QUEENSLAND
ACID SULFATE SOIL TECHNICAL MANUAL

SOIL MANAGEMENT GUIDELINES

Version 3.8

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To develop the **Queensland Acid Sulfate Soil Technical Manual**, the Queensland Acid Sulfate Soils Management Advisory Committee (QASSMAC) is supported by two committees for each chapter—a small Editorial Committee made up of scientists from the Queensland Government and academia, and a larger Technical Committee, comprising broad stakeholder representation including people with an interest or experience in ASS.

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1. INTRODUCTION

1.1 Occurrence of acid sulfate soils

Acid sulfate soils (ASS) occur naturally over extensive low-lying coastal areas, predominantly below 5 metres Australian Height Datum (AHD)[1]. These soils may be found close to the natural ground level but may also be found at depth in the soil profile. All disturbances to the groundwater hydrology or surface drainage patterns in coastal areas below 5 metres AHD, including the subsoil or sediments below 5 metres AHD where the natural ground level of the land exceeds 5 metres AHD, should be investigated, designed and managed to avoid potential adverse effects on the natural and built environment (including infrastructure) and human health from ASS. In some situations, ASS may also occur at elevations greater than 5 metres AHD, and these guidelines also apply to the management of those soils.

1.2 The soil management guidelines

The **Queensland Acid Sulfate Soil Technical Manual, Soil Management Guidelines** are risk-based, with the risk to the environment for a variety of 'preferred' and 'higher risk' strategies that can be used to manage ASS documented. When there is the possibility for ASS to be disturbed (directly or indirectly), the project should be subject to an appropriately rigorous risk assessment. Once the risk is assessed for a site, then the level of environmental management that should be implemented can be determined. The guidelines also document management issues that need to be considered for each management strategy. The environmental risks associated with 'generally unacceptable' strategies have also been documented. The guidelines are applicable to Queensland sites, and have been developed on the basis of experience in managing ASS in Queensland.

Determining the presence or absence of ASS and implementing appropriate management can involve substantial costs that may compromise a project's design or financial viability. These factors should therefore be taken into account as early as possible when considering projects in areas likely to contain ASS. It should be noted that soils that have previously been disturbed might also warrant treatment and management, to prevent acid generation and to neutralise existing acidity.

The *Soil Management Guidelines* are conservative in nature because they are written from a risk management perspective. However, they are not a regulatory or policy document, rather they are a guideline document for all stakeholders on ASS management issues and should not be followed blindly. The document is not a recipe book for persons who are acting outside their field of competence or experience. The professional environmental manager for each project must make decisions regarding the extent to which guidance provided here is applied to a given situation to adequately manage environmental risk in those circumstances. The guidelines may not be applicable to every site. They will not address management solutions for all situations and there may be exceptions where it is acceptable to deviate from the advice provided, particularly due to changes in technology. Alternative management strategies will need to be scientifically justified and must be consistent with the eight management principles (see section 3).

The *Soil Management Guidelines* is one of a series of chapters of the **Queensland Acid Sulfate Soil Technical Manual.** It should be read and implemented in conjunction with other chapters of the Technical Manual including the *Water Treatment and Management Guidelines*, *Sampling Guidelines*, *Laboratory Methods Guidelines*, *Legislation and Policy* and *Environmental Management Plan Guidelines*. It should particularly be noted that a separate chapter *Remediation Guidelines*, deals with remediation of existing acidified landscapes. The Technical Manual has been written with a multi-disciplinary approach to ensure that all relevant issues are covered.

[1] It should be noted that not all soils in the low-lying parts of coastal floodplains below 5 metres AHD are ASS; however in Queensland, ASS predominantly form at these elevations.

Although care has been taken to minimise overly technical language, expertise in a variety of disciplines may be required to fully implement ***best practice environmental management***[2].

The *Soil Management Guidelines* will be reviewed regularly to ensure that they remain up to date with the latest scientific research and technology.

1.3 Terminology

The term disturbance in the guideline refers to any movement, excavation or drainage of ASS.

For the sake of brevity, ASS, as used throughout these guidelines, refer to the spectrum of ASS, ranging from:

- *in situ* non-oxidised and therefore non-acidic soils, sediments and peats with significant amounts of oxidisable iron sulfides;
- partially oxidised soils, sediments and peats with variable ratios of existing acidity and unoxidised iron sulfides; through to
- completely oxidised (no remnant sulfides) soils, sediments and peats with significant existing acidity[3].

ASS Tip 1 – Inland ASS

In some inland areas significant distances from the coast, ASS can form under freshwater conditions in saline discharge areas (where sulfur, iron and clay have accumulated after mobilisation). These inland ASS form as a result of land clearing, excess discharge of sulfate-rich saline groundwater and erosion, forming scalds (Fitzpatrick 2002).

Also included are soils, sediments and peats that contain one or more of a spectrum of salts such as jarosite, that can form during the oxidation of sulfides and subsequent reactions. Such salts are capable of generating further acidity on dissolution or other chemical reactions (this acidity is referred to as 'retained acidity'). AASS and PASS as defined in the glossary refer to actual and potential acid sulfate soils, sediments and peats respectively.

ASS Tip 2 – Peat with pyrite

Some Western Australian peat deposits of the Swan Coastal Plain contain sulfides and high levels of arsenic (and other heavy metals). These peats are predominately inundated by groundwaters of high iron concentrations.

Levels up to 9350 moles H^+/tonne (15 %S) and 1100 mg/kg (arsenic) have recently been reported in these soils at 6–12 m AHD in the suburb of Stirling. The peats are up to 6 m thick and located near existing or historical wetlands. In situations where the peat has been drained, groundwaters (down hydraulic gradient of the disturbed site/s) have recorded pH values as low as 2.4, with arsenic and aluminium levels of up to 7.3 mg/l (note: typically less than 800 µg/L) and 200 mg/L, respectively.

Note: not all peats are estuarine in origin.

Generally, the ultimate source of inorganic acidity in ASS is pyrite, but other crystalline or amorphous iron sulfides can also generate acidity on oxidation; for brevity, ***sulfides*** and ***sulfidic*** are used throughout to refer to all these minerals and precipitates, and in context, may also refer to non-sulfidic soils containing acid-generating salts. Unless otherwise stipulated, ***%S*** refers to the percentage of oxidisable inorganic sulfur (by weight), and/or equivalent values for existing acidity, including acid-generating salts if any (see the *Laboratory Methods Guidelines* for description of methods to determine %S).

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[2] Only general directions and advice on how to achieve *best practice environmental management* are offered in these guidelines due to site-specific differences and the range of matters that need to be taken into account in deciding best practice. Achieving best practice environmental management is also reliant on the strategic planning, administrative systems, public consultation, product and process design, waste prevention, treatment and disposal and other measures instigated by the persons undertaking the works. *Best practice environmental management* is discussed in detail in the section on the *Environmental Protection Act 1994* in the *Legislation and Policy* chapter of the Manual.

[3] This definition may include some naturally acidic soils and peats with no past history involving iron sulfides. Such soils are not ASS but some management of acidity is still relevant.

Existing acidity may also refer to those soils with appreciable organic acidity without any detectable %S, but have an *in situ* pH of less than 5.5, and a Titratable Actual Acidity (TAA) greater than 18 moles H^+ per tonne (equivalent of 0.03 %S). The environmental management implications of these soils must be taken into consideration.

Throughout these guidelines soils are described using terminology consistent with McDonald *et al*. 1990 (The Yellow Book). Appropriate soil engineering terms in accordance with AS1726-1993 (Standards Australia 1993) may also be used to describe ASS. Administering authorities may need to be familiar with both classification systems. The term 'soils' also refers to sediments and peats.

Note: Once an ASS has been fully treated (including the safety factor), it is no longer considered to be an ASS. It is then available for use as bunding, preload, or fill etc.

ASS Tip 3 – Forms of acidity

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 (eg. Fe or Al^{3+} ions).

Retained acidity – acidity retained from sparingly and insoluble sulfur compounds (other than sulfides) that slowly produce acid (eg. jarosite, natrojarosite and tamarugite).

Existing acidity – includes actual acidity and retained acidity.

Potential acidity – acidity associated with the complete oxidation of sulfides (mainly pyrite).

Note: It is not uncommon for soils to have a mixture of the above forms of acidity, which may change forms during wetting, drying and aeration conditions that occur due to seasonal climatic changes and particularly after soil disturbance.

Refer to the *Laboratory Methods Guidelines* for further information.

2. PURPOSE OF THE GUIDELINES

The intent is to provide technical and procedural advice to avoid environmental harm and to assist in achieving ***best practice environmental management***[2] through the use of eight management principles (discussed later in section 3). The guidelines have also been designed to assist decision-making and provide greater certainty to the construction and agricultural industries, state and local governments and the community in carrying out planning for activities that may disturb ASS. It is anticipated that the guidelines will be used by consultants, earthmoving contractors, developers, agricultural and aquaculture producers, sand and gravel extraction operators, community groups and administering authorities from state and local government.

Regulators and assessment managers should also have regard to this intended use of the guidelines, and show caution in how they apply the recommendations to ensure that acceptable innovations in management practice are not discounted. The *Soil Management Guidelines* do not provide mandatory or inflexible standards; rather they seek to achieve acceptable environmental outcomes.

3. MANAGEMENT PRINCIPLES

The *Soil Management Guidelines* should be applied in accordance with the following management principles.

Management Principles

1. The disturbance of ASS should be avoided wherever possible.
2. Where disturbances 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; and
   - strategic reburial (reinterment)[4].

   Other management measures may be considered but must not pose unacceptably high risks.
3. Works should be performed in accordance with ***best practice environmental management***[5] when it has been demonstrated that the potential impacts of works involving ASS are manageable to ensure that the potential short and long term environmental impacts are minimised.
4. The material being disturbed (including the *in situ* ASS) and any potentially contaminated waters[6] associated with ASS disturbance, must be considered in developing a management plan for ASS and/or in complying with the ***general environmental duty***[5]**.**
5. Receiving marine, estuarine, brackish or fresh waters are not to be used as a primary means of diluting and/or neutralising ASS or associated contaminated waters[7].
6. Management of disturbed ASS is to occur if the ASS ***action criteria*** listed in Table 1 of these guidelines is reached or exceeded.
7. Stockpiling of untreated ASS above the permanent groundwater table with (or without) containment is not an acceptable long-term management strategy. For example, soils that are to be stockpiled, disposed of, 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*** listed in Table 1 should be treated/managed.
8. The following issues should be considered when formulating ASS environmental management strategies:
   - the sensitivity and environmental values of the receiving environment. This includes the conservation, protected or other relevant status of the receiving environment (eg. Fish Habitat Area, Marine Park, Coastal Management District and protected wildlife);
   - whether groundwaters and/or surface waters are likely to be directly or indirectly affected;
   - the heterogeneity, geochemical and textural properties of soils on-site; and
   - the management and planning strategies of Local Government and/or State Government, including Regional or Catchment Management Plans/Strategies and State and Regional Coastal Management Plans.

Figure 1. The eight Management Principles for ASS management.

[4] Within the preferred management strategies avoidance and minimisation of disturbance are the most preferred. The other strategies are not ranked in any order as many site specific factors need to be considered in determining the most appropriate strategy for a particular project.

[5] Refer to the **Queensland Acid Sulfate Soil Technical Manual, Legislation and Policy** chapter and the sections on the *Environmental Protection Act 1994, Fisheries Act 1994, Coastal Protection and Management Act 1995*.

[6] The term 'waters' includes river, stream, lake, lagoon, pond, swamp, wetland, unconfined surface water, unconfined water natural or artificial watercourse, bed and bank of any waters, dams, non-tidal or tidal waters (including the sea), stormwater channel, stormwater drain, roadside gutter, stormwater run-off, and any under ground water, and any part-thereof.

[7] Note that receiving waters are sometimes relied upon in broadacre remediation strategies where an existing acid or metal load is already posing a risk to the receiving environment. This will be covered in more detail in the *Remediation Guidelines*.

4. RISK ASSESSMENT OF DISTURBANCE

Projects involving the disturbance of ASS must assess the risk associated with disturbance through the consideration of both on- and off-site impacts. A thorough ASS investigation (in compliance with the *Sampling Guidelines*) is an **essential** component of risk assessment. Such an investigation is needed to provide information on the environmental setting, location of and depth to ASS, existing and potential acidity present in the soil, and soil characteristics. The *Sampling Guidelines* contains further information on ASS investigations, including staged approaches to assessment of large disturbances/developments. Successful management of ASS depends on the results of the investigation—and results from the investigation determine the most appropriate management strategy for a site.

For disturbances greater than 1000 m^3 and for disturbances affecting groundwater, it is recommended that a suitably qualified person experienced with ASS conduct the investigation and develop the management plan. Such a suitably qualified person would be a professionally accredited soil scientist (Queensland Government 2002).

All projects should consider ASS if they involve earthworks or disturbances to groundwater hydrology and/or surface drainage patterns, regardless of the project size. Small disturbances in high-risk areas can have considerable impact without appropriate management strategies, particularly if a number of smaller disturbances are occurring simultaneously in a catchment. Cumulative impacts from a number of smaller disturbances need to be considered.

The texture of the soil or sediment also influences the risk associated with a disturbance. Coarse-textured sulfidic sands may oxidise readily in an oxidising environment. Such soils have a higher permeability, facilitating an accelerated oxidation processes, with faster lateral movement of pore water or groundwater to transport leachate. Fine textured medium to heavy clays or silty clays, tend to oxidise at a slower rate than sandy soils and possess a higher buffering capacity. Clay soils often have substantially higher concentrations of sulfides than sandy soils.

ASS Tip 4 – Buffering capacity

A soil's buffer capacity is its capacity to naturally resist pH change (in this case during the production of acid by the oxidation of sulfides). Clays with a high cation exchange capacity (CEC) tend to have a higher buffering capacity than sands or other soils with low CEC. The presence of organic matter can also increase the buffer capacity of a soil. Highly effective buffering compounds in some soils are calcium magnesium carbonates (eg. fine shell, exo-skeletons).

If measured appropriately, the buffering capacity of a soil can be used to reduce the level of treatment, provided that particle size distribution and reactivity is also assessed.

In Queensland, ***action criteria*** define when ASS disturbed at a site will need to be managed (Table 1). ***Action criteria*** are based on the sum of existing plus potential acidity. This is usually calculated as equivalent sulfur (eg. s-TAA + S_{CR} in %S units) or equivalent acidity (eg. TAA + a-S_{POS} in mol H^+/tonne units)[8]. As clay content tends to influence a soil's natural buffering capacity, the ***action criteria*** are grouped by three broad texture categories—coarse, medium and fine. The ***action criteria*** for medium and fine textured soils is reduced to 0.03% oxidisable sulfur (%S) for projects where greater than 1000 tonnes of soil is being disturbed. A detailed management plan will be required for disturbances greater than 1000 tonnes.

[8] A combination of symbols/abbreviations is 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^+/tonne). Conversely, if TAA (mol H^+/tonne), 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*.

Table 1. Texture-based acid sulfate soil *action criteria* (after Ahern *et al*. 1998a).

Type of Material		*Action criteria* if 1 to 1000 tonnes of material is disturbed		*Action criteria* if more than 1000 tonnes of material is disturbed	
		Existing + Potential Acidity		Existing + Potential Acidity	
Texture range (McDonald *et al*. 1990)	Approx. clay content (%)	Equivalent sulfur (%S) (oven-dry basis)	Equivalent acidity (mol H^+/tonne) (oven-dry basis)	Equivalent sulfur (%S) (oven-dry basis)	Equivalent acidity (mol H^+/tonne) (oven-dry basis)
Coarse texture *Sands to loamy sands*	≤5	0.03	18	0.03	18
Medium texture *Sandy loams to light clays*	5–40	0.06	36	0.03	18
Fine texture *Medium to heavy clays and silty clays*	≥40	0.1	62	0.03	18

Oven-dried basis means dried in a fan-forced oven at 80–85°C for 48 hours.

Note that the ***action criteria*** refer to existing plus potential acidity for given volumes of ASS. The highest result(s) should always be used to assess if the relevant ***action criteria*** level has been met or exceeded; using the average or mean of a range of results is not appropriate. This issue is discussed in the *Sampling Guidelines.*

Note: If a soil shows evidence of self-neutralising or self-buffering eg. Titratable Potential Acidity (TPA) = 0 and the acid neutralising capacity (ANC) >S% using equivalent units, then a case may be made for reduced or no treatment (see ASS Tip 14 on self-neutralising soils).

4.1 Risk categorisation to guide management planning

Table 2 has been developed to assist in evaluating the environmental risk posed by ASS disturbance by identifying the level of treatment required to treat all existing and potential acidity resulting from such a disturbance. Five treatment categories (Low, Medium, High, Very High and Extra High) have been defined in the table, based on laboratory results and the weight of material to be disturbed. It should be noted that there is a general correlation between the level of treatment required and the environmental risk. There are additional factors that will also influence the level of treatment required including the nature of the works to be undertaken, the staging and duration of construction, the soil characteristics (eg. variability of sulfide concentrations, soil bulk density, physical characteristics such as texture, and self-neutralising capacity), surface and sub-surface hydrology, sensitivity of the surrounding environment, and the past history of the site.

Table 2 can also be used to define the total amount of fine agricultural lime (aglime)[9] required to neutralise the total existing plus potential acidity of a particular volume of soil, including the minimum industry safety factor of 1.5. Neutralisation agents other than fine aglime can be used to treat ASS. If other agents are being used, the figures in Table 2 will need to be adjusted accordingly. The tonnes of pure fine aglime (NV=100%) required for treating the total mass of ASS can be read off Table 2 at the intersection of the mass (tonnes) [row] and the existing plus potential acidity (converted to equivalent S% units) [column]. Where the exact weight or soil analysis figure does not appear in the heading of the row or column, interpolate between the respective values. The *Laboratory Methods Guidelines* contains information about appropriate laboratory methods to determine acidity.

