfur (%S) | |
| *Coarse* | <10 | 449 mol H$^+$/t<br>0.72 %S | 58 |
| *Medium* | 10–35 | 1067 mol H$^+$/t<br>1.71 %S | 139 |
| *Fine* | >35 | 1634 mol H$^+$/t<br>2.62 %S | 213 |
| *Peats* | - | 1478 mol H$^+$/t<br>2.37 %S | 192 |

The results of Net Acidity vs sample count are shown below for texture categories of sands, loams, clays and peats.

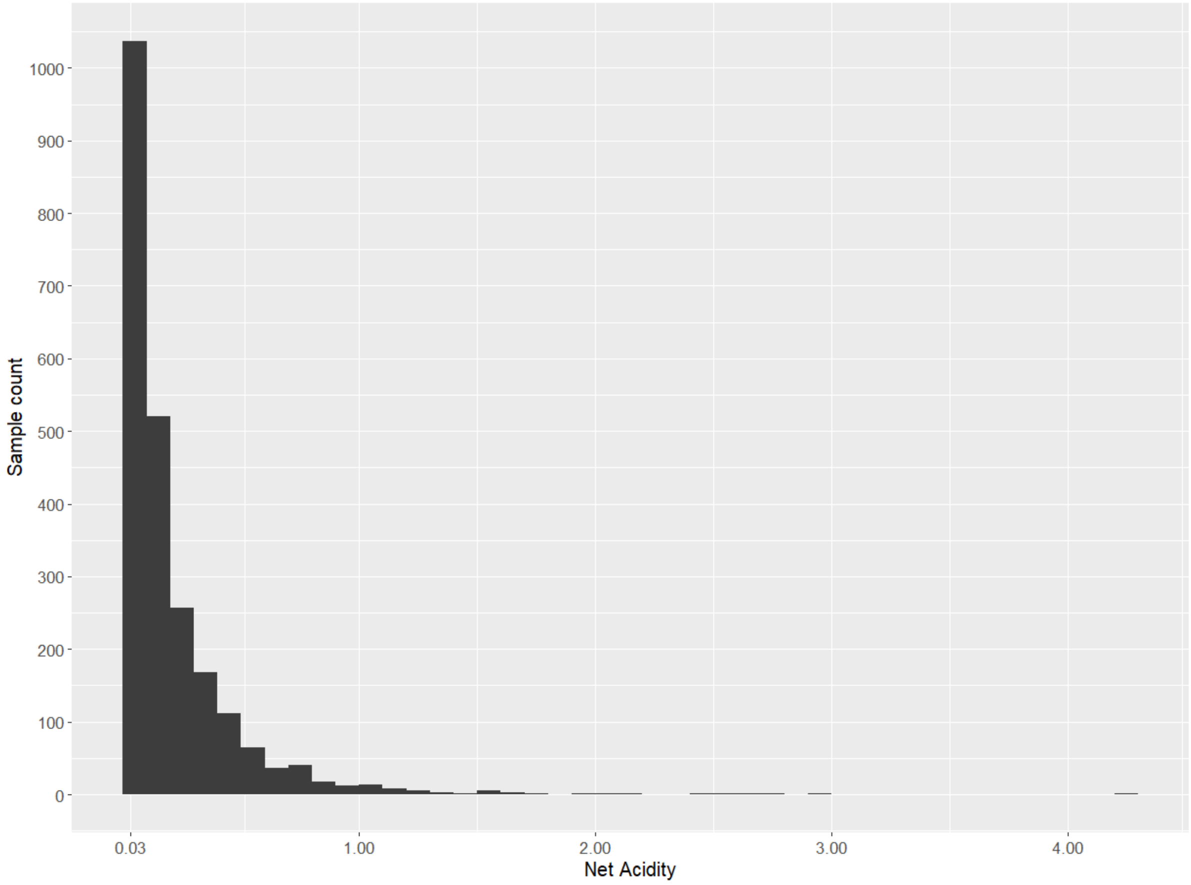


**Figure A7-1: Sample count versus Net Acidity for coarse textured ASS (sands)**

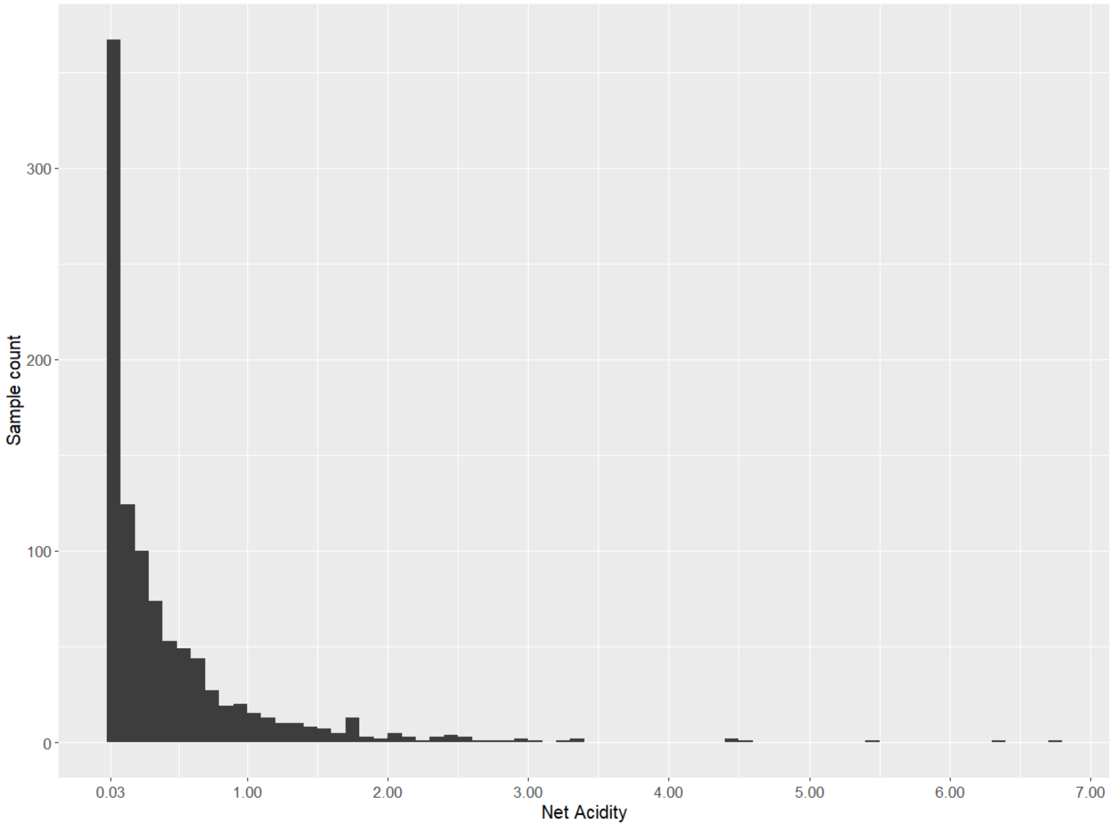


**Figure A7-2:** **Sample count versus Net Acidity for medium textured ASS (loams)**

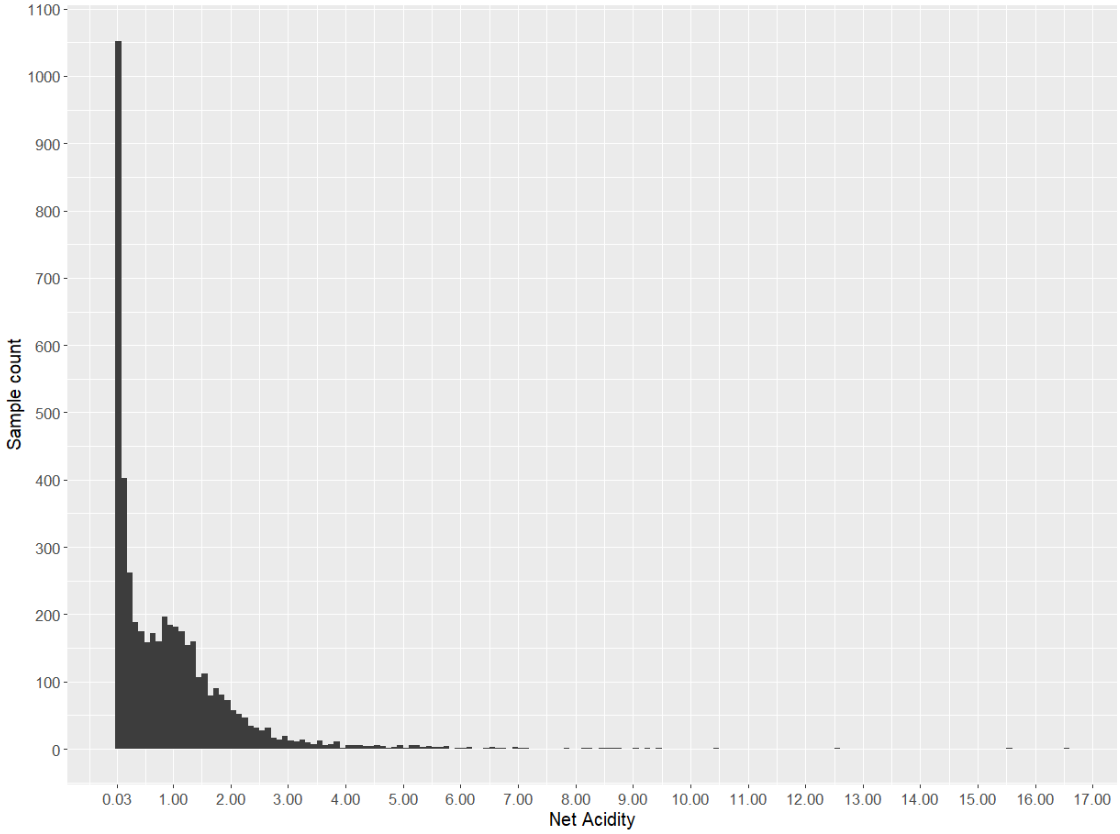


