AN INVESTIGATION OF ACID SULFATE SOILS IN THE LOGAN–COOMERA AREA

Volume 1

Report on Acid Sulfate Soil Mapping

JA Manders, CD Smith, KM Watling, JJ Adams and CR Ahern
Queensland Acid Sulfate Soils Investigation Team
Queensland Department of Natural Resources and Mines

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SUMMARY

This report presents the findings of acid sulfate soil (ASS) mapping undertaken on land in southeast Queensland at the northern end of the Gold Coast City Council's jurisdiction. The work was carried out by the Department of Natural Resources and Mines as part of a three year Natural Heritage Trust funded project with extra funding from the Gold Coast City Council.

Approximately 14 552 ha of land less than 5 m AHD was assessed between the Logan and Coomera rivers involving description and sampling of approximately 725 boreholes. During the course of the project 7566 samples were collected for laboratory analysis. Oxidisable sulfur (%S) results were obtained for 7028 of these samples using several analytical methods, including 6805 results by Total Oxidisable Sulfur (TOS), 403 results by Peroxide Oxidation Combined Acidity and Sulfate (POCAS) and 457 results by Chromium Reducible Sulfur (S_{CR}) analyses. The oxidisable sulfur values ranged from below detection levels to a maximum of 4.7 %S across mapping areas and soil texture groups. Average oxidisable sulfur values for sulfidic clays across all areas was 0.82 %S whilst for sulfidic loams the average was 0.38 %S and for sulfidic sands the average was 0.15 %S.

The ASS mapping defined several mapping categories over the 14 552 ha of land assessed. Potential acid sulfate soils (PASS) were defined as soils with field pH (pH_F) >5, and oxidisable sulfur (%S) results meeting or exceeding the texture-based ASS action criteria (see Table 1 in Appendix 2). Strongly acidic soils contained pH_F >4 and ≤5, with %S results less than the action criteria. Low probability soils had pH_F >5 and %S results less than the action criteria. Actual acid sulfate soils (AASS) contained pH_F ≤4. AASS are likely to be a significant source of acidity with respect to surface and ground waters.

The areas mapped in the different categories are:
- Potential acid sulfate soils   ~27% of total area (3947 ha)
- PASS with strongly acidic soil layers   ~22% of total area (3158 ha)
- PASS with actual acid sulfate soil layers   ~27% of total area (3902 ha)
- Actual acid sulfate soils   ~6% of total area (886 ha)
- Low probability soils   ~5% of total area (724 ha)
- Low probability soils with strongly acidic soil layers   ~13% of total area (1935 ha)

In terms of pH, approximately 33% (4788 ha) of the assessed area is mapped as an actual acid sulfate soil with pH_F values ≤4; approximately 35% (5093 ha) is strongly acidic with pH_F values >4 and ≤5; and the remaining area of 32% (4671 ha) has pH_F values >5.

Users of mapping products such as Acid Sulfate Soils maps must be aware of the limitations implied in the scale of mapping undertaken. At a scale of approximately 1:25 000, the Logan–Coomera mapping is suitable for use in regional property management and development planning. Individual property planning or developments will require more detailed ASS investigations at scales of 1:10 000 or better, depending on the type and location of development. In addition, it is expected that boundaries of map units will be updated as additional field and laboratory data becomes available.

End users of QASSIT mapping products should refer to Appendix 5 to become acquainted with the methodologies used and the limitations of the product. Further information on sampling and management of acid sulfate soils can be found in the *Guidelines for Sampling and Analysis of Lowland Acid Sulfate Soils (ASS) in Queensland* (Ahern *et al*. 1998) and the *Soil Management Guidelines* (Dear *et al.* 2002).

1. INTRODUCTION

During the 1990s, several serious environmental events in the lowland areas of Northern New South Wales created a major concern about acid sulfate soils (ASS). Little was known about the areal extent or the severity of risk of these problem soils in Queensland. As a consequence, the Department of Natural Resources and Mines undertook to investigate the situation. With the aid of Natural Heritage Trust funding, broad scale (1:100 000) mapping was undertaken to identify the location of sulfidic sediments in southeast Queensland. The 1:100 000 scale coastal mapping component that extends from the southern border of Queensland to Noosa has been completed. These initial investigations indicated that ASS underlay large areas of southeast Queensland coastal lowlands.

The mapping program in southeast Queensland (SEQ) was carried out by the Queensland Acid Sulfate Soils Investigation Team (QASSIT) and funded by the National Landcare Program (NLP) of the Natural Heritage Trust (NHT) and the Queensland Government. More intensive mapping of the Logan–Coomera Area (this Report) at 1:25 000 scale was funded by the Gold Coast City Council (GCCC).

The findings of the mapping program have been reported to the Gold Coast City Council and NHT. It is envisaged that this work will provide a basis for better regional property management as well as valuable information for the GCCCs Wastewater Re-use Scheme. It will also highlight areas in which more detailed assessment may be required on individual properties.

2. THE USE OF HIGH INTENSITY MAPPING

Mapping scale is directly related to survey intensity, that is, the number of soil profiles and associated information collected per unit area. The mapping in this report is carried out at approximately 1:25 000 scale in an area selected by the GCCC, which translates to an average field survey intensity of 16 fully described and sampled soil profiles per square kilometre (one per 6.25 ha or every 250 m). Other areas within the mapping region vary in intensity from 1:25 000 to 1:50 000 scale—the latter translates to four (4) fully described and sampled soil profiles per square kilometre (one per 25 ha or every 500 m). The remaining areas are at a broad scale of mapping, that is, 1:100 000 which implies one borehole per square kilometre or that mapping was completed by aerial photograph interpretation.