[9] Aglime is a neutralising agent used to treat acidic soils; by composition, it is commonly 95–98% pure calcium carbonate, $CaCO_3$; it is sparingly soluble in pure water, and has a pH in water of ~8.3; application rates will depend on the purity and fineness of the product. More information is contained within the *Information Sheets* on *Neutralising Agents – Aglime*.

Management options other than neutralisation can be used to treat ASS, for example, material may be hydraulically separated or strategically reburied. However, the fine aglime requirement has been listed in the table because:

- it allows the treatment category to be easily selected by reading from Table 2; and
- 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; and
- it enhances the awareness of the proponent about the 'reality' of the extent and risk of the disturbance that they are planning (eg. it is easier for most people to visualise the management required to mix 25 tonnes of fine aglime through 900 tonnes of soil than it is to visualise the potential harm that may result from the acid that may be generated by 900 tonnes of soil containing 0.6 %S).

See section 8.3.4 for further information on calculating liming rates.

Table 2. Estimating treatment levels and aglime required to treat the total weight of disturbed acid sulfate soil – based on soil analysis (after Ahern *et al.* 1998a).

The tonnes (t) of pure fine aglime, $CaCO_3$ required to fully treat the total weight/volume of acid sulfate soils (ASS) can be read from the table at the intersection of the weight of disturbed soil [row] with the existing plus potential acidity [column]. Where the exact weight or soil analysis figure does not appear in the heading of the row or column, use the next highest value.

Disturbed ASS (tonnes) (≈m³×BD) †	**Soil Analysis# – Existing Acidity plus Potential Acidity (converted to equivalent S% units)**													
	0.03	***0.06***	***0.1***	***0.2***	***0.4***	***0.6***	***0.8***	***1***	***1.5***	***2***	***2.5***	***3***	***4***	***5***
1	0	0	0	0	0	0.03	0.04	0.05	0.1	0.1	0.1	0.1	0.2	0.2
5	0	0	0	0.05	0.1	0.1	0.2	0.2	0.4	0.5	0.6	0.7	0.9	1.2
10	0	0.03	0.05	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
200	0.3	0.6	0.9	1.9	3.7	5.6	7.5	9.4	14	19	23	28	37	47
250	0.4	0.7	1.2	2.3	4.7	7.0	9.4	12	18	23	29	35	47	59
350	0.5	1.0	1.6	3.3	6.6	10	13	16	25	33	41	49	66	82
500	0.7	1.4	2.3	4.7	9.4	14	19	23	35	47	59	70	94	117
600	0.8	1.7	2.8	5.6	11	17	22	28	42	56	70	84	112	140
750	1.1	2.1	3.5	7.0	14	21	28	35	53	70	88	105	140	176
900	1.3	2.5	4.2	8.4	17	25	34	42	63	84	105	126	168	211
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
10000	14	28	47	94	187	281	374	468	702	936	1170	1404	1872	2340

L	**Low treatment:** (≤0.1 tonnes lime)
M	**Medium treatment:** (>0.1 to 1 tonne lime)
H	**High treatment:** (>1 to 5 tonnes lime)
VH	**Very High treatment:** (>5 to 25 tonnes lime)
XH	**Extra High treatment:** (>25 tonnes lime)

Note: Lime rates are for pure fine aglime, $CaCO_3$ assuming an NV of 100% and using a safety factor of 1.5. A factor that accounts for Effective Neutralising Value is needed for commercial grade lime. (See the *Information Sheets* on *Neutralising Agents – Neutralising Considerations*).

† An approximate soil weight (tonnes) can be obtained from the calculated volume by multiplying volume (cubic m) by bulk density (t/m^3). (Use 1.7 if B.D. is not known.) Dense fine sandy soils may have a BD up to 1.7, and hence 100 m^3 of such soil may weigh up to 170 t. In these calculations, it is necessary to convert to dry soil masses, since analyses are reported on a dry weight basis.

Potential acidity can be determined by Chromium Reducible Sulfur (S_{CR}), Peroxide Oxidisable Sulfur (S_{POS}) and Total Oxidisable Sulfur (S_{TOS}). For samples with pH <5.5, the existing acidity must also be determined by appropriate laboratory analysis eg. Titratable Actual Acidity (TAA). Soils with retained acidity eg. jarosite or other similar insoluble compounds have a less available acidity and will require more detailed analysis. The amount of treatment required may be reduced if the self-neutralising capacity of the soil is appropriately measured. Consult the **Queensland Acid Sulfate Soils Technical Manual, Laboratory Methods Guidelines**.

4.2 Treatment categories

The treatment categories (Low, Medium, High, Very High and Extra High) are based on the weight of soil to be disturbed and the existing plus potential acidity present in the soils. The categories relate to managing risk by neutralisation of ASS so that there is no adverse impact on the receiving environment.

4.2.1 *Low level of treatment – category L*

For disturbances of ASS requiring treatment at a rate of less than 0.1 tonnes of fine aglime as per Table 2, the management should ensure:

- management of site runoff and infiltration; and
- treatment of soils according to their existing plus potential acidity with appropriate amount of neutralising agent (up to the equivalent of 0.1 tonnes of fine aglime).

Note: Neutralising agents other than aglime may be used, in which case the dosing rates need to be modified according to the neutralising value (NV) of the material.

4.2.2 *Medium level of treatment – category M*

For disturbances of ASS requiring treatment at a rate of between 0.1 and 1 tonne of fine aglime as per Table 2, the management should ensure:

- treatment of soils according to their existing plus potential acidity with appropriate amount of neutralising agent (up to the equivalent of 1 tonne of fine aglime);
- management of site runoff through bunding, and prevent or treat infiltration passing through ASS to groundwater during earthworks; and
- the fine aglime is thoroughly mixed with the soil.

4.2.3 *High level of treatment – category H*

For disturbances of ASS requiring treatment at a rate of between 1 and 5 tonnes of aglime as per Table 2, (and no alteration of the permanent groundwater table levels are involved[10]) management should include:

- more detailed plans of disturbance and detailed ASS investigation report;
- treatment of soils according to their existing plus potential acidity with appropriate amount of neutralising agent (up to the equivalent of 5 tonnes of fine aglime);
- ensuring that the fine aglime has been thoroughly mixed with the soil;
- providing bunding of the site using non-ASS material to collect all site runoff during earthworks;
- monitoring of pH of any pools of water collected within a bund (particularly after rain) and treating water to keep pH in the range 6.5–8.5 (or as per site specific conditions); and
- prevention of infiltration passing through ASS to groundwater or apply extra layer of aglime to intercept any infiltration from ASS.

> **ASS Tip 5** – Preventing infiltration
>
> Infiltration from any ASS stockpiling/treatment area can be reduced by providing a compacted clay liner. The liner might be constructed from limed clay, however this may reduce the efficiency of compaction and hence increase the permeability of the liner.

4.2.4 *Very high level of treatment – category VH*

For disturbances of ASS requiring treatment at a rate of between 5 and 25 tonnes of fine aglime as per Table 2, (and no alteration of the permanent groundwater table levels are involved[10]) then the proposed management should include (but not be limited to):

[10] More detailed environmental management will be required if the disturbance involves an alteration of the permanent groundwater table level, and in these circumstances, the disturbance should be categorised as requiring an Extra High level of treatment.

- more detailed plans of disturbance and ASS investigation report (using a higher laboratory analysis intensity if minimal laboratory analysis was undertaken);
- treatment of soils according to their existing plus potential acidity with appropriate amount of neutralising agent (up to the equivalent of 25 tonnes of fine aglime);
- verification that the ASS have been appropriately treated and that aglime has been thoroughly mixed with the soil;
- substantial bunding of the site using non-ASS material to collect all site runoff during earthworks;
- monitoring of pH of any pools of water collected within the bund (particularly after rain) and treat water to keep pH in the range 6.5 to 8.5 (or as per site specific conditions);
- prevention of infiltration passing through ASS to groundwater or apply extra layer of aglime to intercept any infiltration from ASS; and
- provide a simple but adequate environmental management plan based on the requirements outlined in *Environmental Management Plan Guidelines.*

Note: If the assessment manager judges that the proposed works are likely to alter the groundwater table of the area or that the site is close to an environmentally sensitive area (even if <5 tonnes of lime treatment are required), then the disturbance may need to be treated as Extra High level of treatment as below, ie. an environmental management plan may be required. Refer to the Water Treatment and Management Guidelines for guidance on treatment and management of surface and drainage waters.

4.2.5 *Extra high level of treatment – category XH*

For disturbances of ASS requiring treatment with greater than 25 tonnes of aglime as per Table 2 and/or where alteration of the groundwater table levels may occur, a comprehensive environmental management plan must be formulated. See *Environmental Management Plan Guidelines* for details on the content and format of comprehensive environmental management plans.

This plan should provide for ongoing management and monitoring of the effects of the disturbance of ASS through the entire construction or operation period of a project and describe the construction schedules and environmental management procedures. The disturbance should be staged so that the potential effects on any area disturbed at any one time are limited and easily managed.

ASS Tip 6 – EMPlans Vs EMPrograms

Environmental Management Plans (EMPlans) are often requested by local government to support a development proposal, or prepared by a proponent who wishes to demonstrate their ***general environmental duty*** effectively.

There is no statutory mechanism for approval of EMPlans, although they may be given legal standing by incorporation into a development approval through a condition of the approval (eg. under the *Integrated Planning Act 1997)*. EMPlans may be simple for smaller disturbances; however, the complexity increases with the level of risk for larger disturbances.

In comparison, Environmental Management Programs (EMPrograms) are a statutory tool under Part 3 of the *Environmental Protection Act 1994* and are approved or refused by the Environmental Protection Agency. An EMProgram is a specific program that is designed to achieve compliance with the *Environmental Protection Act 1994* by reducing the environmental harm of an operation (if it is currently in breach of the *Environmental Protection Act 1994*); or by detailing the transition of an operation to a particular environmental standard where it is known that compliance with the *Environmental Protection Act 1994*, Environmental Protection Policy or regulation cannot be attained as the operation moves towards the standard.

While the EPA can require an EMProgram to be submitted for assessment under certain circumstances, a proponent can also voluntarily submit them. Proponents of high-risk activities should be aware of this as the preparation of an EMProgram (instead of an EMPlan) may have benefits through the authorisation/approval of the activity. However, proponents need to be aware that it is a legal document and penalties may apply if not complied with; conditions can be imposed; approval may not be given; and that fees are associated with the assessment and administration of EMPrograms.

5. MANAGEMENT STRATEGIES

As outlined in the Management Principles 1 and 2 (see Figure 1), the preferred strategy to deal with ASS is **avoidance** (see section 6). Avoiding the disturbance of ASS should be considered at all sites. This may include a review of the construction design or layout. There will be situations where disturbance is **unavoidable.** For these situations, the following risk-based management strategies are preferred:

- minimisation of disturbance (section 7);
- neutralisation of acid sulfate soils (section 8);
- hydraulic separation on its own or in conjunction with dredging (section 9); and
- strategic reburial of <u>potential</u> ASS below the permanent groundwater table. This method alone is not suitable for soils with significant existing acidity (section 10).

Within the preferred management strategies avoidance and minimisation of disturbance are the most preferred. The other strategies are not ranked in any order as many site specific factors need to be considered in determining the most appropriate strategy for a particular project. It should be noted that even though the above management strategies are preferred, there are still environmental risks associated with the techniques. In addition, the strategies may not be suitable for every site.

Sections 7, 8, 9, and 10 outline the significant environmental risks associated with the particular management strategies. Sections 8, 9, and 10 outline the major management considerations associated with the particular strategies. Project managers will need to determine whether the issues raised in these sections apply to their sites. These lists are not intended to be comprehensive, and in some circumstances, other forms of environmental risk or management considerations may also be relevant. As a consequence, all projects should be subject to a risk assessment to determine the level of the environmental risk for the site.

Management strategies other than those listed as preferred may be considered; however where there is limited information on their successful implementation, there is an associated higher risk. Innovative management strategies that are neither described in these guidelines nor precluded, will need to be scientifically justified. Higher risk management strategies that are documented in section 11 include stockpiling ASS; strategic reburial of soils with existing acidity; large-scale dewatering or drainage; and vertical mixing. Strategies described as generally unacceptable in section 12 include above ground capping; hastened oxidation; seawater neutralisation and offshore disposal of ASS.

In a new disturbance, any potential or existing acidity should be fully treated, and the receiving environment (eg. seawater) should not be relied upon as a primary means of treatment. A possible exception to this principle may be the case of remediation of a disturbed site where the disturbance occurred prior to 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 options (eg. broadacre acidity associated with agricultural production). In such situations, some of the strategies with higher risk may be permitted (if there is no viable alternative and it can be demonstrated that existing risk to the environment can be lowered by this means). See the *Remediation Guidelines*.

Larger developments (eg. >5000 tonnes of soil disturbance) should be staged to ensure that the disturbance is manageable. In addition, to reduce the level of risk a variety of management strategies may be utilised to provide the most appropriate management for the specific soil type or situation. For example, hydraulic separation might be used to treat soils extracted from sandy areas; and fine textured soils with low levels of sulfides could be neutralised with a suitable neutralising agent; and areas with high levels of sulfides and heavy, hard-to-treat clays could be strategically reburied or 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).

In managing risk and selecting preferred management strategies in situations where all relevant approvals have been obtained, it is still the responsibility of the developer/operator to satisfy themselves 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/operator will have a greater level of assurance of the impact that will be accepted by government.

6. AVOIDANCE STRATEGIES

Avoiding the disturbance of ASS is always the most preferred option; it carries the least environmental risk, as ASS are inert as long as they remain in an anoxic, preferably anaerobic (reducing) environment. It is also often the cheapest option, as the risks and costs associated with long-term discharge of acid, iron or aluminium leachate, the potential for degradation of aquatic ecosystems, remediation costs, delays associated with development approvals, and the potential long-term management and monitoring requirements may outweigh the benefits of major earthworks.

Documented evidence should be provided that avoiding the disturbance of ASS has been seriously considered at all sites and sound reasons identified for choosing to disturb ASS.

6.1 Planning to avoid ASS

In areas that have a high probability of containing ASS, local government planning strategies should, as far as practicable, give preference to land uses that avoid or minimise the disturbance of ASS. Land uses such as extractive industries, golf courses, marinas, canal estates, agriculture uses requiring drainage systems and land uses with car parking, storage etc. below ground level which are likely to result in significant amounts of excavation or filling, should be avoided in high probability areas. However, where the ASS occur at a significant depth, the above land uses may be appropriate if they are unlikely to result in the disturbance of ASS layers. This issue is further explained in the *State Planning Policy 2/02 Guideline: Planning and Managing Development involving Acid Sulfate Soils*.

In situations where the ASS investigation has identified high levels of sulfides in the soil (ie. significantly above the ***action criteria)***, it may be appropriate to investigate the use of alternative development sites, or alternative sites to locate drains, roads, pipelines, or agricultural enterprises etc (Ahern *et al.* 1998b). Refer to section 4.1 for advice on how to determine when levels of sulfides are significantly high.

6.2 Cover *in situ* soils with clean fill

If groundwater levels are not affected by earthworks, undisturbed *in situ* PASS can be covered with clean fill. This strategy can be used to provide adequate depth for building foundations, infrastructure trenches or other incidental excavations such as swimming pools if the sulfides are located close to the soil surface (Ahern *et al.* 1998b). A minimum depth of fill for residential development cannot be specified. It will be related to the depth to ASS, concentrations of sulfides, flood levels, proposed land use and depths of any future disturbance. It is always preferable to use clean non-ASS fill rather than using treated ASS on site from a risk minimisation point of view.

Filling activities may disturb *in situ* ASS by:

- bringing AASS into contact with the groundwater (and thus potentially mobilising and transporting existing acidity out of the AASS into the groundwater);
- displacing or extruding previously saturated PASS above the groundwater table and aerating these soils or sediments[11]; and/or
- raising acidic groundwater tables with the short-term release of acid into waterways.

See Figures 2 and 3.

Loading fill on clayey ASS can be problematic because some clayey soils have a high water content (up to 70 to 80% on a volume basis), and low hydraulic conductivities. Under load, such clayey soils may flow like gels resulting in subsidence at the load point. Some of the displaced soils may be pushed upwards outside the load areas into oxidising environments. In extreme

[11] For example, aeration may occur at the margins of the filling area if the weight of fill exceeds the failure limit of the underlying soil or sediment.

situations, the fill materials may sink into the mud. This is of particular concern in areas where houses, rail, roads or other heavy infrastructure is constructed on such material. This can also be an issue in poorly managed dredging sites where dredge fines are placed above the groundwater table and buried under clean sands. Historic dredging sites should be investigated for the presence of such materials prior to making changes to land use that may cause such subsidence.

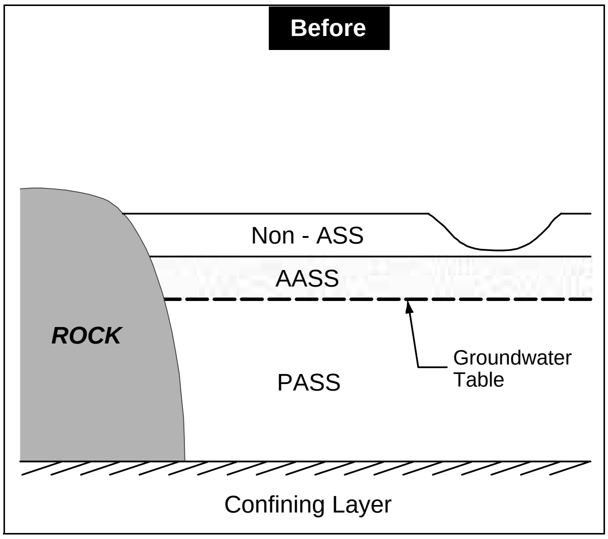

Figure 2. Schematic cross-section of an ASS prior to filling. AASS is above the groundwater table; and PASS is below the groundwater table.