**Figure A7-3:** **Sample count versus Net Acidity for fine textured ASS (clay soils)**

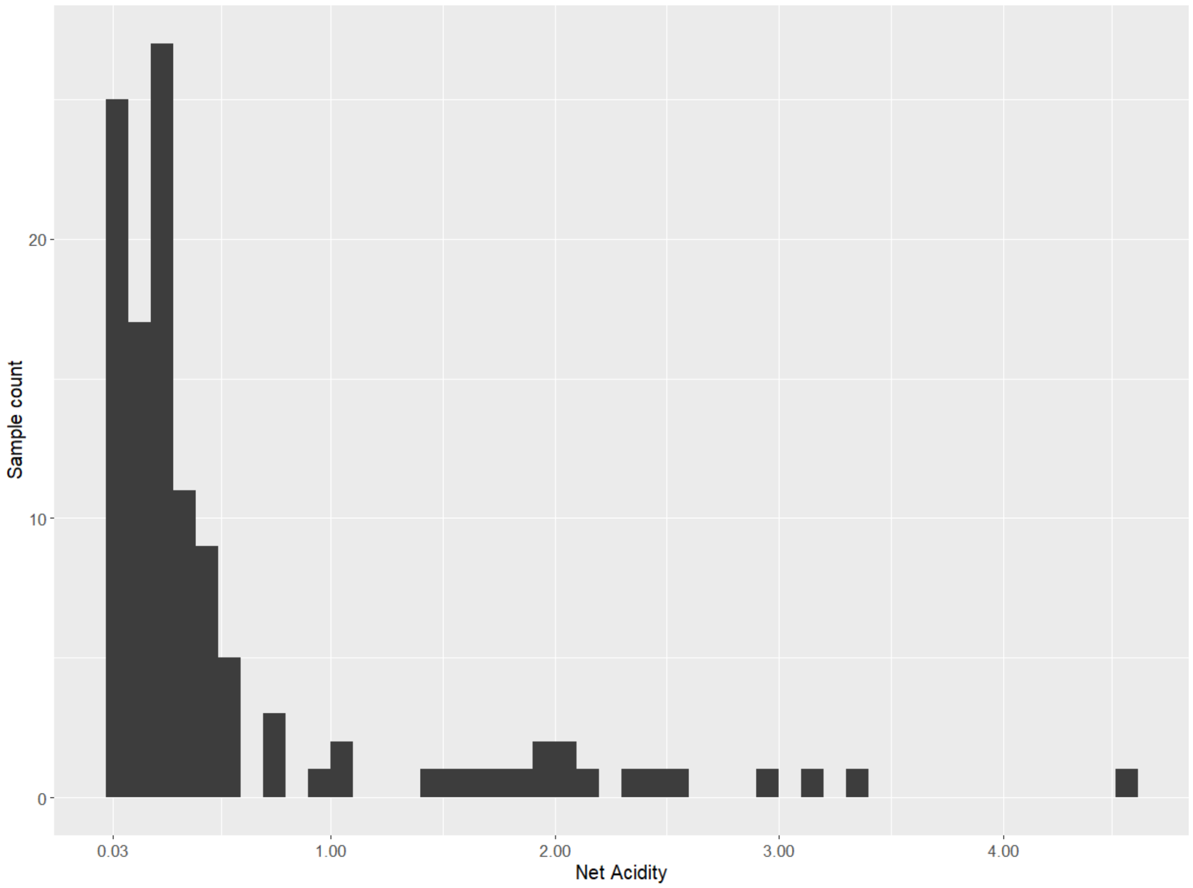


**Figure A7-4:** Sample count versus Net Acidity for peat textured ASS

# Appendix 8: Sulfidisation Poem

*The Sulfidisation Poem* is for teaching and entertainment purposes, **modified from and ideally sung to the tune of the song Ebb tide** (written by Carl Sigman and composer Robert Maxwell).

*Only text in bold black and not in parentheses is to be sung or recited. Other text is for illustration or explanation purposes.*

**First the tide rushes in.**
**Plants a kiss on the shore.**
**Then roll out to sea.**
**And the sea is very calm once more.**

**But with the tide that comes in.