The resultant mapping provides map boundaries that indicate the presence of both actual acid sulfate soils (AASS) and potential acid sulfate soils (PASS) at various depth intervals. Areas of disturbed land that are likely to contain ASS have also been identified but because of the difficulty of assessment, or of accessibility, limited or no field verification has been carried out.

Mapping at 1:25 000 scale allows a relatively greater indication of: the depth at which ASS occurs; the texture or particle size of the differing layers, and the concentration of sulfides within them. This additional information can be vital to ASS management decisions relating to current or future land use. It should be noted that this is a reliable scale for regional property management and development planning but is not suitable for individual property planning or proposed disturbances.

3. *REPORT COMPONENTS*

- **VOLUME 1: (This volume)** Contains information on ASS along with the methodology and results from the mapping program. It is accompanied by a 1:25 000 scale map that portrays the areal extent of ASS as well as the locations of all boreholes.

- **VOLUME 2:** Contains decoded descriptions of soil profile morphology and results from ASS field testing for all boreholes.

- **VOLUME 3:** Contains tabulated laboratory data together with selected soil profile morphological properties, for example, texture and presence of jarosite. This data commonly includes: ASS analysis for each soil horizon and/or every 0.5 m down the profile to depth of sampling; interpreted information including the identification of all samples that exceed the ASS texture-based action criteria.

4.   DESCRIPTION OF THE STUDY AREA

The Logan–Coomera study area is located at the northern end of Queensland's Gold Coast (see Figures 1 and 2). The main land use within the mapping area is sugar cane with the remaining land use including aquaculture, sand extraction, golf course and urban development.