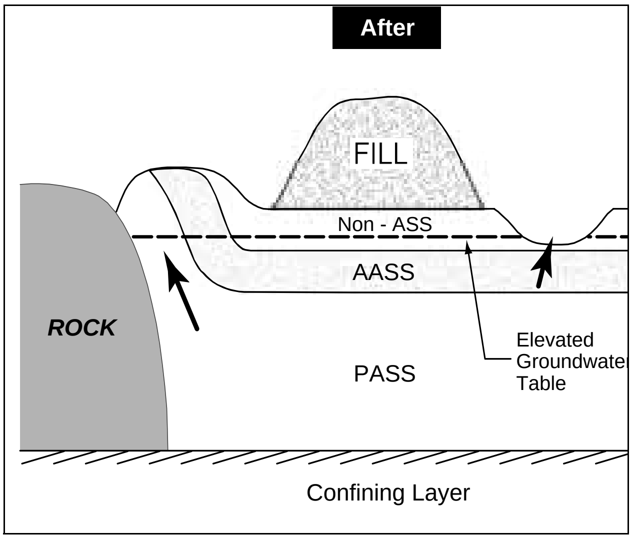

Figure 3. Schematic cross-section of an ASS after filling. The groundwater table is raised, the AASS is brought into contact with the groundwater, and PASS and AASS are displaced above the groundwater table.

Both geotechnical and hydrological investigations may be necessary to assist in devising management strategies including any pre-loading and management of potential impacts on groundwater levels and acidity. See the *Water Treatment and Management Guidelines* with respect to hydrological investigations.

Untreated ASS should not be used as pre-load material. Refer to section 11.1 on stockpiling acid sulfate soils.

7. MINIMISATION OF DISTURBANCE

The minimisation of disturbance is a preferred management option where disturbance of ASS is unavoidable. Several strategies that minimise disturbance of the soils themselves and the groundwater are available. Completion of a detailed ASS investigation is essential for minimisation of disturbance to be effective. This includes an assessment of the concentration and spatial distribution of potential and existing acidity, and groundwater characteristics. Refer to the *Sampling Guidelines*. Once the site has been adequately characterised, alternative strategies that minimise the disturbance can be investigated. The following list provides strategies to minimise disturbance of ASS.

7.1 Redesign earthworks layout

Areas may contain relatively low, or negligible levels of sulfides, within the boundaries of some sites, while ASS with high levels of sulfides can dominate other areas within the site. An effective minimisation strategy may entail the redesign of an earthworks plan or agricultural enterprise to avoid the ASS with high levels, and focus disturbance into the areas containing low or negligible levels of sulfides. It should be noted that agricultural enterprises should avoid cropping sandy soils with high levels of sulfides, especially if the sulfides are located close to the surface. However, this approach is likely to be suitable for large construction sites or farms containing variable soil types. Alternative uses such as ‘open space’ or wildlife corridors may be allocated to the areas of high sulfide concentration. Conversely in situations where avoidance of all ASS is not possible and the project is to proceed, then the earthworks should be designed so areas with the highest levels of sulfide are not or minimally disturbed, and overall ASS disturbance is minimised (Ahern *et al*. 1998b).

Unfavourable soil texture is another reason to avoid certain areas as soil textures may dictate which management techniques will be associated with the lowest risk and be the most effective. For example, an important consideration is how the material would be extracted. Sandy areas might be considered lower risk for extraction as the sandy material could be removed using a floating dredge allowing the groundwater table to be maintained, and the soils might then be treated by hydraulic separation techniques.

On the other hand, extraction of large areas of clay material that is difficult to work would require dewatering or drainage of large areas to permit dry excavation. Dewatering/drainage poses a higher risk to drainage of adjacent *in situ* PASS, which may then require remediation. In such circumstances higher risk and even more intensive management would be involved. Clays may be difficult to break up to allow effective treatment by neutralisation or hydraulic separation. In such cases, it is soil texture rather than its geochemistry that establishes the level of risk and design motivation.

For this approach to be successful, detailed ASS investigations, soil type investigation, planning for future management, stratigraphic mapping of the sediments and an understanding of groundwater hydrology and oxidation are necessary. See the *Sampling Guidelines* and *Water Treatment and Management Guidelines.*

7.2 Shallow disturbances

The extent of earthworks on site can be altered to ensure that only shallow disturbances are undertaken and the ASS remains undisturbed. This strategy relies on an in-depth understanding of the spatial distribution of ASS, and is only viable in situations where sulfidic soils are located in the deeper horizons within a soil profile.

7.3 Redesign existing drains

> **ASS Tip 7 –** Acid export
>
> The drainage system is often the conduit for acid export from the system. Thus by reducing or eliminating the number of drains in a given area, the rate of acid export should also reduce.

Existing drains may need to be redesigned so that they are shallower and wider and do not penetrate the sulfide layers. Shallow and wide drains can increase the efficiency of surface water drainage, while reducing the drain density (number and spacing of drains) and drain depth. Hydrological studies may be required to ensure the drains 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 (Ahern *et al*. 1998b). Laser levelling of a paddock is a tool frequently used to accompany the redesign of existing drains to enhance surface water drainage. However, avoid scalded areas, the base of existing drains, and areas where the sulfides are <0.5 m below soil surface. If the sulfides are >0.5 m from the soil surface, the vertical distance between the lower level of cut and the sulfides should be at least 0.5 m (Tulau 2000). In situations where the sulfides cannot be avoided, these areas should be neutralised before earth works associated with laser levelling commences.

The relevant local government should always be consulted and appropriate permits obtained prior to undertaking any works that may change floodwater hydrology. Soils excavated to fill drains may require neutralisation (eg. with fine aglime) or may need to be sourced from off-site.

7.4 Minimise groundwater fluctuations

> **ASS Tip 8 –** Livestock and ASS
>
> Cattle, other livestock and feral pigs accessing creeks can contribute to the erosion of streambanks and pugging of surface ASS. This can expose additional ASS and accelerate the export of acid leachate.

Activities that result in fluctuations of groundwater and in particular permanent lowering of the groundwater table should be avoided, as these may lead to exposure of *in situ* sulfidic soils to oxygen. Acidic flushes can be brought to the surface as a result when the groundwater rises again or through evapotranspiration or as a result of fill emplacement. There are also possible health affects caused by ASS impacts on groundwater, particularly arsenic contamination, which has recently been identified as a significant issue in Western Australia and is currently a major problem in Asia (see the *Water Treatment and Management Guidelines*). It is preferable to maintain the groundwater levels in a steady state and works to be avoided include:

- construction of deep drains and canals which unnecessarily lower the groundwater table;
- operation of drains which do not have gates or 'drop boards' to maintain groundwater levels;
- significant water level fluctuations during dry periods caused by the operation of drains;
- installation of new groundwater extraction bores in ASS areas, and use of existing groundwater extraction bores if they will expose ASS to oxidising conditions, or if it will result in the dispersal of waters containing acid and metals to locations that may result in further contamination of the receiving environment;
- uncontrolled groundwater extraction and drawdown from bores[12];
- dewatering or drainage of construction sites, mines, or sand and gravel extraction pits[13];
- changes in vegetation type from pastures to trees, or replacement of native vegetation with crops that can increase transpiration rates and lower the groundwater table during dry periods, and/or cause rises in acidic groundwater tables; and
- construction of on-farm water storages, sediment/nutrient ponds or ponded pastures in acid sulfate soils.

(modified from Ahern *et al*. 1998b).

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[12] Controls on overall abstraction, 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 dewater should dewater small isolated cells with sheet-piling or similar devices. Dewatering can also be carried out in a number of steps to allow material to be skimmed off at the watertable in a number of increments. See section 11.3.

The *State Coastal Management Plan – Queensland's Coastal Policy August 2001* identifies that loss of groundwater quality can have impacts on the quality of coastal waters and on coastal ecosystems such as wetlands. One of the ways that groundwater is increasingly affected in the coastal zone includes lowering of groundwater table levels through activities such as draining, and contamination from acid sulfate soil leachate and iron. Policy 2.4.5 requires that "*Land uses and activities are not to lower the groundwater table to expose acid sulfate soils*….".

8. NEUTRALISATION OF ACID SULFATE SOILS

A technique commonly used in ASS management is neutralisation where alkaline materials are physically incorporated into the soil. Sufficient neutralising agent(s) needs to be used to ensure that there is the capacity to neutralise all **existing** acidity that may be present and all **potential** acidity that could be generated from complete oxidation of the sulfides over time. *Note: if there is existing acidity, no effective natural buffering capacity remains.*

8.1 Environmental risk

There can be significant risks to the environment if a neutralisation treatment is poorly managed. The following issues that can effect the environmental risk need to be considered when neutralisation treatment is being proposed.

8.1.1 *Soil texture*

There are inherent risks associated with the neutralisation of coarse sandy soils as these soils may dry quickly and oxidise within hours of exposure to air. If there is a rainfall event while the soils are stockpiled the generated acid 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 have a similar appearance. In high rainfall areas such as far north Queensland or through coastal Queensland in the wet season it may be particularly difficult to dry and treat these soils. A pilot trial may be appropriate to demonstrate 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.

Monosulfidic black oozes are reactive gels that accumulate in waterways. They can be difficult to work, treat and dry, and can oxidise readily once in contact with oxygen.

ASS Tip 9 – Monosulfidic black oozes

Monosulfidic black oozes are highly reactive organic-rich gels with extremely high moisture contents. They are commonly enriched in ultra-fine grained reactive iron sulfides eg. amorphous FeS, greigite $\approx Fe_2S_3$ and mackinawite $\approx Fe_9S_8$, which are intermediate products in the formation of pyrite. Monosulfidic black oozes may also contain pyrite. They can form as thick accumulations (eg. greater than 1 m thick) in drains and waterways that drain ASS landscapes, and are easily mobilised or resuspended during runoff events. Monosulfidic black oozes can oxidise readily once exposed to oxygen, and can cause severe acidification and/or deoxygenation of floodwaters (Sullivan and Bush 2002; Bush *et al. 2002*). The management of monosulfidic black oozes warrant special attention in any environmental management strategy.

8.1.2 *Neutralising agents*

Gypsum and other by-products of sulfide oxidation may form coatings on the grains of the neutralising agent during neutralisation. These coatings may reduce the neutralising capacity of the agent and can affect the level of risk associated with large-scale neutralisation.

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 levels of alkalinity that may impact on the receiving environment. Soluble neutralising agents may also be more readily flushed from the system before full oxidation of the PASS occurs. There are additional workplace health and safety issues associated with soluble neutralising agents such as hydrated lime and quicklime, CaO.

8.1.3 *Dewatering or drainage*

Large sites utilising the neutralisation treatment are sometimes dewatered for considerable periods to allow dry excavation. Dewatering or drainage poses a high risk to adjacent *in situ* PASS and these will then require remediation if oxidation occurs. This process is discussed further in section 11.3.

8.1.4 *Impacts on wildlife*

Ideally, ASS in or adjacent to the habitat of particularly sensitive protected species (eg. acid frogs and fish) should **not** be disturbed due to the potential threat to the species. Provisions of state legislation including the *Nature Conservation Act 1992*, and protection of environmental values under the *Environmental Protection Act 1994*, and the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* must be addressed when making decisions that may impact on protected species. See the chapter on *Legislation and Policy*.

Mildly acidic aquatic environments occur naturally in some coastal areas and treatment by neutralisation may impact on these areas if incorrectly administered. This can increase the inherent risks of using this technique in coastal areas. Greater detail on both these risks and managing them is provided in the *Water Treatment and Management Guidelines.*

8.2 Performance criteria and verification testing

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

1. The neutralising capacity of the treated soil must exceed the existing plus potential acidity of the soil; and
2. Post-neutralisation, the soil pH is to be greater than 5.5 (see section 8.3.2 regarding upper limit of pH range); and
3. Excess neutralising agent should remain within the soil until all acid generation reactions are complete and the soil has no further capacity to generate acidity[14].

Samples of the treated soil should be taken and laboratory analysed to demonstrate compliance with the performance criteria (ie. verification testing).

These performance criteria equate to there being no net acidity in the soil following neutralisation. Soil that has been treated by neutralisation techniques and has not met these criteria must be re-treated until the above performance criteria are met.

8.3 Management considerations

When neutralisation treatment is proposed as a form of ASS management, the following issues are important to consider.

8.3.1 *Site characterisation*

It is essential to undertake an accurate and thorough Phase 1 ASS investigation (ie. pre-excavation sampling and laboratory analysis in compliance with the *Sampling Guidelines* of this Manual). Adequate Phase 1 sampling prior to earthworks must be completed to provide decision-makers with sufficient information on which to confidently conclude that the soils can be managed in an ecologically sustainable manner. The level of Phase 1 sampling is likely to vary depending on the site and proposal. Phase 2 (ie. sampling and laboratory analysis during excavation), and Phase 3 (ie. verification sampling and laboratory analysis of treated material after earthworks to ensure appropriate rates of neutralising agents are applied for soil neutralisation) sampling are also a

[14] Choice of an appropriate neutralising agent is important to achieve this long-term performance criterion (see section 8.3.3).

significant component of such a management strategy. Phases 1, 2 and 3 sampling options are discussed in more detail in the *Sampling Guidelines*.

The better the characterisation of the site, the better the understanding of the stratigraphy of the soils on site, and the lower the environmental risks if a large volume of material is to be neutralised.

8.3.2 *pH range*

The solubility of iron and aluminium is controlled in part 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. McElnea and Ahern (2000) demonstrated that leaching of iron and aluminium can be controlled by maintaining the soil pH above 5.5 with fine aglime. Consequently the pH of soil needs to be raised above 5.5 when neutralising ASS; an upper pH limit of 8.5 should not be exceeded. The upper limit may need to be lower if revegetation with native pH-sensitive flora is proposed or if a lower pH is more appropriate to the surrounding environment.

Coastal soils in some locations within Queensland may have a natural pH of 8.5 or greater. These soils should not be treated with an agent to reduce the pH below 8.5.

ASS Tip 10 – Redox potential

The redox potential is a quantitative measure of the tendency of a particular system to accept or donate electrons (ie. produce or maintain reducing or oxidising conditions). For some iron reactions, solution pH and redox potential determines the stable phase (Willett 1983).

This is a complex issue but in general, reducing conditions prevail in the absence of oxygen and the presence of organic matter and/or sulfate reducing bacteria. Oxidising conditions prevail when the material is in direct contact with air or permits the ready diffusion of oxygen into soil masses. Other oxidising or reducing agents can also occur in the soil or the soil water.

8.3.3 *Neutralising agents*

A variety of neutralising agents are available to increase the pH of soil to acceptable levels and neutralise potential and/or existing acidity from the oxidation of sulfides. Factors to consider when choosing a neutralising agent include solubility, pH, neutralising value, fineness/coarseness of the product, Ca:Mg balance of the soil, spreading and transport costs, and chemical composition and purity of the agent.

Fineness and Effective Neutralising Value (ENV) are particularly important in ASS management. By-products of sulfide oxidation (particularly gypsum and iron and aluminium compounds) may form insoluble coatings on the neutralising agent (particularly larger limestone or marble particles). Such coatings reduce the neutralising capacity of the agent.

Neutralising agents for treating ASS should be slightly alkaline, with a low solubility, and a pH ranging from 7 to 9. Such products will not flush out with the first heavy rain event, and have minimal potential to contaminate surrounding waterways and groundwater. The preferred agent for treating ASS is fine aglime, $CaCO_3$. However, there can be difficulties in effectively mixing fine aglime with wet, lumpy, clayey or cohesive sediments. Furthermore, wind or water erosion of stockpiles must also be prevented to minimise impacts on receiving environments. Other agents with low solubility include dolomite $(Ca,Mg)CO_3$, magnesite $MgCO_3$ and burnt magnesite MgO. Caution must be taken with these magnesium compounds as they can react to produce magnesium sulfate during neutralisation reactions. Magnesium sulfate is quite soluble and may impact on water quality in waterways if large quantities are involved. The production of calcium sulfate (gypsum) during neutralisation reactions involving fine aglime avoids such environmental problems because of its lower solubility (Ahern and Watling 2000).

ASS Tip 11 – Common oxidation and reaction products

There are a number of variables affecting the oxidation of sulfides, and the reactions are complex. Common oxidation and reaction products are listed below. However, there are many more reactions and compounds that occur in ASS.

- 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 and a value chroma of 6 or more (see the Munsell colour chart); are relatively insoluble, and are stable at low pH and under dry conditions;
- Gypsum $Ca_2SO_4.2H_2O$ is formed in ASS by reaction between the acid and calcium carbonate. It has moderate solubility;
- Iron products can include the soluble ferrous iron Fe^{2+}, highly reactive ferric iron 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 eg. tamarugite $NaAl(SO_4)_2.6H_2O$.