**
**Sea water sulfate comes along**
**It meets some dead OM**
**And by *Desulfuvibrio desulfuricans* living there**
**getting energy from the reaction.**
**The sulfate S is reduced to sulfide as the OM gets oxidized.**

*(Pronounce Oh M)*

$SO_4^{2-} + 2CH_2O \rightarrow H_2S + 2HCO_3^-$

**The tiny S plus-six cation of sulfate**
**gains 8 electrons and greatly expands to become an S two minus sulfide anion.**
**That shares two electrons with H pluses.**
**To become stinky hydrogen sulfide.**

*O Relative size of $S^{6+}$ cation*

*O Relative size of $S^{2-}$ anion*

**The carbon of the OM with its lost electrons.**
**Becomes C plus four**
**And combines with three oxides and an H plus.**
**And sloshes out to sea as bicarbonate.**

**Much of the hydrogen sulfide**
**Rises up to the air**
**To give a stinky aroma**
**To the marsh.**

**But some H two S meets goethitic iron oxyhydroxide**
**Eroded to the marsh in soil from the upland.**
**The S re-oxidizes a little as it chemically reduces**
**The ferric to the ferrous form of Fe.**

$2FeOOH + 3H_2S \rightarrow FeS_2 + FeS + 4H_2O$

*(Pronounce as eff E)*

**But pairs of partially oxidized S's, that reduced the ferric Fe's,**
**come together to form S two *(pronounce as S two)*, two minus, disulfide.**
**That precipitates with the ferrous Fe.**
**To form pyrite, some even in framboidal form.**

*$S_2^{2-}$ Disulfide formula, S two, two minus.*
*$FeS_2$ Iron disulfide, the formula for pyrite.*