The Logan–Coomera area drains directly into the Broadwater and Moreton Bay; both these areas have high natural habitat conservation values and are also intensively used for commercial and recreational fishing.
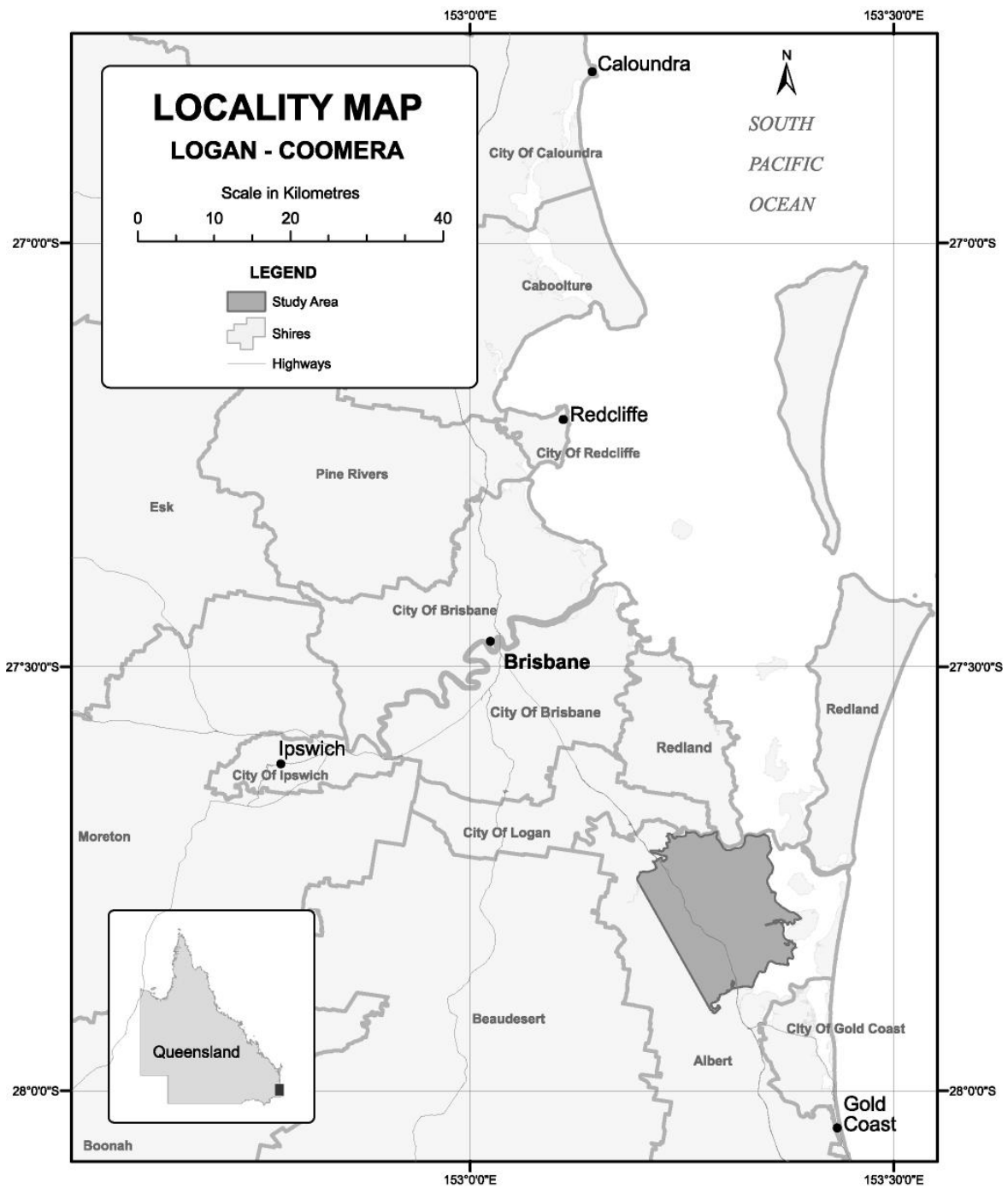
Figure 1.   Location of Logan–Coomera study area
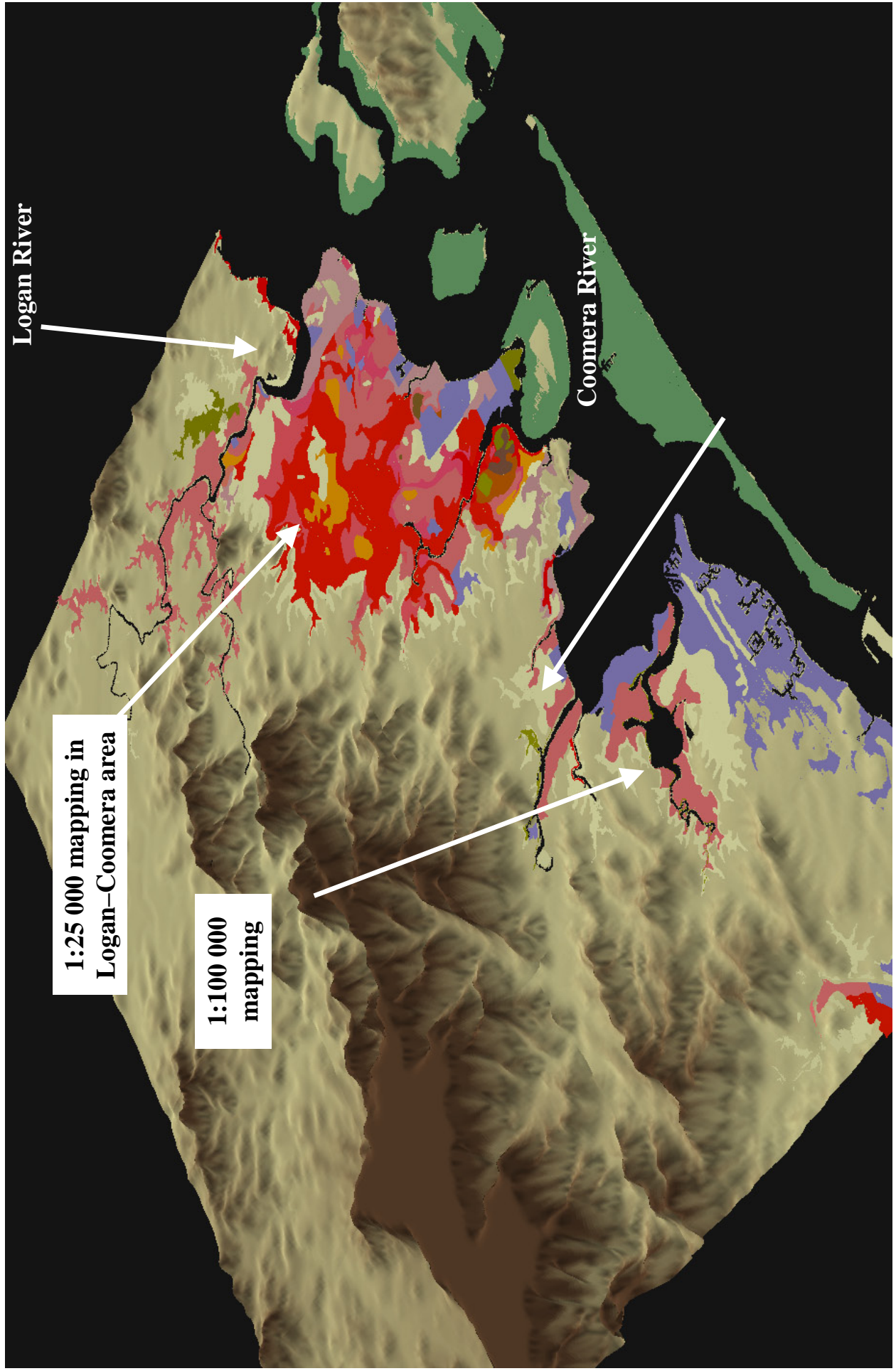
Figure 2. Logan–Coomera mapping area

Logan River

Coomera River

1:25 000 mapping in Logan–Coomera area

1:100 000 mapping

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5. ACID SULFATE SOILS – AN OVERVIEW

5.1 Brief description

The term 'acid sulfate soil' is a generic term given to naturally occurring soils and sediments principally of marine origin that contain iron sulfides, mainly pyrite (FeS_2). ASS require sulfate, iron, organic matter and anaerobic conditions to form. In the presence of organic matter (eg. from decaying plant material), anaerobic sulfide-forming bacteria extract sulfate from seawater and reduce it to sulfide. Through a series of chemical reactions, this sulfide combines with iron from terrestrial, freshwater sediments to form iron sulfides. The most common iron sulfide is pyrite, although iron monosulfides and hydrogen sulfide gas can also be formed. Flushing, for example by tidal regimes, removes bicarbonate ions assisting the formation of pyrite as per the following equation:

$$4SO_4^{2-} + Fe_2O_3 + 8CH_2O + \tfrac{1}{2}O_2 \rightarrow 2FeS_2 + 8HCO_3^- + 4H_2O \quad (1)$$
$$\text{sulfate ions} + \text{iron oxide} + \text{organic matter} + \text{oxygen} \rightarrow \text{pyrite} + \text{bicarbonate ions}$$
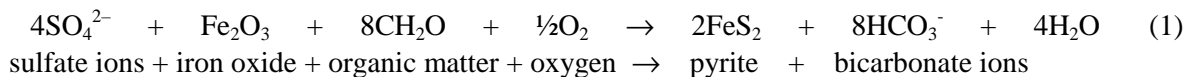
These soils can be either 'potential' or 'actual' acid sulfate soils or a combination of both in the one profile. Normally actual acid sulfate soils (AASS) overlie and grade to potential acid sulfate soils (PASS) (see Plate 1). AASS generally occur in upper layers more prone to oxidation such as the zone of watertable fluctuation. PASS generally remain in a reduced state below the watertable.

Plate 1. A typical acid sulfate soil profile. The oxidised actual acid sulfate soil layer is visible from 0.35–0.95 m, with jarositic (yellow-coloured) mottles present. The dark grey, unoxidised potential acid sulfate soil layer underlies the AASS layer.

The nature of the formation of these materials and their low position in the landscape (<5 m AHD) has meant that most have been preserved under anaerobic conditions below the watertable. While under the watertable they are relatively stable and are called potential acid sulfate soils (PASS). In the field, PASS are usually grey to dark olive grey in colour (2.5Y41 to 5Y41 to 5GY31 in the Munsell soil colour chart). They are typically wet, fine textured soils (eg. mangrove muds), but may be sandy or more rarely, gravelly. When PASS remain in their undisturbed, natural, waterlogged state, they are environmentally 'benign'.

Upon exposure to the atmosphere (as a result of drainage, cultivation or excavation), chemical reactions involving water and oxygen convert the iron sulfides to sulfuric acid (H_2SO_4). The acid released as a consequence of an ongoing drying and wetting process, has the ability to lower the natural pH of the soil and soil water to less than pH 4.0. Under these conditions, potentially toxic quantities of acid, iron, aluminium and heavy metals are released into the surrounding environment. PASS that undergo this process are referred to as actual acid sulfate soils (AASS).

AASS are usually browner in colour than PASS due to their oxidised nature. They can vary in texture from sands through to clays. They often show significant red and orange mottles, indicating their oxidised state. AASS are generally but not exclusively characterised by a yellow coloured mottle called jarosite, which is strong evidence that sulfuric acid has been released (see Plate 1). Jarosite is formed as an intermediate product of the oxidation process and as a result is most often observed in old root channels (where the oxygen has reached the iron sulfides as the root decomposed), in soil cracks, and on banks or cuttings. Jarosite requires strong oxidising conditions, a potassium source and a pH of approximately 3.7 or lower to form (Ahern and McElnea 2000). As there are few natural situations that cause pH to drop to these levels, jarosite is one of the better indicative signs of AASS.

5.2   Oxidation of iron sulfides

Oxidation of pyrite, the main source of the acidity in acid sulfate soils, can be described by the following equations. The initial step in pyrite oxidation is the production of elemental sulfur (S) and ferrous ion (Fe II) (White and Melville 1993):

$$FeS_2 + \tfrac{1}{2}O_2 + 2H^+ \rightarrow Fe^{2+} + S_2 + H_2O \tag{2}$$

The sulfur is then oxidised to sulfate and acid (sulfuric acid):

$$S_2 + 3O_2 + 2H_2O \rightarrow 2SO_4^{2-} + 4H^+ \tag{3}$$
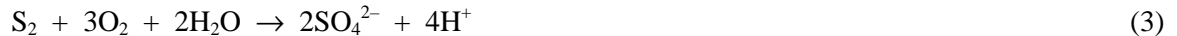
The complete reaction of pyrite to ferrous ion (Fe II) and sulfate can be written as:

$$FeS_2 + {}^7/_2O_2 + H_2O \rightarrow Fe^{2+} + 2H^+ + 2SO_4^{2-} \qquad (2) + (3) = (4)$$
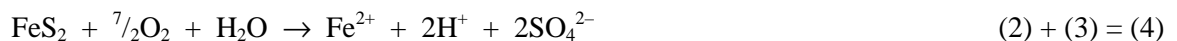
This initial pyrite oxidation reaction tends to be very slow but given an oxygen supply, is inevitable. As the ferrous ion is soluble, it can be transported large distances into streams or it can stay in the original site area. Eventually, the ferrous ion may (in turn) be oxidised to the ferric ion (then goethite), releasing more acid in the process:

$$Fe^{2+} + \tfrac{1}{4}O_2 + {}^3/_2H_2O \rightarrow FeOOH\downarrow + 2H^+ \tag{5}$$
$$\text{ferrous ions + oxygen + water} \rightarrow \text{goethite} + \text{acid}$$
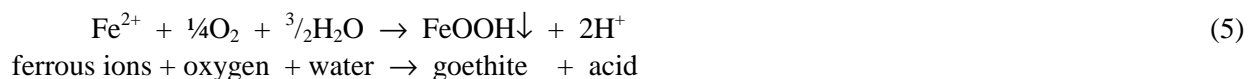
This reaction produces additional acidity and removes dissolved oxygen (DO) from the waterways—both low dissolved oxygen and extreme acidity can cause fish kills.