More soluble neutralising materials such as hydrated lime, $Ca(OH)_2$ or sodium bicarbonate $NaHCO_3$ can be used to neutralise acidity at depth in soil profiles where excavation and mechanical mixing are not feasible. However, there may be potential risks to the environment (and workers) when such products are used. Subsequent rain events also may 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 and 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 3 (see section 8.2).*

Other neutralising agents such as red mud, cement kiln dust, crushed concrete and other industrial by-products may be appropriate for some sites, subject to their associated risks being addressed. For more detailed discussion on specific neutralising agents, refer to the *Information Sheets* on *Neutralising Agents.*

8.3.4 *Aglime requirements*

Calculations of fine aglime requirements to effectively treat soils can be obtained from Table 3. It is important to remember that the fineness, purity of the neutralising agent and its neutralising value need to be considered when determining liming rates. For example fine aglime typically has an acid neutralising value of about 97% $CaCO_3$. Accordingly a correction factor of 100/97 = 1.03 needs to be applied to reach the equivalent of pure fine aglime.

ASS Tip 12 – Lime use and sustainability

It should be noted that the use of lime products to treat ASS will generate carbon dioxide in production, transport, spreading and in neutralisation reactions. This may be a consideration in selecting the management strategy for large disturbances. Larger sites may also need to consider measures to reduce greenhouse gases eg. planting and maintenance of local endemic trees.

ASS Tip 13 – Liming rates

The formula to calculate liming rates is:

%S *x* 30.59 *x* 1.02 *x* 1.5 = kg $CaCO_3$/tonne of soil

Note: 30.59 converts to H_2SO_4; 1.02 converts to $CaCO_3$; and 1.5 is the safety factor

To convert units from tonnes to cubic metres, multiply the kg $CaCO_3$/tonne of soil by the bulk density

To change units from %S to mol H^+/tonne, multiply the %S by 623.7

Table 3. Acid sulfate soil conversion rates for calculating liming requirements.
(based on 1 mol sulfides producing 2 mol sulfuric acid)

Oxid. Sulfur S%	**moles H^+/kg** (S% x 0.6237)	**moles H^+/tonne or moles H^+/m^3** (S% x 623.7)	**kg H_2SO_4/tonne or kg H_2SO_4/m^3** (S% x 30.59)	**kg $CaCO_3$/tonne soil or kg $CaCO_3/m^3$** Safety factor = 1.5
0.01	0.0062	6.237	0.306	0.47
0.03	0.0167	18.71	0.92	1.4
0.05	0.0312	31.19	1.53	2.3
0.06	0.0374	37.42	1.84	2.8
0.1	0.0624	62.37	3.06	4.7
0.2	0.1247	124.7	6.12	9.4
0.3	0.1871	187.1	9.18	14.0
1.0	0.6237	623.7	30.6	46.8
2.0	1.2474	1247	61.2	93.6
3.0	1.8711	1871	91.8	140
5.0	3.1185	3119	153	234

Note: Assumes a bulk density of 1.0 g /cm^3 (1 tonne/m^3); bulk density generally ranges between 0.7 to 2.0, but can be as low as 0.2 for peats. Where bulk density is >1 g/cm^3 (or 1 tonne/m^3), then the correction factor for bulk density will need to be used. This increases lime requirements (eg. if BD=1.6, then 1 m^3 of soil with 624 moles H^+/tonne (1.0 %S) will require 75 kg lime/m^3 instead of 47 kg). Correction factors for lime purity, neutralising value and effective neutralising value may also be required.

8.3.5 *The safety factor*

Soils require neutralisation with an agent at 1.5 to 2 times the theoretical acid production potential. 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 and 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.

ASS Tip 14 – Self-neutralising soils

Some ASS are partially or completely 'self-neutralising' due to an abundance of naturally occurring calcium or magnesium carbonates (eg. crushed shells, skeletons, coral, foraminifera[15]). The self-neutralising potential of a soil is an environmental safeguard. In calculating the neutralising capacity of these soils, shell size needs to be taken into consideration. The finer the shell, the more reactive. Generally, the neutralising capacity of shells <2 mm is more effective, due to large unit surface area. On larger shells, there will be a smaller unit surface area and hence gypsum and insoluble coatings of iron and aluminium are more likely to retard complete reaction.

Laboratory methods can be used to detect the presence of carbonates, however if fine grinding is used during sample preparation, the neutralising component will appear more reactive than it will be in the field for reasons discussed earlier. Shells greater than 2 mm need to be removed prior to analysis. This can be relatively easy for sands, but this may be more difficult for wet clays. If the shells >2 mm can be removed, techniques are available to determine the fine (<2 mm) shell content of soils.

These soils may still require the addition of neutralising agents due to the potential for incomplete reaction of shells through either fineness or formation of coatings. The need for additional neutralising agents will need to be assessed on a site-by-site basis. In addition, the once common procedure of determining Acid Neutralising Capacity (ANC) by applying excess mineral acid and back titrating unreacted acid can give an inflated ANC, depending on the method used.

Ahern *et al.* (1998b) stated that an excess of neutralising agent within the soil tends to prevent a build up of extreme acidity within the soil despite some oxidation occurring as a result of the drying of the sediments. Furthermore, bacterial assisted oxidation may occur in disturbed ASS when the pH is less than 4, accelerating oxidation by a factor of 10^3 if oxygen is readily available. Consequently, the acid production rate will be kept low if the pH is maintained at levels greater than 5.5. This will also favour more complete neutralisation of acid by the added neutralising

[15] Marine protozoa contain various amounts of calcite, and hence can contribute to the neutralising capacity of soils. When present in large quantities the soil may be self-neutralising. Foraminifera have been found in some soils at East Trinity near Cairns.

agent. Thus, an excess of neutralising agent in the soil is important. Table 2 and 3 in these guidelines have incorporated a safety factor for fine aglime requirements.

It should be noted that fine aglime, $CaCO_3$ is impure in most situations. Consequently, higher quantities of fine aglime will be required to neutralise the soils than what is stated in Table 3. The effective neutralising value of coarser aglime (>0.03 mm) is further reduced by the coarser grainsize (ie. there is lower grain surface area available for reaction). Procedures to account for impurity and coarseness are detailed in the *Information Sheets* on *Neutralising Agents*. *Note: the safety factor does not take these into account.*

8.3.6 Treatment pad design

For treatment of large volumes of material, neutralisation should be carried out on a treatment or liming pad. The following issues should be considered in the treatment pad design.

Guard layers

A guard layer of neutralising agent should be spread onto the soil surface of the treatment pad prior to the placement of soils (see Figure 4). This will reduce risk by neutralising acidic leachate generated in the treatment pile and not neutralised during the treatment process. This is especially relevant to the first layer of ASS that is placed for treatment prior to application of the neutralising agent. The guard layer will assist in protecting groundwater quality. To further reduce risk, a layer of compacted non-ASS clayey material (0.3–0.5 m thick) might be placed on the surface of the treatment pad and below the guard layer to restrict infiltration from the material being treated. In fully contained situations a physical barrier may be used as an alternative to a guard layer of neutralising agent as a means of protecting groundwater quality and preventing infiltration of acidic water; eg. a bunded concrete slab, paved area or layer of bitumen may be placed under a temporary treatment pad.

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 that is passing though the treatment pile may channel its flows through preferred paths, whereby only a fraction of the guard layer is intercepting and neutralising potential acid flows;
- it is difficult to ensure that there has been adequate mixing of the neutralising agent with the soil; and
- 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.

ASS Tip 15 – Guard layer rate

The rate of neutralising agent used in the guard layer (per square metre) should be based on 0.2 times the average of the potential and existing acidity for every metre depth of the soil to be treated (ie. if 2 metres of soil are to be treated in the treatment pad, then twice 0.2 times the neutralising agent required to neutralise the acidity should be spread as a guard layer). The safety factor of 1.5 to 2 is recommended for all guard layers. The safety factor may need to be increased for sands and for treatment pads that are adjacent to environmentally sensitive areas. For example:

- S_{CR} = 1.9%
- TAA = 125 mol H^+/tonne
- Existing + Potential Acidity = (125 ÷ 623.7) + 1.9 = 2.1%
- 0.2 times the average of the potential and existing acidity = 0.2 x 2.1% = 0.42 %S
- Depth of soil on treatment pad = 2 m
- The situation would require 39 kg $CaCO_3/m^2$ of soil as the guard layer for 2m (vertical) of fill

In all cases a minimum of 5 kg fine aglime per m^2 per vertical metre of fill should be used in the guard layer.

See the *Laboratory Methods Guidelines* for information about determining existing and potential acidity.

The guard layer should be employed as a precaution to neutralise acidity that has not been adequately treated during the soil neutralisation process.

The rate of neutralising agent used in the guard layer will depend on the final treatment pile height, existing and potential acidity of the sediments, and the soil texture. The rate may need to be increased where the receiving environmental values warrant higher protection. The rate may also need to be increased to enable a neutralising agent to be incorporated in situations where significant delays occur in drying soils due to soil texture or climatic conditions.

Note: Reapplication of the guard layer may be necessary under temporary treatment pads, if the guard layer is disturbed or removed with the treated soil.

Soil treatment

Soils may be neutralised on a temporary treatment pad or alternatively the soils may be neutralised as they are placed permanently. Essentially, treatment of the soils is the same process whether it is performed on a temporary treatment pad, or on a treatment pad in their permanent location. Treating soils on a temporary treatment pad may promote better mixing of the neutralising agent with the soil as the soils and agent may be further mixed as they are moved. However, there is the added expense of double handling of the soil.

> **ASS Tip 16 –** Depth of soil
>
> If wet materials are being placed, shrinkage may be allowed for. To allow for shrinkage, layers of greater depth may be initially placed.
>
> Ultimately it is up to the contractor to ensure that they have appropriate equipment to incorporate the neutralising agent to the depth of fill.

Acid sulfate soil material should be placed on top of the guard layer in 150 to 300 mm thick layers on the treatment pad, to allow drying. The appropriate amount of neutralising agent, including the calculated safety factor should be spread once the ASS are sufficiently dry. The ASS may require reworking several times to achieve adequate mixing of the neutralising agent and/or drying of the soil. The treated layer will require Phase 3 sampling (ie. verification analysis) to confirm whether appropriate amounts of the neutralising agent have been incorporated into the soil, which should be subsequently compacted before treatment of the next layer commences, or when moved to the permanent placement area if initially mixed on temporary treatment pads.

Guard layers may need to be applied between each compacted ASS layer as a precaution in environmentally sensitive areas, areas with high levels of sulfides or where soils are difficult to mix.

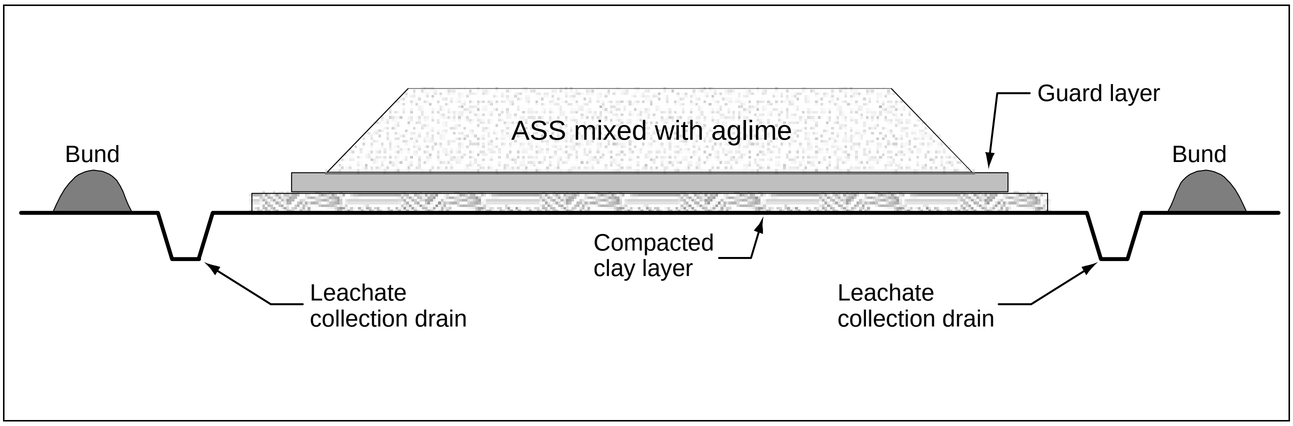


Figure 4. Schematic cross-section of a treatment pad, including a compacted clay layer, guard layer, leachate collection system and containment with bunding.

Containment
Stormwater runoff should be contained within treatment pads by appropriate bunds and may be collected in a sump. Diversion drains should be installed to prevent stormwater run-on into the treatment pad. Surface liming of earth bunds and diversion drains can assist with neutralising 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 an appropriately low permeability to avoid leakage.

Earthworks strategy
An earthworks strategy should be formulated to ensure that sufficient space is available to accommodate the number of treatment pads required to allow adequate drying and treatment of the ASS. Expected rates of throughput in m^3, drying, mixing and compaction times along with the capacity of the treatment pads to accept the materials, need to be identified in any strategy.

The earthworks strategy should also ensure that adequate time is available to obtain the results of Phase 3 testing (ie. verification testing) before treatment of the next layer begins. Climate, seasonal conditions, and soil texture may affect drying and treatment rates and hence the size of treatment pads required.

Spatial tracking
The accurate spatial tracking of large volumes of ASS during the neutralisation process (eg. survey with a hand-held Global Positioning System (GPS), differential GPS, designated lot numbers or conventional survey, depending on the level of accuracy required), is essential to ensure that initial soil testing can be correlated with prescribed treatment and any required Phase 3 sampling (ie. verification testing). Some sites may have difficulty developing an appropriate tracking program, due to spatial constraints. In such situations, alternative management and treatment facilities should be developed.

8.3.7 *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 volumes 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. 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 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 require cleaning and maintenance from time to time. See the *Water Treatment and Management Guidelines* for more information.

It is inappropriate to apply neutralising agents into natural watercourses or water bodies unless carefully planned and approved. Refer to the *Remediation Guidelines.* 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 or black water[16] creek ecosystems. Refer to the *Water Treatment and Management Guidelines* for more information.

8.3.8 *Treatment of water*

When significant volumes of water require pH adjustment, as opposed to cautionary applications of neutralising agent to drainage lines, then more soluble neutralising agents are more effective. Refer to the *Water Treatment and Management Guidelines.*

[16] Highly coloured, organic-stained water (Reeve and Fergus 1982).

9. 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 grainsize and grain density.

For such 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 or the soil contains too much clay as these materials do not separate easily.

> **ASS Tip 17 –** Grain density
>
> Pyrite has a density of 5 g/cm^3 in solid crystals, or ~3.5 g/cm^3 in framboids. The common sand and soil minerals (quartz and feldspar, clays) have densities ≤ 2.7 g/cm^3.

Types of hydraulic separation that will be discussed in this section include (hydro)**sluicing** and **hydrocycloning**. Both of these techniques are hydraulic separation methods because the sediment particles to be separated must be suspended in water for the processes to work. The water element of these processes is important as it minimises the exposure of the fine sulfide particles to oxygen during the separation process. Sulfidic fines or 'slimes', are generated as a result of the process, and require specialised management, similar to the principles outlined in section 8 Neutralisation and section 10 Strategic Reburial. Other hydraulic separation techniques eg. 'boiler-box or sluice-box' may efficiently separate sulfides, however they too should be validated and similar management considerations applied.

Dredging of ASS may be feasible for lake and canal developments, during extraction of sand and gravel and when carrying out maintenance or capital dredging of navigation channels in ports and harbours. Both 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.

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 (<50µm) and have a low organic matter content. The associated costs involved are the intensive management and monitoring of the process itself and final management of the concentrated sulfidic fines; however, savings on earthmoving and neutralising agents may be achieved using hydraulic separation techniques.

> **ASS Tip 18 –** Hydraulic separation as affected by soil texture
>
> - <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 → consider alternative management strategy.
>
> Hydraulic separation does not work unless all the material can be adequately broken up and maintained in suspension.
>
> Dredge operators may avoid large clay layers and treat them separately eg. through screening.
>
> Other factors may also influence whether hydraulic separation is suitable at a site.

Rigorous site management is required 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.

9.1 Environmental risk

Considerable risk to the environment may occur during the process of hydraulic separation. These are outlined below.

9.1.1 *Site management*

There is a significant reliance on technology and consequently a higher degree of process and site management required during hydraulic separation techniques. In situations where washed sands are trucked off-site[17], such as in the sand and gravel extraction industry, then quality control procedures should be in place to ensure that only material that has satisfied the performance criteria is allowed to leave the site. Alternatively, further management off-site may be warranted, and this may be difficult to implement and enforce.

9.1.2 *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 implemented during:

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

There are greater risks to the receiving environment if acidity is generated within the stockpiles when stockpiles of sandy material are deposited and 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 the generated acid is likely to be mobilised.

The risks of both acidification and/or deoxygenation of the waterbody 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).

9.1.3 *Inefficient separation*

Neither sluicing nor hydrocycloning will remove 100% of the sulfides and not all source material is suitable for separation by these processes. However, even if the separation has not been sufficiently successful, a significant reduction in sulfide concentration will still lower the overall environmental risk inherent in the processed material especially if the sulfidic materials were excavated dry.

Poorly separated fill material may result in large clumps of sulfidic material that are placed in potentially oxidising conditions, scattered throughout the washed sands. This can cause long-term problems associated with acid leachate.

Neutralisation will be necessary if the separation process is inefficient. There are difficulties with mixing insoluble neutralising agents such as fine aglime beyond the depth of incorporation. Working stockpiles of dredged sand that are up to a metre high may require considerable effort to achieve sufficient mixing of the neutralising agent. Alternatively, the materials may need to be reprocessed.

Neutralisation will also be necessary if enclosed water bodies become acidified. Neutralisation of water bodies with soluble neutralising agents such as hydrated lime, $Ca(OH)_2$ may involve risk due

[17] This approach contains greater environmental risk as management protocols can no longer be controlled by the sand/gravel supplier.

to the possibility of overshooting the pH, resulting in a large body of strongly alkaline water. Refer to the *Water Treatment and Management Guidelines.*

9.1.4 *Process water*

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 require separate treatment or replacement. Such process waters may become acidic, and if so will require neutralisation.