**But one of three sulfide ions doesn't oxidize at all.**
**It meets an already formed ferrous Fe.**
**And precipitates.**
**To make black Fe monosulfide.**

*FeS, Iron Monosulfide, may be the mineral mackinawite. black as ace of spades, evolves $H_2S$ with HCl.*

$FeS + 2HCl \rightarrow H_2S + Fe^{2+} + 2Cl^-$

**As these processes continue on.**
**Tidal cycle after tidal cycle, as the moon circles the earth,**
**or as earth spins under its moon?**
**With the bicarbonate washed away to the sea.**
**A sulfidic material, as defined by Soil Taxonomy, is formed**.

By Delvin Fanning, Emeritus Professor University of Maryland and Poet Laureate of the Mid Atlantic Association of Professional Soil Scientists Organisation. *Soil Science Academic, Phragmites Activist and Poet!*

**Figure A8-1:** **A Chesapeake Bay tidal marsh in which sulfidisation occurs. The man presumably detects the odour of hydrogen sulfide from the marsh**

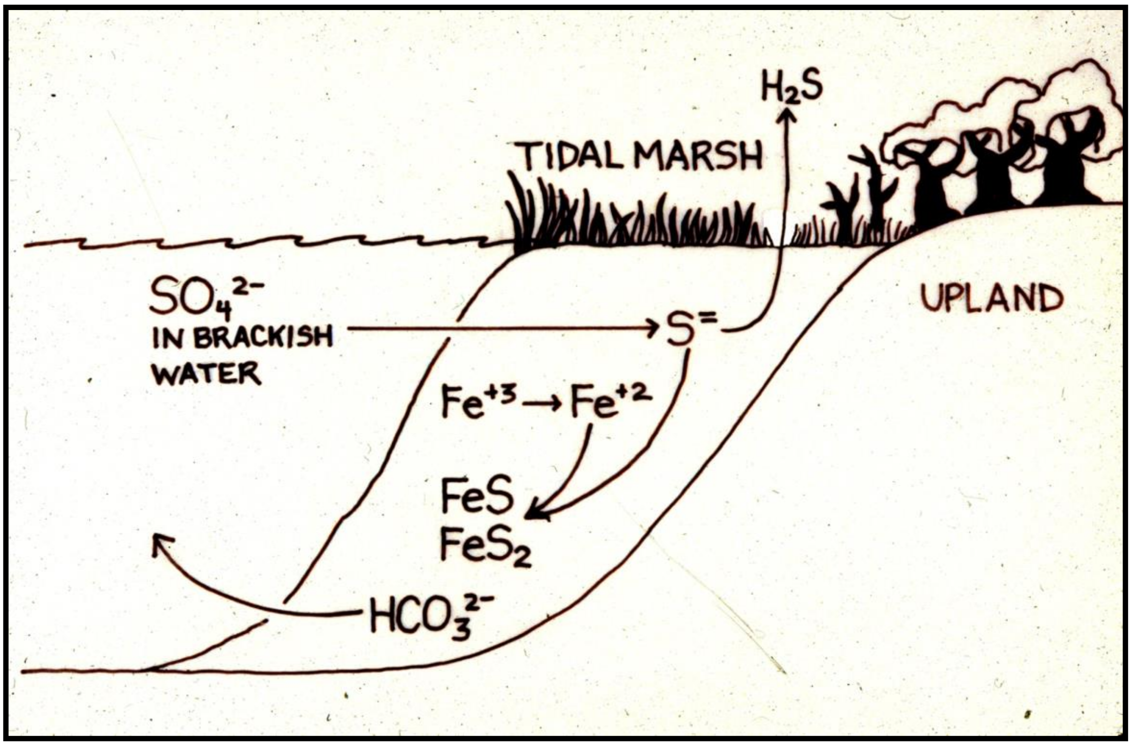


**Figure A8-2:** **Idealised diagram to represent sulfidisation occurring in a tidal marsh soil**

*(Modified from Fanning and Fanning 1989)*