At the site of acid sulfate soils, the products of the pyrite oxidation process will be acting on the environment or even on each other. The sort of actions required to pre-empt harm or to remedy it, will depend on whether groundwater flows or surface run off removes some or all of the ions involved.

Acid release

The acid released during the oxidation of pyrite can directly cause fish kills and other biotic damage. (It is rarely concentrated enough to affect humans through short-term skin contact). While on-site, the contaminated water or soil can be neutralised by the addition of agricultural lime ($CaCO_3$) or other alkaline neutralising agents. The indirect affects of acid are also serious:

- The acid attacks the insoluble aluminium (Al) in the clay lattice of soils, releasing Al^{3+} into the water where it is extremely toxic to fish and vegetation;
- The acid also upsets the availability of other nutrients in the soil (particularly phosphorus) and can solubilise heavy metals, which can also move into waterways and be taken up by biota (thus entering the food chain); and
- The acid corrodes steel and concrete infrastructure.

Ferrous and ferric ion

As stated earlier, the ferrous ion may also be oxidised to the ferric ion [which further reacts depending on the pH of the solution or soil—see equations (7) and (8) below]:

$$Fe^{2+} \; + \; H^+ \; + \; \tfrac{1}{4}O_2 \; \rightarrow \; Fe^{3+} \; + \; \tfrac{1}{2}H_2O \tag{6}$$
ferrous   ferric

The generation of Fe^{3+} from Fe^{2+} can be a rate-limiting step in the oxidation of pyrite without the presence of bacteria but *Thiobacillus ferrooxidans* can accelerate this reaction ten to ten thousand fold. Optimum conditions for the growth of the bacteria are a temperature around 30ºC and pH of approximately 3. The reaction in equation (6) also removes dissolved oxygen from waterways.

The ferric ion is highly reactive and may oxidise more pyrite. The ferric ion component has several actions, none of which are beneficial to the environment:

- At **pH >4**, Fe^{3+} is precipitated as ferric hydroxide $Fe(OH)_3$ and releases even more acid into the surroundings. The precipitate is seen as a rusty discolouration on bridges or as floccules on the sea-bed (often at distances from the site of production):

$$Fe^{3+} \; + \; 3H_2O \; \rightarrow \; Fe(OH)_3\downarrow \; + \; 3H^+ \tag{7}$$

- **At low pH (<4)**, Fe^{3+} can remain soluble and very importantly when it remains in the soil, it speeds up the pyrite oxidation process, while helping to liberate large amounts of additional acid:

$$FeS_2 \; + \; 14Fe^{3+} \; + \; 8H_2O \; \rightarrow \; 15Fe^{2+} \; + \; 16H^+ \; + \; 2SO_4^{2-} \tag{8}$$
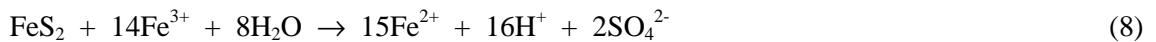
  Note: This reaction, equation (8), does not require oxygen to oxidise pyrite and can occur within an actual acid sulfate soil that has generated ferric ions, even when oxygen is denied by re-flooding or deep burial. For this reason, actual ASS require neutralisation even if being buried.

At different points in time, the acid levels in the solution will vary and therefore one or more of the above reactions [(4) to (8)] may be operating. One of the important factors in moderating the pH is the buffering capacity of the soil—which is dependent on the types and quantities of the clay minerals present, the form of any carbonates present (fine or coarse), and the rate at which the chemical reactions occur.

The **overall reaction for the complete oxidation of pyrite** is given by Dent (1986):

$$FeS_2 \; + \; {}^{15}/_4O_2 \; + \; {}^{7}/_2H_2O \; \rightarrow \; Fe(OH)_3 \; + \; 2SO_4^{2-} \; + \; 4H^+ \tag{9}$$
1 mol   2 mol   +   4 mol
pyrite   sulfate   acid
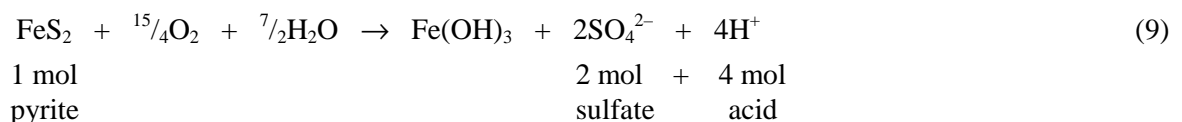
5.3 Impacts

Oxidation of waterlogged sulfidic sediments (ie. PASS) has occurred naturally over time when watertable levels dropped during periods of drought. Acid release would however have been slow and natural buffering capacity in undisturbed landscapes would have reduced the likelihood of environmental damage. However, when large amounts of pyritic sediment are excavated or artificially drained, acid can be produced rapidly and in large quantities. The acid attacks the insoluble aluminium (Al) in the clay lattice of soils, releasing Al^{3+} into the water where it is extremely toxic to fish and vegetation. The acid also upsets the availability of other nutrients in the soil (particularly phosphorus) and can solubilise heavy metals, which can also move into waterways and be taken up by biota (thus entering the food chain).

The impacts of acid sulfate soils are widespread and can be divided into three broad categories: agronomic impacts; engineering impacts; and environmental impacts.