9.1.5 *Stratigraphy*

In general, sites with highly variable soil stratigraphy pose the greatest risk when undertaking sluicing or hydrocycloning. Hydrocycloning requires a constant feed to be most efficient and this is a rare occurrence in most sandy sites. Whilst small bands of marine clays within the sandy sediments may wash sufficiently, large bands of heavy marine clays, or cemented bands of coffee rock situated within the predominantly sandy soils may be difficult to isolate and treat, resulting in poor separation.

The better the characterisation of the site, then the better the understanding of the stratigraphy of the soils on-site, and the lower the environmental risks if a large volume of material is to be hydraulically separated.

9.1.6 *Volume of sulfidic fines*

It can be difficult to calculate the projected 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 when fines are separated from the coarser (ideally largely sulfide-free) fraction. These fines are poorly draining, and will take significant periods of time to compact (and dewater). It is the uncompacted wet volume of fines which must be considered and not the final compacted volume when calculating the volume of void for the reburial of the sulfidic fines (ie. sufficient void needs to be available to accommodate the uncompacted fines). A mineralogical assessment of the fines may be required 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 required for reburying the fines in these situations and the volume of the fines generated after hydraulic separation.

9.1.7 *Post separation*

At the completion of hydraulic separation, the sulfidic fines will be concentrated and may be either:

1. stored in an anoxic environment; or
2. dried sufficiently to be treated by neutralisation techniques for their potential and existing acidity.

Two further management issues will need to be addressed if the fines are to be stored in an anoxic environment. First, the stream of suspended fines must be managed to minimise any further exposure to oxygen following separation. This should include avoiding spraying or otherwise increasing the turbulence in this stream as it may increase the concentration of dissolved oxygen within the suspension water. Second, the suitability of the anoxic storage location to be used should have been demonstrated prior to any works. This storage is a form of Strategic Reburial (refer to section 10).

If the fines are to be dried and neutralised, this method poses a high environmental risk due to the amount of potential acidity that may be produced by the fine textured material while it is drying out. However, this risk may be acceptable if the drying and treatment area is hydrologically isolated from the receiving environment. The risk may be unacceptable if pH-sensitive environmental values are in proximity and threatened by the quantities of acid and/or neutralising agent (see section 8).

9.1.8 *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 required to achieve acceptable levels of environmental risk (assuming the sand can be recovered with an acceptable sulfide content). Rehandling of older (potentially partly oxidised) dredge fines may entail a much higher usage of neutralising agents to maintain pH of water and soil at acceptable levels.

9.1.9 *Sulfidic fines and existing acidity*

There may be risks to the environment if soils that have significant measurable existing acidity are hydraulically separated. After these fines have been reburied in anoxic conditions, existing acidity may still contribute to the acidification of the waterways or extraction pond. Furthermore, aluminium, iron and other heavy metals that are more soluble in acidic waters may be mobilised from the AASS. Other oxidising agents, which may be present in partially oxidised soils (eg. Fe^{3+} ions in pre-existing acidic pore waters) may cause further sulfide oxidation and generation of acid despite the exclusion of oxygen until the readily available Fe^{3+} ions have been consumed by the reaction (see section 11.2).

9.1.10 *Sulfidic fines and potential for oxidation*

There are instances where dissolved oxygen (DO) can be high enough in water 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 proceed even faster. Both oxygen concentration and oxygen transport mechanisms should be considered.

In some cases strategic reburial is below surface water that will generally not be flowing eg. a lake. However, even in these situations, the abovementioned risks may increase when water circulation is driven by high winds, rainfall and flood events etc.

There may be risks to the environment if large bodies of acidic water develop as a result of situations where anoxic, preferably anaerobic (reducing) conditions cannot be permanently maintained, and the sulfidic sediments have oxidised.

9.2 Performance criteria and verification testing

Performance criteria for washed, hydrosluiced or hydrocycloned soil where only residual levels of sulfides or pyrite are to remain, are:

- target of ≤18 moles H^+/tonne (0.03 %S);
- no sample shall exceed 25 moles H^+/tonne (0.04 %S);
- if any single sample exceeds 18 moles H^+/tonne (0.03 %S), then the average of any 6 consecutive samples (including the exceeding sample) shall have an average not exceeding 25 moles H^+/tonne (0.03 %S);
- if more than one sample in any 6 consecutive samples exceeds 25 moles H^+/tonne (0.03 %S), then the average of any 6 consecutive samples (including the exceeding samples) shall have an average content not exceeding 16 moles H^+/tonne (0.03 %S).

Samples of the washed soil should be taken and laboratory analysed to demonstrate compliance with the performance criteria (ie. verification testing).

An exception to the normal performance criteria for ASS that have been treated by hydraulic separation arises when these materials are to be promptly incorporated into concrete. In those cases the acceptable level of sulfides in hydrocycloned sands for an end use in concrete may be higher than performance criteria/action levels **if that is permitted by industry standards for concrete manufacture**. However, prior to use in the concrete, such sands and gravels must be appropriately contained (and leachate or runoff collected and managed) as with any other ASS.

9.2.1 *Failure to meet performance criteria*

If the above performance criteria are not met, the material will need to be fully treated with a neutralising agent (refer to section 8) or reprocessed (hydraulic separation) to reduce the sulfidic fines content to achieve the above performance criteria. A neutralising basal guard layer will serve to reduce risks in cases of exceedences (see section 9.4.4).

Reprocessing may be preferable to neutralisation if the fill has been placed to a depth of greater than 30 cm, and has failed the above performance criteria. It may be difficult to effectively mix insoluble neutralising agents (eg. fine aglime) in thick layers of placed fill. However, there can be problems 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 existing acidity can be neutralised (eg. 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 required 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 turn-around of the verification tests, and the need to take into account time delays to facilitate verification.

9.3 Hydraulic separation techniques

Hydraulic separation is used in the development industry for wet excavation of artificial water bodies and in the sand and gravel extraction industry. These are described in the following section.

9.3.1 *Sluicing*

(Hydro)sluicing has become the common term for the process whereby sulfidic fines are hydraulically separated from sands at the discharge point during a dredging operation and the heavier sands are then used as fill. In these situations, the 'sluice' is the artificial channel for conducting water or regulating flow from or into a still water body or pond (receptacle). Sluicing is a form of settling-based separation operated in a continuous process stream (as opposed to a batch type settling process that might apply to a sedimentation basin removing suspended solids). Sluicing is a relatively complex 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 sluicing channel where fine particles are settled in a still water body. This should be sufficiently deep 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). It should be noted that the drying of sulfidic fines would present a high environmental risk.

Enhancing the removal of sulfidic fines during sluicing

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

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

Some or all of the above may be implemented on a case-by-case basis, depending on the site and the materials to be dredged, and cost-benefit analysis.

ASS Tip 19 – Dredging

A ‘bucket wheel cutter suction dredge’ contains a series of buckets on the wheel of the dredge that assist the mechanical cutting of the material to be dredged. This in conjunction with suction will break up the material more effectively than a ‘suction dredge’ alone. A ‘suction dredge’ may use water jets to help loosen the sediments.

The arc is the angle between which the dredge swings and cuts. After the dredge cuts each arc, the material above it generally collapses to the basement, and is further cut and suctioned during the next sweep of the dredge.

The dredging operator must be able to break up all the material and keep it in suspension until it reaches the settling area.

9.3.2 *Hydrocycloning*

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 5). In 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 required as the material fed to the hydrocylcone 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 hydrocylone, 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 (section 9.2).

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 and must be managed to prevent the oxidation of sulfides (for example by strategic reburial) or treated using neutralising techniques.

Like sluicing, hydrocycloning is not a perfect separation method, hence the need 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 re-processed to obtain multiple size fractions of the product, eg. coarse sand, fine sand of similar density. The sulfidic fines should be removed during the first round of separation during the hydrocycloning process, and processed once with minimal exposure to oxygen**.**

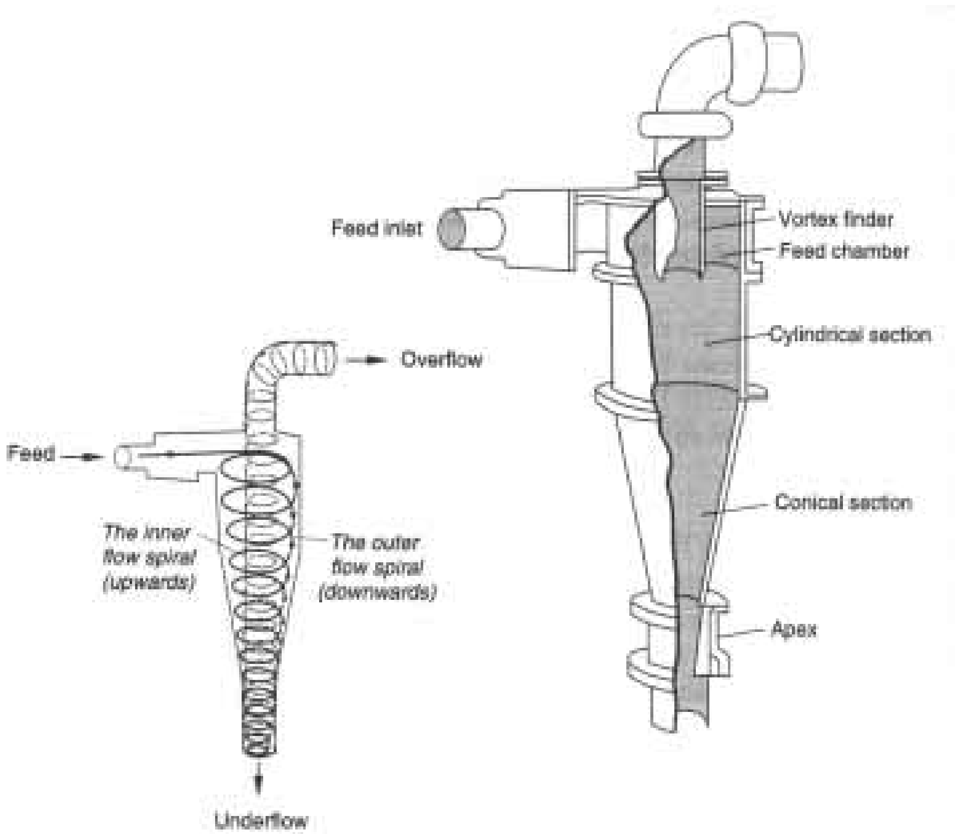


Figure 5. The hydrocyclone, showing main components and principal flows.
[This figure has been reproduced from Napier-Munn *et al.* (1996) with permission from the Julius Kruttschnitt Mineral Research Centre (JKMRC) at The University of Queensland].

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 (grainsize distribution, ratio of clays to sand, sulfide content etc.);
- if the material being processed is fairly consistent, it is theoretically possible to establish 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 have benefits to the ASS manager if a relationship can also be established with the results of verification analysis; and
- cyclone efficiency can be graphed for various particle size fractions and may assist in the selection of an appropriate hydrocyclone to achieve the desired results.

9.4 Management considerations

The following management issues should be considered when hydraulic separation methods are proposed for dredging or sand and gravel extraction.

9.4.1 *ASS site characterisation*

An ASS investigation that demonstrates the concentration and spatial distribution of the sulfides is required where hydraulic separation activities are proposed in areas of suspected ASS. Areas with high levels of sulfides should be avoided or additional management may be required. In some circumstances it can be cost effective on large sites to survey the sampling holes and test pits to work up a 3-dimensional model for the distribution of sulfide content, and for the delineation of clay and peat lenses and horizons. Many dredges are now fitted with GPS units, and an experienced operator should be able to position the dredge within 1 m of specific or problematic materials (Dobos and Neighbour 2000). See the *Sampling Guidelines* for further information on site characterisation.

9.4.2 *Pilot trial in previously unworked terrains*

A pilot trial should be conducted on a relatively small area of up to 1 hectare to determine whether sufficient separation could be achieved prior to overall approval of the operation being issued and in some circumstances after approval but prior to commencement of full works. Dobos and Neighbour (2000) stated that in sites with considerable clayey silts and sands, it might be necessary to take representative bulk samples of 10 kg and run bench tests in the laboratory to determine the efficiency of the separation process.

9.4.3 *Containment*

All 'dredge-for-fill' and extractive industry sites should be hydrologically isolated using bunding and diversion drains. Surface neutralisation of the earth bunds and diversion drains can also assist with neutralising any acidic water. 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 materials used should have an appropriately low permeability to avoid leakage.

The systems in the sand and gravel extractive industry tend to be closed with the sulfidic fines concentrated in a series of settlement ponds. Management techniques should ensure that there is no discharge from the settlement ponds until the sulfidic fines have settled on the bottom. The location of all settlement ponds should also be recorded.

The processing area used in extractive industry operations should be cleaned up at the end of each working day. Any escaped fines that may have been exposed to oxidising conditions should be treated using neutralisation techniques. All processing areas should be graded to ensure that all runoff is captured, and treated if necessary. All leachate escaping the stockpiled areas should be contained and neutralised on-site. Recycling water used on-site should be encouraged.

In non-enclosed dredging operations, it may be necessary to design and install structures to ensure containment of discharge from the site. In some situations, engineering design will need to account for the installation of gates on pipes or weirs that can be closed to prevent discharge if an acidic event is detected. Installation of an alarm system is recommended to ensure the appropriate persons become aware of the acidic event. The development of action triggers (eg. pH <6.5) will also be needed. Once the water has been neutralised[18], the gates can then be re-opened. Refer to the *Water Treatment and Management Guidelines* for guidance on selecting appropriate pH ranges.

The use of silt curtains within water bodies provides a flexible barrier that can assist to trap any silts, iron flocculant or other material that may potentially harm the environment. Silt curtains hang down from the surface of the water and require regular maintenance to ensure ongoing effectiveness. Silt curtains are further discussed in the *Water Treatment and Management Guidelines.*

9.4.4 *Guard layers*

A common risk reduction system involves the spreading or basal application of a neutralising agent to the soil surface prior to the placement of any washed sand. A thin layer of washed sand with the neutralising agent incorporated into it may also act as a more effective guard layer. This layer will intercept and neutralise any significant acidity that may be produced (assuming that water flows down through the washed sand and through the guard layer), and will assist in protecting groundwater quality. Guard layers are not a primary management tool and should not be used as a leachate treatment system.

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 existing and potential acidity of the washed sediments. The rate may need to be increased where the receiving environmental values warrant higher protection, or after poor performance of the hydraulic separation process.

Surface preparation of the pad with a guard layer is required during (hydro)sluicing operations; hydrocycloning operations should also use a guard layer unless there is concrete lining of the pad, and a containment system installed that will capture and treat all leachate.

> **ASS Tip 20 –** Guard layer rate for hydrocycloning
>
> Most sites will require a minimum blanket rate of 5 kg fine aglime/m^2 per vertical metre of fill placed. If 2 metres of soil are to be placed, then 10kg of fine aglime/m^2 should be spread as a guard layer.
>
> This rate may need to be increased in sites that have difficulty achieving effective separation or in an area where the receiving environmental values warrant higher protection.

9.4.5 *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 sluicing operations, will be buried within the washed sand. These materials can cause long-term problems associated with acid leachate. Quality control is needed to ensure that inadequately washed soils are detected. Washed sand should meet the performance criteria in section 9.2.

[18] When using neutralising agents an absolute upper pH limit of 8.5 should be used, however a reduced upper limit will be appropriate in some environments.

During hydrocycloning operations, care needs to be taken to ensure that there are negligible amounts of sulfide within the final product due to the potential for corrosive leachate production. In NSW and Queensland, legal complications have arisen after supplies of extracted material contaminated with sulfides have been sold. Such materials need to be identified and treated prior to sale or use, and should satisfy the performance requirements stated for ASS being treated by hydraulic separation techniques. In addition, large quantities of **coarse textured sand** with less than 18 moles H^+/tonne (equivalent of 0.03% oxidisable sulfur) may still generate significant amounts of acidity. Depending on final application and placement of the hydrocycloned sands, even these low levels of sulfides may require management eg. the addition of some neutralising agent.

It is preferable to maintain the washed sand stockpiles in thin layers (eg. less than 1 metre) until verified (due to the difficulties associated with incorporating insoluble neutralising agents beyond the plough layer).

The accurate spatial tracking of soils (eg. survey with a hand-held GPS, differential GPS, designated lot numbers or conventional survey, depending on the level of accuracy required) during hydraulic separation activities is critical to ensure that the location of soils requiring re-processing or liming can be readily identified.

It is generally recommended that a third party be employed to carry out the monitoring to assess performance of the hydraulic separation.

9.4.6 *'In-line' applications of neutralising agents*

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

- maintaining process waters in a neutral pH range during processing should any oxygenation of fines occur during processing;
- providing additional neutralising capacity to the sulfidic fines fraction:
  - i. to protect against minor acidification that might occur during separation and prior to storage; or
  - ii. to achieve a well mixed neutralising agent application to the fines if they are to be treated by neutralisation; and
- providing additional neutralising capacity to the coarse fill or sand and gravel product fraction:
  - i. to manage the risk of any inefficiencies in the separation process that might leave sulfidic fines entrained within the coarse fraction. This does not negate the need for verification testing unless a sufficiently rigorous pilot study specific to the project has demonstrated that sufficient neutralising capacity will be applied to the soil to compensate for inefficiencies in the separation process; or
  - ii. to directly treat existing acidity (including sulfidic and possibly organic acidity) that may already be present in the soil.

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

- correct selection of the type of neutralising agent to treat the desired 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 selection of the particle size of neutralising agent to ensure its entrainment and deposition with the desired fraction of the suspended sediment. For example a superfine particle to be entrained with the sulfidic fines and coarser particles to be entrained with the coarse sand and gravel fractions;

- deciding where in the process stream to add the neutralising agent to the slurry for most effective treatment of the desired process stream;
- accurate dosing with the neutralising agent to ensure that the relevant type and amount of existing and/or potential acidity is neutralised. This will be greatly dependent on the soil type, the existing/potential 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 require overdosing, which in turn will raise treatment costs (and the upper pH level needs to be kept in mind also);
- determining the mixing efficiency that can be achieved; and
- selecting appropriate verification analysis methods given the presence of the neutralising agent in the soil.

9.4.7 *Earthworks strategy*

An earthworks strategy should be formulated to ensure that the capacity of fill placement/treatment areas and sulfidic fines strategic reburial areas are sufficient to accommodate the projected extractive rates; **and** appropriately located to minimise environmental risk from those uses. The quality of the earthworks strategy is critical to the smooth running of the project particularly on smaller sites. It is important to consider all activities that will be taking place on-site (preferably against a timeline with the earthworks), to ensure that temporal 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 required time, location and volume of that void. Sufficient space must be available within the void to accommodate the volume of slurried sulfidic fines.

An earthworks strategy should be accurate enough to ensure that stockpiles of sulfidic sandy material are not allowed to dry out while waiting to be separated. If this is unavoidable additional management measures must be undertaken (see section 11.1 on stockpiling issues).

9.4.8 *Location of sulfidic fines*

The location of the sulfidic fines and the depth of the reburial should be recorded (eg. survey with a hand-held GPS, differential GPS, or conventional survey, depending on the level of accuracy required), and reported to the relevant local government and any other administering authorities required by approvals. Local governments will need this information to enable them to make informed decisions about future land uses that could potentially impact on these areas.

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

Any management requirements associated with sulfidic fines locations should be clearly identified for all stakeholders to ensure that responsible short- and long-term management occurs at the site.

9.4.9 *Management of the sulfidic fines*

At the completion of hydraulic separation, the sulfidic fines will require further management. See section 10 if the fines are to be stored in an anoxic environment (ie. strategic reburial). See section 8 if the fines are to be dried sufficiently to be treated by neutralisation techniques for their potential and existing acidity.

Note: Dredged sulfidic fines have a greater risk of resuspension and oxygen transfer than non-dispersive clays. Consequently, a limnological investigation may be required (see section 10.4).

10. STRATEGIC REBURIAL

Strategic reburial requires a void into which **potential** ASS will be placed. 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 (eg. within the base of a lake, canal or artificial wetland) and covered by standing or surface waters[19]. Alternatively the void may be beneath the groundwater table, and hence also below compacted non-ASS or neutralised material (see Figure 6 and 7). **Potential** ASS should be placed in anoxic, preferably anaerobic (reducing), conditions at the base of a void where sulfide oxidation and hence acid generation, is permanently precluded.

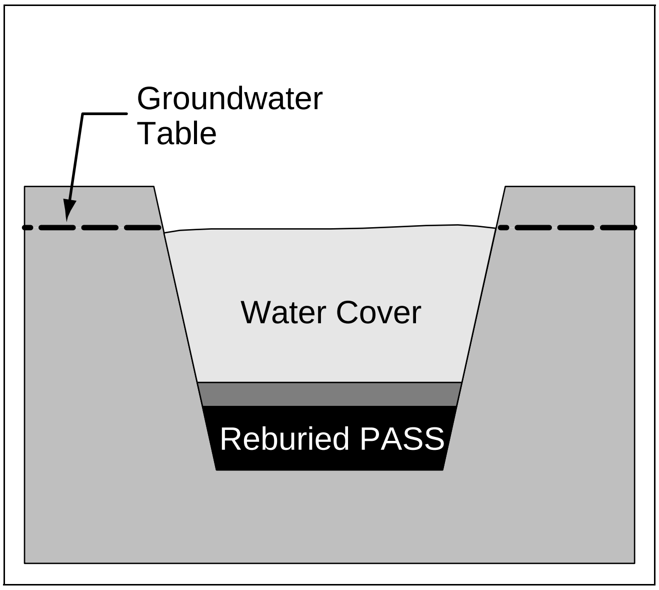


Figure 6. Schematic diagram of strategic reburial below surface or standing water.

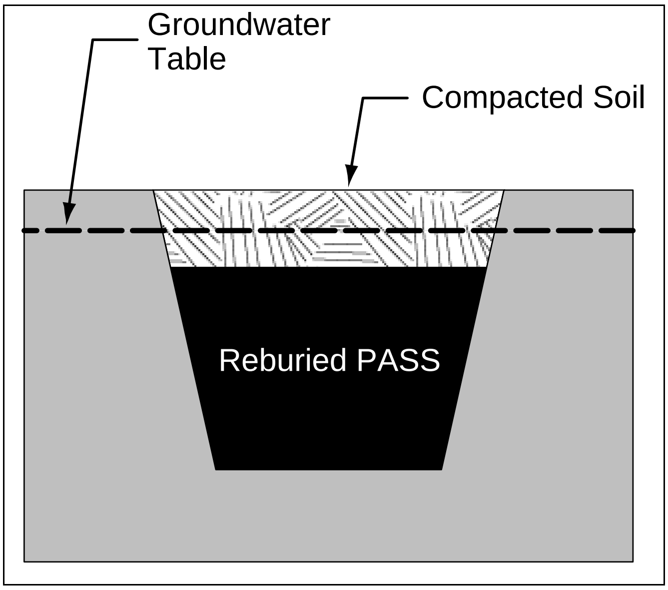


Figure 7. Schematic diagram of strategic reburial below groundwater and compacted soil.

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 eg. sulfidic fines, pose much greater risks than blocky non-dispersive clays (see section 10.1.2). The level of risk associated with different elements to be strategically reburied is represented in Figure 8.

Strategic reburial is most appropriate for **potential** ASS although it is theoretically possible to manage ASS that have undergone some oxidation and have been treated using a neutralising agent for their existing acidity (plus safety factors). However the practicalities and intensity of management processes involved in the latter increases costs and environmental risks. This issue is discussed in section 11.2.

ASS Tip 21 – To submerge or flood?

How the material for strategic reburial is placed below water must be decided based on project-specific factors. The important thing to remember is to avoid oxidation of the material being placed. For example, ideally dredged sulfidic fines should be placed at the bottom of a waterbody with as little mixing and aeration and suspension as possible; ie. they might be piped.

The technique of strategic reburial is based on the principle of maintaining potential ASS in anoxic, preferably anaerobic (reducing) conditions at all times. Limiting or excluding oxygen from the reburied soils governs the effectiveness of strategic reburial as the amount of sulfide oxidation is

[19] The waters may be fresh, brackish or saline and therefore different management issues may apply.

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;
- 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; and/or
- placing soils under the groundwater table 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 (eg. under appreciably sloping ground or in a preferred groundwater flow pathway such as a paleochannel).

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 precludes oxygen. The reburial location must be carefully planned to ensure void space is available when needed. Timelines for an earthworks strategy need to be calculated and met to ensure that the above conditions are consistently achieved.

10.1 Environmental risk

The level of risk associated with strategic reburial of **potential** ASS in a location that permanently precludes oxygen is significantly lower than placing ASS above the groundwater table. While the level of overall risk may be lower, there are other risks that need to be considered.

10.1.1 *Existing acidity*

There may be risks to the environment if soils that have significant measurable acidity are re-interred through this process **without** first neutralising existing acidity. Strategic reburial is inappropriate for **actual** ASS as any existing 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. Other oxidising agents, which may be present in partially oxidised soils (eg. 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 until the readily available Fe^{3+} ions have been consumed by the reaction (see section 11.2).

10.1.2 *Potential for oxidation and the nature of the material to be reburied*

There is a limited potential for oxidation in soils with a low hydraulic conductivity that are reburied (under either surface waters or groundwater and compacted soil). However, there may be instances where dissolved oxygen (DO) concentration in water is high enough to cause significant oxidation of some submerged sediments (eg. dredged sulfidic fines). Risks 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 proceed even faster. Both oxygen concentration and oxygen transport mechanisms need to be considered.

Strategic reburial under standing or surface waters relies on the fact 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/rinds that resist further oxygen transport into the ‘blocks’. Moreover, 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[20], or from sustained high winds. Under these circumstances, the results of episodic or sustained oxygen transport to these materials may pose no significant environmental risks.

At the other end of the spectrum, fine-grained unconsolidated sulfidic materials, such as sulfidic fines produced by hydrosluicing 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 maintained in contact with oxygenated water, such as may occur during tidal flushing, or after heavy rains or flooding, or during high sustained 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.

There may be risks to the environment if large bodies of acidic water develop as a result of situations where anoxic, preferably anaerobic (reducing) conditions cannot be permanently maintained, and the sulfidic sediments have oxidised.

Therefore, it is highly recommended that an appropriate risk assessment be carried out prior to strategic reburial of sulfidic materials under standing (surface) water. This 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 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 (see section 10.4.1). *Note: The resuspension of sediments is very important in some circumstances, but not common to all.*

Additionally or alternatively, the risk assessment may include the prediction of likely 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.

Monosulfidic black oozes can be difficult to work and can oxidise readily once in contact with oxygen. Such material may not be suitable for strategic reburial.

Figure 8 is a schematic representation of the level of risk associated with a variety of storage conditions including:

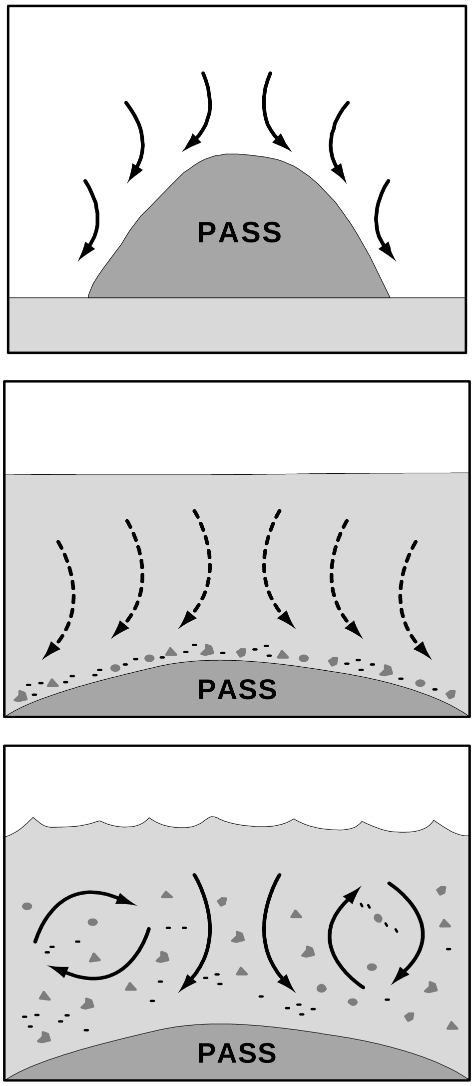
- stockpiling ASS above the water table where oxygen delivery to the stockpile occurs by diffusion and advection, and there is an infinite supply of oxygen;
- strategic reburial below **still** surface water conditions where oxygen is transported to the sediments by diffusion; and
- strategic reburial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

This figure demonstrates that the level of risk associated with strategic reburial of PASS below water is significantly less than stockpiling untreated PASS above the groundwater table. This figure also demonstrates that the level of oxygen transport to reburied sediment can increase in moving water where oxygen transport is not limited to diffusion.

[20] Other reasons may exist to preclude strategic reburial in tidally flushed areas.

ASS Tip 22 – Diffusion and advection

Diffusion is the movement of (in this case oxygen) **through** a static medium (in this case still 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.



Atmosphere

- relatively high $[O_2]$ of 21%
- oxygen delivery to the material is via advection and diffusion
- effectively infinite source of oxygen
- high risk

Absolutely still water

- relatively low $[O_2]$ of 9 ppm
- oxygen delivery to the material is via diffusion and is very slow
- low risk

Moving water

- relatively low $[O_2]$ of 9 ppm
- oxygen delivery to the material is principally via advection
- oxygen delivery to the material via diffusion is negligible
- risk is variable, depending on the rate and duration of water movement

Figure 8. Schematic representation of the level of risk associated with stockpiling ASS above the water table and strategic reburial of materials under water, under the scenario of absolutely still water and moving water.

10.2 Performance criteria and verification testing

Performance criteria for strategically reburied PASS are:

1. Potential ASS are maintained in anoxic, preferably anaerobic (reducing) conditions at all times.
2. Soils with significant untreated existing acidity are not interred.

A verification testing procedure should be implemented to demonstrate that materials with existing acidity are not being reburied. During the reburial process soil and/or water pH will provide an indication of compliance with performance criterion 2. If soil pH drops below 5.5, then samples of the soil should be taken and laboratory analysed to determine how much existing acidity is present and to determine an appropriate alternative management strategy for those soils.

Failure to satisfy these performance criteria may necessitate the re-excavation of the soils and neutralisation of the existing acidity.

10.3 Management considerations

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

10.3.1 *Site characterisation*

The effectiveness of this strategy is largely determined by 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. All AASS, PASS and areas of non-ASS that are to be over-excavated to provide voids as reburial sites must be adequately defined (see the *Sampling Guidelines*).

The better the characterisation of the site, then the better the understanding of the stratigraphy of the soils on site, and the lower the environmental risks if a large volume of material is to be strategically reburied.

10.3.2 *Timing*

Ideally, all material should be transported immediately from the excavation area to the burial site and placed at the base of the void in anoxic, preferably anaerobic (reducing) conditions. On some sites maximum delays due to unforseen circumstances for operational management is one night (18 hours) for coarse-textured material such as sands and a weekend (70 hours) for medium and fine textured material such as silts and clays. At some sites the example above may be too conservative, and in some circumstances not conservative enough (eg. during hot weather some sands may begin to oxidise within a matter of hours). It is recommended that appropriate operational delay times be determined for the specific circumstances. See also sections 11.1 (stockpiling ASS) and 11.2 (strategic reburial of soils with existing acidity).

10.3.3 *Staging the excavation*

Staging the excavation activities to ensure that sufficient void is available for immediate reburial is highly recommended. Double/repeated 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 only be placed directly in 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.

10.3.4 *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. It is important that the local government and any potentially affected landowners are consulted about this issue and have a clear understanding of any long-term implications that the reinterment may have on land use.

Locations must be accurately surveyed and both extent and depth of the burial should be recorded (eg. survey with a hand-held GPS, differential GPS, designated lot numbers or conventional survey, depending on the level of accuracy required), 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.

10.3.5 *Likelihood of disturbance*

Potential ASS that have been reinterred below the groundwater table may be further 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.

10.3.6 *Dewatering or drainage*

Water bodies that will need to be dewatered or drained in the future (for whatever reason) are also unsuitable reinterment locations. For example, if a lake or canal will be dewatered for the construction of revetment walls (and management issues associated with that dewatering can be addressed), then ideally that should be performed prior to use of that area as a reinterment location.

10.3.7 *Hydrographic surveys*

Hydrographic surveys may also be required after strategic reburial of PASS to assess whether the material has been placed and/or remained where they were supposed to be.

10.4 Management considerations for strategic reburial under surface water

Strategic reburial under surface waters within a lake, canal, or artificial wetland may be feasible 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 anoxic conditions; and
- the material to be reburied will remain in its intended location, ie. it will not be moved by currents or other forces.

ASS Tip 23 – Is strategic reburial going to work?

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

- can you permanently maintain the water cover?
- what is being buried?
- how much sulfide is being buried?
- if the material is unconsolidated or dispersive, what is the surface area of sulfide per unit of reburied material?
- what is the worst predicted rate of oxygen transport?
- do the sulfides need a cap, and if so, will the sulfides support a cap?
- are there other management issues to consider such as stratification of water bodies, lake mixing, or algal blooms?
- will the material from its reinterred location?

Oxygen transport must be minimised, preferably halted 'permanently' for reburial of PASS under surface water to be an effective management strategy. The following factors can influence the rate of oxygen transport to the PASS, and should be considered before a decision is made regarding such a management technique[21]:

- nature of material to be reburied (sulfide concentrations, texture, dispersive nature, presence of Fe^{3+});
- waterbody chemistry (fresh, brackish or saline);
- frequency of flushing;
- water column depth;
- thermal and wind-driven mixing;

[21] In some circumstances, bioturbation of buried sulfidic sediments by benthic and other aquatic organisms may also assist oxygen transport eg. where highly sulfidic fines are interred in shallow, fresh water. This issue may be difficult to quantify.

- frequency of dredging and/or silt removal;
- scouring and/or resuspension by storm waters, flood waters or other flows;
- capping by non-ASS materials, to further reduce potential oxygenation;
- potential reactivity of the sulfides at the water-solids interface, eg. bottom water mixing may resuspend buried ASS or increase downwards oxygen transport during abnormal climatic conditions;
- potential for dewatering of the water body or decreasing water depth; and
- mechanical disturbance by powerboats, fishing etc.