Agronomic impacts

Acid sulfate soils pose chemical, biological and physical problems for crops (Dent 1986). The sulfuric acid produced causes severe acidity often attaining pH levels less than 3. These acid conditions also enable heavy metals to become soluble causing plant toxicities of aluminium, iron III and manganese, which can severely restrict crop growth and cause death (Dent 1986). Farm productivity can also be reduced by acid sulfate soils (see Plate 2), as nutrient availability for pastures can be severely restricted by acidic conditions allowing unpalatable acid tolerant weeds to invade paddocks. Grazing animals living in these areas are at risk of consuming excess amounts of aluminium and iron (Sammut and Kelly 2000).

Plate 2. Cane death due to acid sulfate soil disturbance

Engineering impacts

In the undisturbed state, pyritic muds behave as super-saturated gels that have very low bearing strength (Dent 1986) and this makes them unsuitable for foundation support. The sulfuric acid produced following exposure of sulfidic sediments corrodes both concrete and steel (see Plate 3). The iron in pyrite oxidises to form iron oxides, which can choke drains (Plate 4) and pipes for significant distances downstream of the acid source.

Plate 3.   Acidified water from disturbed acid sulfate soils attacks concrete bridge pylons

Plate 4.   Iron oxides produced during oxidation of pyrite can choke drains

Environmental impacts

ASS disturbance has a very real potential impact on water quality and aquatic life. Acid leached into water bodies is not beneficial to aquatic life, and moreover it can increase the solubility of aluminium and release various forms of soluble and precipitated forms of iron (Plate 5). Aluminium in particular has severe effects on gilled organisms causing death and disease of fish and crustaceans.

Plate 5. Iron stained Pimpama River (pH 3.2, EC 3.15 mS/cm, DO 1.2% saturation)

Fish diseases attributed to acidic discharges include red spot (Epizootic Ulcerative Syndrome), which occurs when the protective mucous covering the fish is removed by acid water. This allows a fungus to enter the skin and create large red ulcers on the body of the fish. A decrease in the growth rates and productivity of aquaculture species such as oysters has also been attributed to acid release from disturbed acid sulfate soils (White *et al.* 1996). Certain forms of the iron released from ASS disturbance can deplete oxygen in aquatic habitats, which in turn can cause or contribute to the death of aquatic species. The release of acid can also acidify poorly buffered soils such as those dominated by sand. This can restrict growth and kill intolerant native flora.

Plate 6. Red spot disease (Epizootic Ulcerative Syndrome)

6. *GEOMORPHOLOGY*

6.1 Background

Sea level fluctuations coinciding with periods of glaciation over the last 140 000 years and particularly the last 10 000 years, have produced conditions along the Australian coastline that were conducive to the formation of pyrite. Dent (1986) states 'Pyrite accumulates in waterlogged soils that are both rich in organic matter and flushed with dissolved sulfate usually from seawater'. These soils can range in texture from sands through to muds.

Stradbroke Island to the east of the study area is essentially a sand island of quaternary sand deposits, which built up behind a rock barrier composed of undifferentiated rhyolitic lavas in the northeastern corner of the island. These sand deposits were formed in a much earlier period, when the sea level was lower. Sand on the continental shelf to the east would have washed onto beaches where wind action blew it further westward to create high dunes.

During an interglacial period (140 000 to 120 000 years ago) within the Pleistocene epoch, there is evidence to suggest that sea levels were several metres higher than present (Pickett *et al*. 1985). This caused the drowning of river valleys and lowlying coastal areas. In general, shorelines were pushed many kilometres west and estuaries similar to those of today were formed. The dark blue areas seen in Figure 3 indicate the approximate area of this flooding.

Since the high level of 140 000 to 120 000 years ago, sea level has oscillated between 80 and 140 metres below present (Hekel and Day 1976) and the shoreline would have been up to 40 kilometres east of where it is today (Jones 1992). It is reasonable to assume that as the sea retreated to such a low level, the associated increasing hydrological gradient gave accelerated erosional power to the Logan River. The Logan River today has a catchment area of approximately 3850 square kilometres, however with the falling sea level this would have been much greater. Consequently, the Logan River and other local rivers would have excavated channels and basins of varying size and depths, according to the size of the river itself and the resistance of the various components of the land surface.

The most recent sea level rise at the end of the last glacial period (post glacial transgression) began around 19 000 years ago. At this time sea level was approximately 140 metres lower than present and the shoreline would have been up to 40 kilometres east of where it is today (Jones 1992).

At the commencement of the Holocene period (10 000 years ago), the sea level was approximately 25 metres below present and still rising (Thom 1981). Present sea level was reached around 6 500 years ago (Thom and Roy 1985). There is evidence to suggest that a minor rise of approximately 1 m occurred along the southern Queensland coast sometime after this with sea level returning to its present position around 4 000 years ago (Jones 1992).

The rapid rate of sea level rise during the Holocene far outstripped the rate of coastal deposition processes and thus again drowned valleys and lowlying coastal areas as it did during the Pleistocene. However once sea level rise stabilised, new estuaries were formed and coastal deposition processes were able to commence filling the newly created subaqueous space (Graham and Larson 1999). The depth of sediment deposited depended on the size of the local river system and the depth of down cutting that occurred during the Pleistocene low sea levels. Deposition of sediments on the Logan–Coomera floodplain varies from filled deep channels, which we now know were up to 30 metres below the present surface, to old resistant 'highs' either below or above the present coastal plain.

When the sea finally retreated back to its current level the rivers and creeks cut back through these deposits removing some and covering others with terrestrial sediments during flood events.
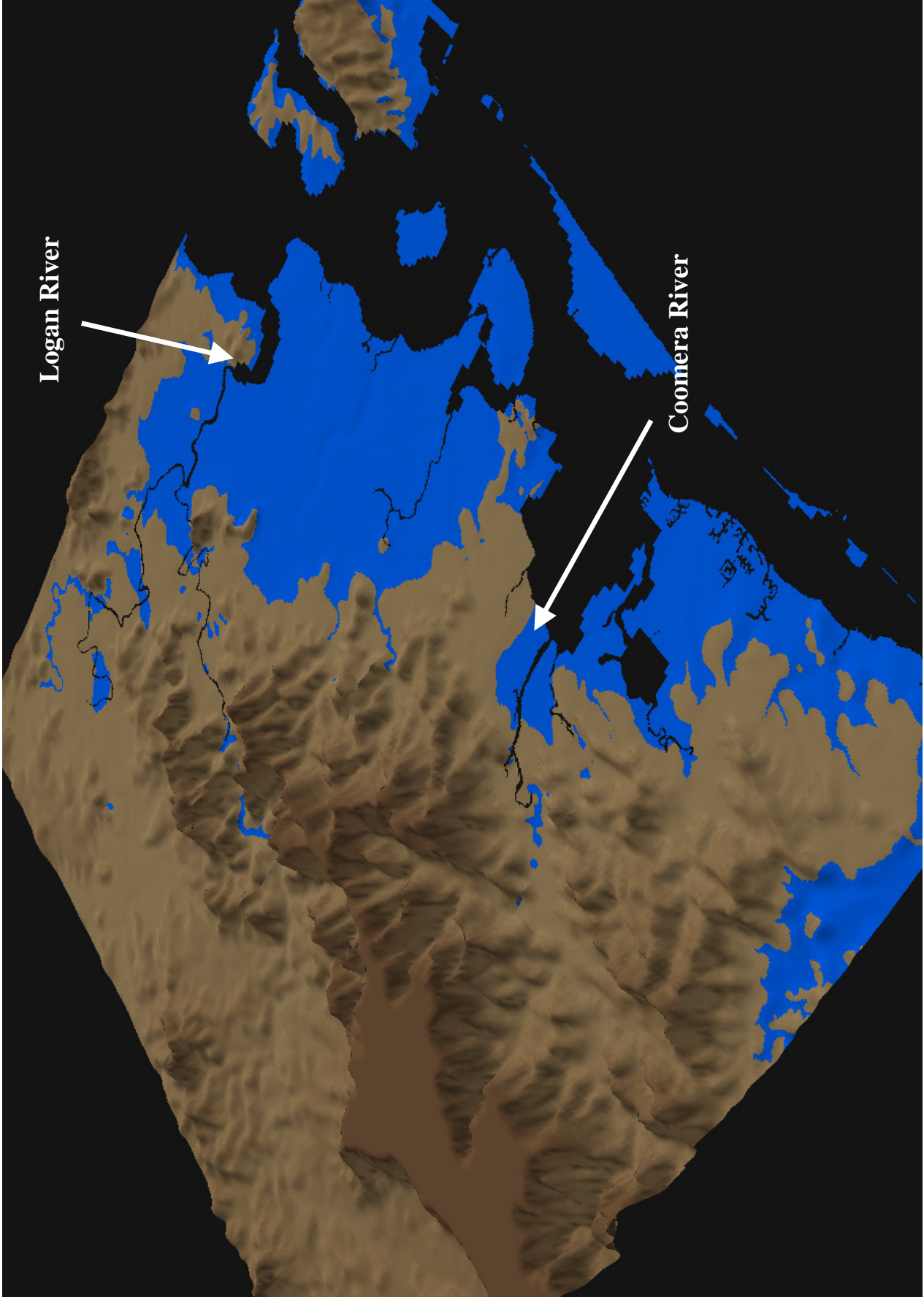
Figure 3. Likely area of inundation by Pleistocene high sea level.

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6.2 Geomorphology of estuaries

Understanding the geomorphology of an area is an integral part of mapping acid sulfate soils. The following provides a basic insight into the coastal processes that have enabled acid sulfate soil formation on the Logan–Coomera area at the northern end of Queensland's Gold Coast.