10.4.1 *Risk assessment: oxygen transport, sulfide oxidation rates and limnology*

Limnology is the study of lakes, and by extension, constructed water bodies with limited inflows/outflows, but the focus here is on physical aspects of water movement in lakes and waterbodies (physical limnology). Limnological investigations can assist with the determination of whether anaerobic or near-anoxic conditions can be maintained at the depth to which PASS are to be reburied (modelling may be used). Similar principles are applied to assessing risks from proposed reburial of PASS under flowing waters. Limnology has been applied to many environmental management circumstances in lakes around the world including burial of pyritic fines from mining and interactions between anoxic bottom waters and oxygenated upper waters in many dams (Catalan *et al*. 2000, Atkins *et al*. 1997, Li *et al*. 1997). *Note: care must be exercised in applying the mining papers to ASS dredge or hydrocyclone fines, as generally there are likely to be substantial differences in milled 'mineral' pyrite versus ASS pyrite grainsize* ***and*** *effective grain density, among other differences.*

Given that the risks of oxygenation are increased in certain conditions, detailed limnological investigations will not be necessary in all situations. As stated earlier, the risks increase when the oxygen transport mechanism is not limited to diffusion (eg. where DO is high enough in water to cause significant oxidation of the submerged sulfidic sediments). The risks are a function of a number of variables. For example, a large freshwater lake with a long fetch in a high wind area, where the sulfidic fines are buried under shallow water, where there is a lot of boat traffic, will have a high probability of mixing and wave action, causing resuspension, oxygenation and finally acidification of the overlying water. The applicant should therefore expect to provide at least a limited or in some circumstances even an extensive limnological investigation when reburial of sulfidic fines is proposed.

Water column depth

A sufficient depth of the water column above the PASS must be available to ensure minimal oxidation. Based on modelling of some sites in southeast Queensland, the depth of a water column over sulfidic fines needed to be a minimum of 4 m; however this may vary in some circumstances and greater depths may be required in northern Queensland (due to the prevalence of cyclonic winds and other extreme weather). In general, the deeper the water above the PASS, 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 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 re-start oxygen transport to sulfidic bottom fines resulting in acid production, and this is especially relevant if monosulfides have been formed under anaerobic conditions. Therefore, different types of stratification and de-

ASS Tip 24 – Nature of material

The risks increase if the sulfides are predominantly monosulfides, or if the sulfide minerals have very high unit surface areas, or have finer grainsizes (which promote faster reaction rates in the presence of oxygen, and lower settling rates after a disturbance).

stratification over normal variations and extremes in annual climatic conditions should be considered when assessing the risk of the proposal.

Mixing in the waterbody

Reinterred PASS may be at risk of exposure to oxygenating conditions from thermally-driven seasonal and diurnal water mixing. This is an efficient oxygen transport mechanism, but velocities involved will generally not resuspend reinterred material. A higher risk may result from wind-driven mixing which depends primarily upon wind velocity and duration, and is also affected by the water body shape, orientation, depth, surface elevation and other site-specific geographic and constructed features because of the potential for resuspension of reinterred material.

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 if significant quantities of fines are to be reinterred under water.

Frequency of dredging and silt removal

Over time, silt may build up on the bottoms or beds of lakes or canals and may require removal for navigation or other purposes. Maintenance dredging operations may disturb interred PASS (this is particularly important if the PASS contains monosulfides which oxidise readily once exposed to oxygen).

Compliance with strict management requirements during such dredging or silt removal operations must ensure that any PASS remain in anoxic conditions at all times. The PASS must not come into contact with oxygenated waters or be placed in an aerobic environment, for example on a beach on the side of the canal.

Water bodies that will require regular maintenance dredging or silt removal are unsuitable reinterment locations unless the PASS can be maintained under anoxic conditions at all times.

ASS Tip 25 – Maintenance dredging

A suction dredge operated with precise depth control is preferred for maintenance dredging as it is less likely to stir up the reinterred PASS. A cutter suction dredge is more likely to penetrate and stir any buried material. If PASS is disturbed, it should be managed in accordance with section 8, 9 and/or 10.

Scouring and resuspension

The risk of scouring and resuspension of PASS on the floor of a waterbody is increased by stormwater inflows, tidal flushing, and flood flows. Such scouring or resuspension might occur frequently (eg. tides) or at intervals (eg. 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.

Disturbance by power boats

The risk of disturbance of the water-sediment interface by power boats is generally determined 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 frequently used by recreational or other powerboats may not be suitable reinterment locations.

10.4.2 *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 options are discussed below.

Increasing the neutralising capacity

Increasing the neutralising capacity of reburied sulfidic fines might reduce the environmental risk of reinterred material. 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 use alkaline neutralising agents in naturally acidic water bodies (see *Water Treatment and Management Guidelines*).

ASS Case Study 1 – Limnological modelling

A risk assessment of sulfidic fines previously reburied in a canal established 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 mean unit surface area of these sulfides was established enabling geochemical and limnological modelling to quantify the likely acid generation rates for various wind-driven mixing scenarios. It was demonstrated that there was some risk of acidification of the waterbody from protracted 1-in-40 year wind events that would cause resuspension and oxidation of the bottom fines.

The risk assessment also identified additional risks associated with the further placement of sulfidic fines with higher sulfide concentrations in this location. Dosing these fines with fine aglime would also mitigate these risks.

The fine aglime grainsize range selected is too small to sink through the fines, and hence remains with the surface sulfide grains, acting to neutralise any *in situ* acidity that may develop in future events.

Capping below surface waters[22]

Capping[23] below surface waters is a means of reducing oxygen transfer to PASS that are buried under the water, however it may be technically challenging and expensive or even impossible. Capping of the reinterred materials may reduce the environmental risk associated with their long term 'storage' at that location by:

- preventing their resuspension and transport by currents or flood waters;
- preventing their exposure to oxidising conditions caused by lake mixing, or other circulation of waters that would deliver oxygen to the bottom of the water column;
- providing greater control over the quality of the artificial sediment in contact with the water column with potential benefits for aquatic ecosystems; and
- providing a separation layer between the sulfidic sediments being stored and any silts that may accumulate and need to be removed by maintenance dredging.

Any sulfidic fines to be reburied must be capable of supporting a capping layer. Concentrated sulfidic fines and sulfidic muds may be unable to support a capping layer unless the cap layer comprises materials of the same density or less as those to be capped—it may be difficult or expensive to source materials that have the same density (or less) as dredged sulfidic fines. If materials of higher densities are used they may settle through the fines, resulting in a decreased depth of water over the fines. Note that many dredge and hydrosluicing fines are actually low-

[22] In cases where capping of strategically reburied material under surface waters is in moving waters such as rivers and streams, or in areas where there may be wave action, this will elevate the risk of the activity to the generally unacceptable.

[23] A cap is a layer of cover material placed over the ASS to prevent infiltration or to reduce exposure to oxygen.

density suspensions and may not support denser capping layers of sand or silt (which tend to sink through the fines) when placed hydraulically under water.

Potential scouring or re-suspension of capping layer
A proponent should demonstrate that the capping layer would not be scoured or eroded away by flow (especially flood flows) over time to decrease the risk to the environment. In some circumstances, there may be problems with re-suspension and/or settling of the capping layer. This can impact on water quality by increasing turbidity and/or could pose a potential source of contamination (eg. from iron or phosphorus) in a largely anoxic environment.

ASS Case Study 2 – Capping hydrosluiced fines

Hydrosluiced sulfidic fines at a tidally connected canal in south-east Queensland were capped with a layer of clean sand to prevent scouring and resuspension. The clean capping layer sand had a higher density than the sulfidic fines and consequently, sank into the fines. Capping was unsuccessful in this case.

Thickness of the cap
Capping of the sulfidic sediments with a thickness of between 0.2–0.5 m of non-ASS material is generally required, but the thickness will depend on the nature of the sulfidic sediments (eg. texture, composition, sulfide concentration etc.) and the density of the capping material.

When is capping necessary?
Capping may be necessary when investigations indicate 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. When we are dealing with dredged sulfidic fines, there is much greater risk of resuspension and oxygen transport. A cap may be necessary if mixing devices are installed in the water body if the mixing devices are likely to increase the oxidation and/or resuspension of the sulfidic sediments.

The need for a capping layer should be discussed with regulatory authorities, and should be based on the results of a risk assessment and/or limnological investigation.

ASS Case Study 3 – Hydrosluiced fines and destratification devices

A deep lake in southeast Queensland was considered unsuitable to use for reinterment of sulfidic fines, as the latter 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. Consequently, 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 previous operations. This complicated the management requirements for the site.*

10.5 Management considerations for strategic reburial below groundwaters and compacted soil

Voids can also be created below the level of the permanent groundwater table for the strategic reburial of PASS. The PASS then lies below the re-established groundwater table and a layer of compacted soil that is placed on top of it (see Figure 7). This technique will not be suitable for sites where the groundwater table takes many months or even years to re-establish. As stated previously, it is the long-term conditions that will preclude the oxidation of the reburied materials that is important. Factors or conditions that might result in the transport of significant amounts of oxygen to the reburied sulfides (eg. by providing unexpected or preferred pathways for oxygen or oxygenated groundwater flow, immediately 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 appreciable groundwater flows might occur;
- placement of PASS where groundwater flows will transport significant oxygen to the sulfidic materials;
- placement of PASS where groundwater levels are lowered to expose the PASS due to seasonal fluctuations or drought;
- placement of PASS materials in locations where future off-site development might periodically or permanently lower the groundwater table around the re-buried 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; and
- placement of wet, low density dredge or hydrocycloned fines without first dewatering, may lead to the sinking of the capping material, squeezing the fines upwards, above the permanent groundwater table.

Note: The PASS should be placed at least 0.5 m below the lowest recorded groundwater table level to ensure that the PASS is 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 groundwater table.

Refer to the *Water Treatment and Management Guidelines* and *Environmental Management Plan Guidelines* for monitoring recommendations.

11. HIGHER RISK MANAGEMENT STRATEGIES

Several management strategies that deal with ASS may entail considerable risk to the environment as there is limited information on their successful implementation. In some situations, justification may be required by the relevant administrative body that the risks to the environment can be adequately controlled. Before any of the following management strategies are used, a proponent will need to provide a risk assessment and documented scientific justification to the relevant administrative body that the process will not impact on the environmental values of the receiving environment. Conversely regulatory agencies should require such information. When sufficient scientific justification cannot be provided, some of the following activities will not be allowed.

11.1 Stockpiling acid sulfate soils

The risks of stockpiling large volumes of untreated ASS may be very high even over the short-term. 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; or
- due to weather slowing treatment or problems with obtaining laboratory results, space in neutralising treatment areas may not be available as quickly as was anticipated in earthworks strategies, leading to the creation of small stockpiles before changes can be made to earthworks programs.

ASS Tip 26 – Stockpiling

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

- **prevent** further increases in stockpile volumes or times; and
- **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.

11.1.1 *Environmental risk*

After soils have been excavated and moved, the soil profile will be mixed. It then becomes difficult to correlate laboratory results with soil profile horizons to identify the specific liming rates needed for those horizons and consequently, matching the soil horizons with their respective liming rates may become difficult. This poses risks to the environment if incorrect liming rates are used.

Significant quantities of acid can build up, especially in porous sandy stockpiles if left in oxidising conditions for even short periods of time. Large stockpiles are difficult to neutralise, primarily due to the earthmoving required. In addition, when determining the amount of neutralisation it is important that by-products of oxidation such as jarosite are properly characterised and that representative sampling of the stockpile is performed. Sampling rates for stockpiles may need to be double or triple that of an undisturbed profile. Costs of representative sampling of stockpiles is much cheaper if sampling is performed as the stockpile is being created. Refer to the *Laboratory Methods Guidelines* for information on analysing soils with retained acidity.

ASS Tip 27 – Secondary sulfate salts

Secondary sulfate salts (eg. jarosite) may dissolve and produce acid with wetting and drying of the stockpiles. Jarosite, and other acid-forming salts, may be 'stores' of acidity that do not require oxygen to generate acid.

Due to varying solubilities, some of these salts may be determined by the Titratable Actual Acidity (TAA) test, while others such as jarosite will require additional testing to measure their retained acidity eg. Suspension Peroxide Oxidation Combined Acidity and Sulfur (SPOCAS) method. Existing and retained acidity are not accounted for by S_{CR}, S_{POS}, or S_{TOS} tests. See *Laboratory Methods Guidelines*.

11.1.2 *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 wet weather and plan for other contingencies.

Short-term stockpiles

The recommended maximum time period for which soils can be temporarily stockpiled without treatment is detailed in Table 4.

Table 4. Indicative maximum periods for short-term stockpiling of untreated ASS.

Type of Material		**Duration of stockpiling**	
Texture range (McDonald *et al*. 1990)	Approx clay content (%)	Days	Hours
Coarse texture Sands to loamy sands	≤5	Overnight	18 hours
Medium texture Sandy loams to light clays	5–40	2½ days	70 hours
Fine texture Medium to heavy clays and silty clays	≥40	5 days	140 hours

At some sites these figures may be too conservative, and in some circumstances not conservative enough (eg. during hot weather some sands may begin to oxidise within a matter of hours). It is recommended that appropriate operational delay times be determined (preferably well prior to the creation of the stockpile) for the specific circumstances. The use of a guard layer under the short-term stockpiles may be warranted under certain circumstances.

The total volume of material that is placed in short-term stockpiles should not exceed 20% of a day's total extraction.

Note: These timeframes do not apply to monosulfidic black oozes. These materials should not be stockpiled without a risk assessment, and the implementation of strict environmental management protocols.

Medium-term stockpiles

Situations where it is necessary to stockpile untreated ASS for moderate periods will need to be justified to the relevant administrating agency. Management to reduce the oxidation of sulfides and the collection and treatment of all leachate and runoff water will need to be implemented during the stockpiling period. The maximum time period for which soils can be temporarily stockpiled in the medium-term is listed in Table 5.

Table 5. Indicative maximum periods for medium-term stockpiling of untreated ASS.

Type of Material		**Duration of stockpiling**	
Texture range (McDonald *et al*. 1990)	Approx clay content (%)	Days	Weeks
Coarse texture Sands to loamy sands	≤5	14 days	2 weeks
Medium texture Sandy loams to light clays	5–40	21 days	3 weeks
Fine texture Medium to heavy clays & silty clays	≥40	28 days	4 weeks

Again, at some sites these figures may be too conservative, and in some circumstances not conservative enough. A risk assessment should be undertaken if soils are to be stockpiled for longer periods than those listed in Table 5. Neutralisation treatment in accordance with section 8 may be necessary if it cannot be demonstrated there is minimal risk associated with the stockpiling. Stockpiling in the medium term should be a contingency measure rather than standard practice.

ASS Tip 28 – Guard layer rate for medium-term stockpiles

The rate of neutralising agent used in the guard layer of medium term stockpiles should be based on 0.3 times the average potential and existing acidity of the stockpile/m^2 per vertical metre of soil that is to be temporarily placed in the stockpile. If the stockpile is 2 metres high, then twice 0.3 times the neutralising agent required to neutralise the potential and existing acidity should be spread as a guard layer. A 1.5 to 2 times safety factor is also required for medium term stockpiles**.** Also see notes on Guard Layers in section 8.

For sandy textured soils, in environmentally sensitive areas, or in situations where the medium term time frames cannot be met, a higher rate of neutralising agent in the guard layer will be warranted.

The potential and existing acidity of the soil can be measured by a range of laboratory methods (see *Laboratory Methods Guidelines*).

A guard layer of a suitable neutralising agent **MUST** be placed under all medium-term stockpiles. In addition the following management strategies may need to be implemented to manage risk:

- the volumes stockpiled should not exceed more than 1 week's volume of extraction;
- all stockpiles will need to be bunded and diversion banks installed upslope to prevent run-on water. 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 materials used should have an appropriately low permeability to avoid leakage;
- leachate collection and treatment systems should be installed;
- the surface area of the stockpile is minimised to reduce exposure to atmospheric oxygen. This may involve shaping the stockpile, and/or capping or lining it with a material that will minimise drying by wind and sun and prevent rainfall entering the stockpile. The cap or liner will need to cover the sides of the stockpile as well as the top;
- keep the surface of the material moist using a spray of water or neutralising solution. The spray should be carefully managed to prevent over wetting the material producing leachate or runoff, and should be a fine-mist to prevent disaggregation of the soil from the stockpile surface; and
- construct erosion and sediment control structures.

Long-term stockpiles

As stated above, any stockpiling exceeding those in Table 5 is considered long-term stockpiling, and is an inappropriate management strategy. To manage any such soils, the recommendations of the risk assessment must be fully implemented. Regulatory agencies should be notified of the existence of the stockpiles and consulted on their management. If risks are assessed as likely to cause environmental harm, then voluntary submission of an Environmental Management Program under the *Environmental Protection Act 1994* is highly recommended. Failure to act on indications of high environmental risk may result in other action being taken under the *Environmental Protection Act*.

ASS Tip 29 – Sampling rates for stockpiles

Sampling of stockpiles should occur on a regular basis during the stockpiling period to monitor any development of acidity.

Stockpiles should be sampled according to the *Sampling Guidelines,* and should be 'performance based'. Any existing acidity detected should be fully neutralised.

Note: If acidity is allowed to develop in a stockpile, sparingly soluble acidic compounds such as jarosite can develop, requiring more complex analytical methods. See Laboratory Method Guidelines.

11.1.3 *Stockpiles of topsoil*

It is routine practice to scrape the topsoil prior to filling, and store it until it is required for top-dressing. Some of the management options listed under medium-term stockpiles may be appropriate for managing topsoil stockpiles, especially if they contain low levels of sulfides. Low levels of sulfides may occur in topsoils as a result of 'over-stripping' that has occurred during its collection, or it may be intrinsic to the topsoil.

All topsoil should be tested prior to stripping and stockpiling. Neutralisation of the potential and existing acidity of the topsoil will be required. It may be cheaper and easier to neutralise the topsoil as it is scraped and placed. For example, the appropriate amount of neutralising agent can be spread over the topsoil and, using a reverse scraper, the lime incorporated prior to stripping; further mixing occurs as the soils are placed into the stockpiles.

11.1.4 *Stockpiles used as preload*

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 considered 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 to the existing and potential acidity and verified (as per performance criteria and verification testing in section 8.2) may be used as preload.

11.2 Strategic reburial of soils with existing acidity

The use of strategic reburial as a management measure for soils with only potential acidity is discussed in section 10. However, the use of strategic reburial in situations where the soil has potential **<u>and</u> existing acidity** is a high-risk activity, which requires more complex site management and site supervision, a greater reliance on technology and higher costs. Large-scale use of this management strategy is not recommended, unless there are only minor amounts of existing acidity that can and have been fully treated, and adequate safeguards to protect the surrounding environmental values can 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 existing acidity. See section 10.

Note: the burial of ASS with existing acidity in a landfill site may need a risk assessment. Note also that if putrescible material is buried with soils with existing acidity in contact with sulfate-rich waters, anaerobic conditions may develop and may lead to the generation of toxic hydrogen sulfide gas (H_2S). Landfill operators should be aware of these risks and manage them appropriately.

11.2.1 *Environmental risk*

A risk assessment will always need to be undertaken in circumstances where strategic reburial of soils with significant[24] existing acidity is proposed and consultation regarding the proposed management should be undertaken with the relevant administering authorities. The following factors should be considered.

[24] The significance of the existing acidity will be determined through the risk assessment.

Forms of existing acidity

The acidic pore waters retained in partially oxidised ASS comprise the most common and obvious form of existing acidity. Other oxidising agents which may be present in partially oxidised soils (eg. such as 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 ferrolysis. Additionally, sulfidic soils that have undergone appreciable oxidation may also contain retained acidity (eg. in salts or precipitates such as jarosite) that can dissolve and generate additional acidity in the absence of oxygen. These sulfate salts require only steady infiltration and groundwater flow (not necessarily oxygenated) to export acidity. Refer to the *Laboratory Methods Guidelines* for methods to measure existing acidity.

If warranted by the risk assessment, neutralisation of all forms of existing acidity (with a 1.5–2 times safety factor) must occur prior to interment.

*Note: Soil horizons with the existing acidity can be **stripped first** and fully neutralised. Underlying soil horizons that contain only **potential** ASS, would then be available for strategic reburial.*

Incorporation of neutralising agents

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 prior to incorporation of the agent. During this time, more acidity may develop that would require additional neutralisation. Fine aglime is slow to react and gypsum and insoluble iron and aluminium products of oxidation may form coatings on the fine aglime and reduce the neutralising ability of the agent.

A slurry of hydrated lime, $Ca(OH)_2$ may be added to the void during the process of reburial to neutralise an acidifying water body when there is limited existing acidity. Hydrated lime is slightly soluble but strongly alkaline, and this activity requires a cautious approach and extensive monitoring to avoid overshooting the required pH. It may take considerable time for the pH of the waterbody 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.

Temporary stockpiling

If temporary stockpiling occurs prior to reburial, then it may be necessary to comply with the requirements discussed under section 11.1.

Performance criteria and verification testing

Soils with existing acidity that are to be strategically reburied (ie. after neutralisation of the existing acidity) will need to comply with the performance criteria and verification testing listed in section 10.2.

11.3 Large-scale dewatering or drainage

Earthworks and/or pumping that result in localised drainage or lowering of groundwater and the exposure of sulfidic soils to the ingress of oxygen may generate acidity as a function of soil type(s), sulfide contents, area exposed, and length of time the excavation remains ‘dry’. The scale of the dewatering or drainage should be defined by the size of the cone of depression rather than the size of the void. Activities of this type are high-risk, and should not be undertaken without technical risk assessment by qualified personnel, and the formulation of management measures sufficient to reduce risk to levels acceptable by the administering authorities. All factors that potentially affect acid generation in both the short- and long-term must be considered for risk assessment, and suitable management methods implemented in this type of operation.

Groundwater drainage or dewatering may start identical acid-generating processes as those described above in section 11.2. Consequently, all dewatering in ASS areas carries a high environmental risk except those which cause limited or localised drawdown. For example, shallow infrastructure trenching if it is staged and of short duration may 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. Also see the *Water Treatment and Management Guidelines.*

11.3.1 *Environmental risk*

A risk assessment will need to be undertaken in circumstances where large-scale dewatering or drainage of ASS is proposed and consultation regarding the proposed management should be undertaken with the relevant administering authorities. The following factors should be considered:

- acidification of the *in situ* soils drained within the cone of depression—the effect will be greater in highly permeable sandy soils or peats;
- processes that influence oxygen delivery to the cone of depression during the dewatering or drainage operation eg. rainfall events and evapotranspiration;
- acidification of the groundwater that will ultimately reside in the cone of depression once the system is re-flooded;
- iron, aluminium and heavy metal contamination of the groundwater that will ultimately reside in the cone of depression;
- acidification and contamination of any water (eg. pit or lake water or adjacent groundwater) that interacts with the groundwater that will ultimately reside in the cone of depression;
- lowering of surface water or the groundwater table on- or off-site via continuous flow into the excavation, along preferred flow paths or palaeochannels;
- higher than expected hydraulic conductivities of soils that may be associated with relic root channel macroporosity and structural ripening of sulfuric horizons—this may have an effect on groundwater movement and acid export (Johnston 2002);
- fish kills in dewatered pits that were not adequately de-stocked;
- difficulties associated with prevention of drying and subsequent acid generation of *in situ* ASS; and
- difficulties associated with neutralising *in situ* actual ASS that has formed in the cone of depression.

ASS Tip 30 – Cone of depression

The cone of depression is the volume of soil around a dewatering point that becomes unsaturated (ie. partially drained) during dewatering.

Before dewatering ASS, the extent, location and soil characteristics of the cone of depression should be determined.

11.3.2 *Management considerations*

Management considerations will depend greatly on site-specific factors, and on larger sites may vary across the site. The following management considerations[25] will need to be evaluated when dewatering is proposed:

- minimise the volumes of soil excavated and thus soils dewatered at any one time. Excavate a series of smaller bunded cells, rather than one large dry hole;

[25] Some of the following techniques are currently being trialled in Queensland sites.

- minimise the drainage of soils within the cone of depression, for example:
  - use sheet piling to minimise groundwater drawdown and to limit seepage into the dry hole,
  - use physical barriers to slow down or stop flow from preferred pathways;
- minimise oxygen delivery to the soils in the cone of depression by using physical barriers to limit vertical and horizontal oxygen transport;
- monitor the groundwater levels and water quality within the cone of depression during and for a period after the dewatered excavation; and
- neutralise existing acidity that develops within the cone of depression.

11.4 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 'self-neutralising soil'[26] profiles (ie. profiles containing horizons with a high proportion of fine crushed shells, coral, skeleton, foraminifera or other naturally occurring deposits of finely ground limestone such as calcium carbonate or magnesium carbonate), that have low levels of sulfides and that are reasonably coarse textured (ie. sands and loams). 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 is only limited validation of this method in Queensland.

Note: It is considered inappropriate to classify the soil as a non-ASS by averaging the acidity or %S within all the soil horizons.

11.4.1 *Environmental risk*

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

A high level of skill and effort is required 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. There are potential long-term problems associated with the remediation of poorly treated ASS, and consequently 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. Further addition of a neutralising agent may also be required at some sites.

11.4.2 *Management considerations*

The following management issues will need to be followed when using vertical mixing:

- ensure soils are adequately mixed;
- extensive monitoring of the stormwater and groundwater ;
- a neutralising agent will need to be incorporated into the mixing process unless there is an abundance of highly 'reactive' neutralising materials within the soils;
- 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 an appropriately low permeability to avoid leakage; and
- a guard layer of a suitable neutralising agent will need to be placed under the mixing area.

[26] Laboratory methods can be used to detect the presence of carbonates in self-neutralising soils, however if fine grinding is used during sample preparation, the neutralising component will appear more reactive than it will be in the field. Shells greater than 2 mm need to be removed prior to analysis. This can be relatively easy for sands, but this may be more difficult for wet clays. If the shells >2 mm can be removed, techniques are available to determine the fine (<2 mm) shell content of soils.

12. GENERALLY UNACCEPTABLE MANAGEMENT STRATEGIES

The following management strategies have been shown to carry unacceptably high environmental risk; or to be generally ineffective; and/or lack scientific data to support their sustainability. In certain situations, they may be effective with appropriately low risk, and in these situations their use is not precluded. However a risk assessment will have to be undertaken and demonstrate this in sufficient detail. Note that if risks cannot be reliably quantified, government policies and procedures are unlikely to approve such strategies.

12.1 Above ground capping

Above ground capping[27] involves the placement of untreated ASS **above** ground, where the ASS is encapsulated under a non-porous cap. The cap is placed over the ASS to prevent infiltration and to reduce exposure to oxygen. Capping ASS above the ground is a potentially high-risk activity and is not recommended due to the associated level of environmental risk.

12.1.1 *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.

Encapsulation or capping of stockpiled sulfidic soils with various engineered ‘covers’ is a potential high-risk management measure to prevent oxidation of the sulfides; and/or preclude the transport of oxidation products (acidic or contaminated leachates) into the receiving environment. There are two main options: the first, ‘oxygen barrier’ covers, rely on a compacted clay layer with suitably low hydraulic conductivity, which must be maintained at 80% saturation, or better, at all times. Such covers can be readily designed and constructed on the horizontal surfaces of stockpiles, but achieving the design characteristics on steeper batters may be technically difficult and expensive.

The second cover design, the so-called store-release or ‘supersponge’ cover, depends on a suitable combination of soil capping and capping thickness, to absorb any rain event within the design criteria, without allowing for transmission of water to the underlying sulfidic soils. If the cover and vegetation, as constructed, meet design criteria, no leachate should exit the sulfidic soils, and hence there should be no contaminant transport to the receiving environment. Such covers may be dependent on the nature, effectiveness and longevity of the vegetation planted on the cover, to aid in the evapotranspiration of the absorbed rain (to ‘drain’ the cover, in preparation for the next rain event).

Covers of both types have been employed in the mining industry, though oxygen barrier covers are generally not recommended on mainland Australia, due to the difficulty of maintaining suitable saturation of the compacted clay during extended El Niño dry periods (eg. Wilson 2000, Currey *et al.* 2000, Miller and Brodie 2000). These covers can be constructed to specific designs, and in many situations, can be effective at least in the short term. Long-term risks arise from the potential loss of cover integrity resulting from settling of the underlying soils, erosion of the covers, and loss or replacement of the designed vegetation due to bushfires and/or natural re-seeding in the case of store-release covers. Capping of sulfidic soils is therefore considered a high-risk strategy, since it will generally require a commitment to monitor and maintain the cover integrity in the long term.

A third type of cover, the ‘reducing’ cover, relies upon a high level of degradable organic matter to intercept and consume oxygen flows to the underlying sulfidic soils. However, once the organic matter is oxidised or consumed, the cover is no longer effective.

[27] Above ground capping is not to be confused with the placement of treated compacted ASS as structural fill over the original undisturbed natural ground surface to elevate the finished land surface level. The natural *in situ* soils below the structural fill layer may contain undisturbed PASS.

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 and consequently future land use of the area has the potential to 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 required for effective above-ground capping would be similar to those required for toxic regulated waste landfill sites. This would generally make the proposal economically unviable. Furthermore, the issue of which organisation 'maintains' the cap in the long term and the associated risks would need to be resolved.

12.2 Hastened oxidation

Hastened oxidation of ASS is considered to be a high-risk management measure, and use of this procedure is not recommended. Soils with high concentrations of sulfidic material may take decades to fully oxidise under natural conditions. However, specific techniques can accelerate the process. The rate of the oxidation is influenced by the permeability of the material, the sulfidic content, temperature, moisture content and bacterial activity. Consequently, regular wetting and mechanical aeration of the soil can hasten the oxidation rate, which enhances the bacterial oxidation processes. There is limited use of neutralising agents involved in this management measure (Ahern *et al.* 1998b).

In specific cases of remediation, this procedure may be the only option available. It may be possible to treat excavated sandy or loamy acid sulfate material with low concentrations of pyrite.

12.2.1 *Environmental risk*

There are significant time delays 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, manganese, 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 requires complex 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 substantial if the leachate treatment and collection system fails to contain leachate during storms and flooding events.

There is substantial reliance on a regular water quality monitoring program of the leachate and surrounding surface water and groundwater for acid, aluminium, iron, manganese and heavy metals. Laboratory analysis of soils is also required to test for complete oxidation. Representative sampling of stockpiles with non-uniform oxidation would be necessary. Costs and difficulties with obtaining representative sampling are likely to be high.

12.3 Sea water neutralisation

Seawater neutralisation of ASS and/or water discharging from these soils is unacceptable as a primary management tool. It is a high-risk activity. Seawater is naturally alkaline, has a moderate acid-buffering capacity as it contains dissolved carbonate and bicarbonate. Up to 2 moles of protons may be neutralised by each cubic metre (1000 l) of seawater, but the potential downstream risks preclude its use. The long-term impacts of using seawater 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 and estuarine organisms and may lead to unacceptable and possibly irreversible changes to tidal and marine ecosystems, particularly those already under stress.

The use of seawater neutralisation may be considered on a case-by-case basis for remediation when the disturbance occurred prior to the recognition of the environmental impacts of ASS; there already is an acid and/or metal load impacting on the environment; and there are no other viable options (eg. broadacre acidity associated with agricultural production). Furthermore, seawater should only be considered in association with the supplementary use of neutralising agents, preferably in a contained area prior to the treated waters entering the receiving environment. For clarity, seawater neutralisation should not be a management method for new developments/disturbances.

Prior to 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 prior to, during and after the treatment. This issue is further explained in the *Remediation Guidelines* and *Water Treatment and Management Guidelines.*

12.3.1 *Environmental risk*

Where acidic waters are discharged to marine waters (eg. marine embayments, tidal channel ways and marine estuaries) the carbonate-bicarbonate within seawater may be consumed during the neutralisation process and the equilibrium balance may change (particularly if the replenishment of carbonate-bicarbonate is exceeded by the volume of acidity for extended and repeated periods of time). These may be more intense 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 that are dependent on carbonate-bicarbonate for shell and exoskeleton growth such as crustaceans and molluscs (and other invertebrates).

There are potentially adverse effects of iron hydroxide and oxyhydroxide precipitates (and other metal compounds) on sediment quality, water quality at the sediment interface, dissolved oxygen concentration and the survival of gilled organisms, filter feeders, benthic species and associated communities.

Carbonate in seawater is available to neutralise acidity generated after natural processes lower the groundwater table (eg. during tidal fluctuations or drought) in estuarine systems. There is, consequently, an ethical debate as to whether it is appropriate to use the natural receiving environment to treat acidity generated from artificial drainage works. There are likely to be significantly lower development costs 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 (Ahern *et al.* 1998b).

12.4 Offshore disposal of ASS

Proposals for offshore disposal of ASS may carry high risk to the receiving environment. The *State Coastal Management Plan – Queensland's Coastal Policy August 2001* policy 2.1.8 states "Dredging from land below highest astronomical tide (eg. within coastal waters) provides navigational and economic benefits to Queensland, and is to be appropriately located and sustainably managed to avoid or minimise adverse impacts on coastal resources and their values". Any offshore disposal of dredged materials must also comply with the federal *Environmental Protection (Sea Dumping) Act 1981*. This act is supported by the *National Ocean Disposal Guidelines for Dredged Material 2002*. In addition, any proposals for offshore disposal of ASS would need to ensure compliance with the state *Environmental Protection Act 1994* and the federal *Environmental Protection and Biodiversity Conservation Act 1999*.

12.4.1 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.

13. CONCLUSION

Acid sulfate soils are commonly found in coastal areas below 5 metres AHD and present a significant risk to the environment. In many of these areas there is pressure to alter the hydrology or drainage patterns and disturb the soils for urban development, agricultural expansion, mineral extraction, infrastructure provision, and tourist and recreational development.

The *Soil Management Guidelines* provide risk-based guidance on how to achieve *best practice environmental management*. The eight management principles provide direction for the preferred management strategies of avoidance, minimisation of disturbance, neutralisation of ASS, hydraulic separation and strategic reburial; higher risk management strategies of stockpiling ASS, strategic reburial of soils with existing acidity, large-scale dewatering or drainage and vertical mixing; and those described as generally unacceptable including above ground capping, hastened oxidation, seawater neutralisation and offshore disposal of ASS. The preferred management strategies all have a degree of environmental risk, and effective management following these guidelines can be complex and costly to implement. There will often be a significant reliance on technology and supervision. Higher risk management strategies may be considered, provided they do not pose an unacceptably high risk to the environment. Generally unacceptable management strategies include those where there is high environmental risk; management strategies have been generally ineffective; and/or a lack of scientific data to support their sustainability.

The guidelines recommend scientifically valid investigation, risk assessment and management planning which in some instances may entail significant costs. However if this process demonstrates that the risks are manageable, it may result in the approval of developments that may have otherwise not been approved.

The guidelines are not a regulatory document and may not be directly applicable to every site, due to site-specific differences and the range of factors that need to be taken into account in deciding best practice environmental management. They will not address management solutions for all situations and there may be exceptions where it is acceptable to deviate from the advice provided, particularly due to changes in technology. Alternative management strategies will need to be scientifically justified and must be consistent with the eight management principles.

An ASS investigation that characterises the spatial distribution of existing and potential acidity of the soils on-site is an **essential** prerequisite in selecting appropriate management strategies.

The *Soil Management Guidelines* should be read and implemented in conjunction with the other chapters of the **Queensland Acid Sulfate Soil Technical Manual** including the *Water Treatment and Management Guidelines*, *Sampling Guidelines*, *Laboratory Methods Guidelines*, *Legislation and Policy*, *Remediation Guidelines* and *Environmental Management Plan Guidelines*.

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