Dalrymple *et al*. (1992) defined an estuary as the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes. According to Dalrymple *et al*. (1992), ideal estuaries can be divided into three energy zones (Figure 4):
   (A) an outer zone dominated by marine processes ie. waves and tidal currents;
   (B) a low energy central zone where incoming marine energy is balanced by river energy; and
   (C) an inner river dominated zone.
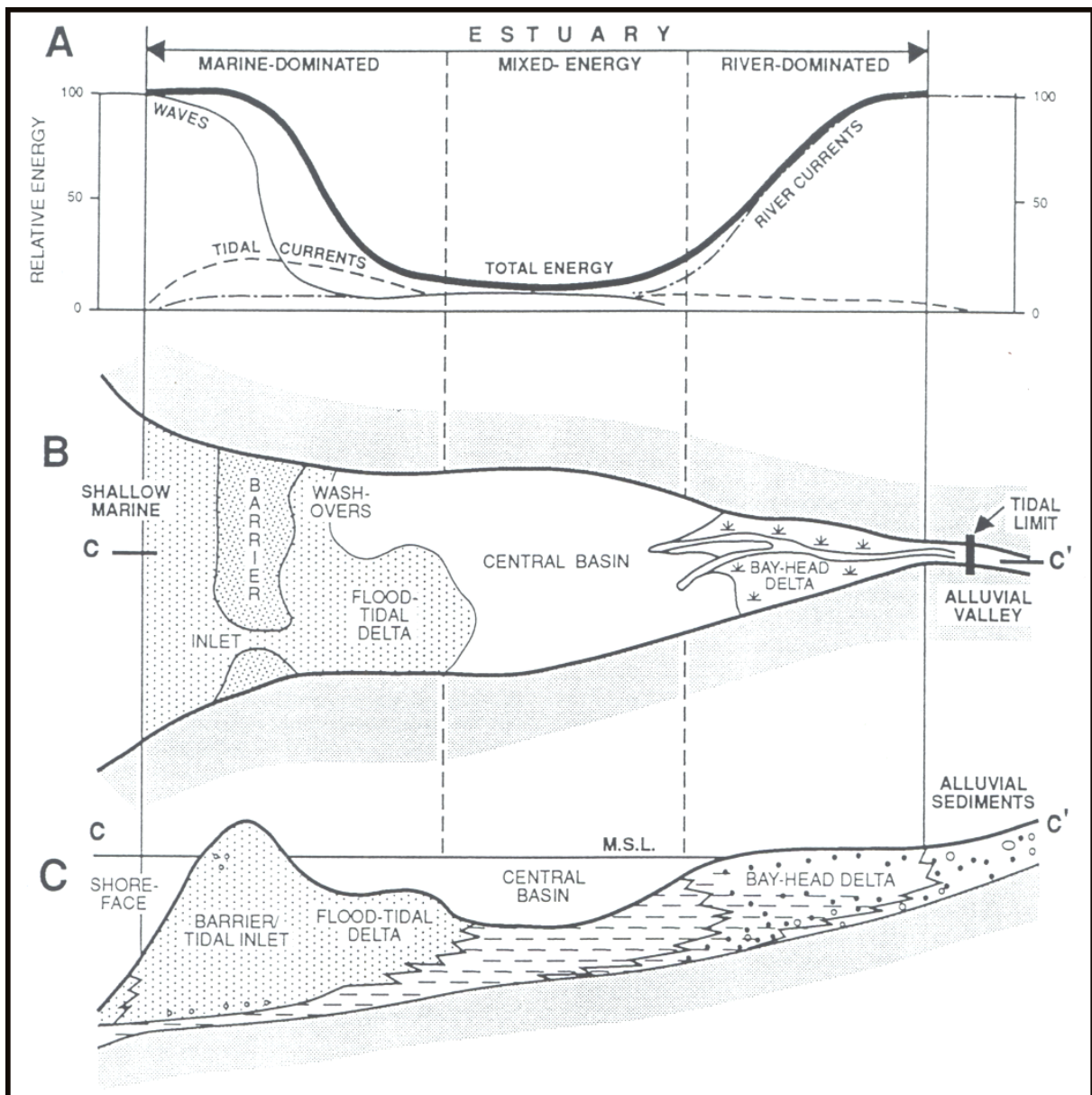
Figure 4.   Estuary energy zones as described by Dalrymple *et al*. (1992).

The coastal classification of Roy (1984) subdivides estuaries into wave and tide dominated types. The Logan River estuary is of the wave dominated type.

In wave dominated or barrier type estuaries, the mouth of the system experiences relatively high wave energy. The high wave energy, in combination with tidal currents causes sediment to move along shore and onshore into the mouth of the estuary where a barrier such as a spit or submerged sand bar forms. These barriers then prevent much of the wave energy from entering the estuary (Dalrymple *et al*. 1992). In general, marine sands are deposited as **tidal deltas** behind the **barrier** by incoming tides. Whilst in the upper reaches (dominated by river energy), fluvial sediments are deposited as **bay head or fluvial deltas**. The area of neutral energy (**central basin**) between the two is generally filled with finer sediment such as clays and silts (shown diagrammatically in Figure 4).

With time and a sufficient sediment supply, estuaries eventually fill with sediment and mature (Roy 1984). The central basins (or lagoons) are filled and river processes begin to build alluvium out over the top of the marine sediments during flood events.

6.3   Reference to Logan–Coomera area

The coastal zone of southeast Queensland is a wave dominated coastline with a tidal range of approximately 3 metres. Moreton Bay itself forms an 80 km long back barrier lagoon system up to 35 km wide and opens to the Pacific Ocean towards the north. The lagoon is bounded to the east by the dune island barrier North Stradbroke Island, and the barrier sand island South Stradbroke Island. North Stradbroke Island was formed by aeolian processes during periods of low and rising sea levels in the Pleistocene. South Stradbroke Island was formed by shoreline process associated with the Holocene post-glacial transgression (Lockhart *et al*. 1998) some 6500 years ago.

The Logan–Coomera area is a coastal plain located at the southern extremity of Moreton Bay where the lagoon narrows to less than 10 km. When sea level stabilised towards the end of the last postglacial transgression some 6500 years ago (Thom and Roy 1985), most of the coastal plain as we know it today between the Logan and Coomera Rivers would have been inundated by seawater creating a large tidal basin.

From this point on, both fluvial and marine processes began to fill the basin with sediment. Fluvial sediment was deposited from the Logan, Pimpama and Coomera Rivers. Marine sand was supplied through the tidal inlet (Jumpinpin) between North and South Stradbroke Islands. The tidal inlet was closed at some time in the past allowing mangrove colonisation to take place. During this time fluvial silt and clay was deposited in the centre of the basin with fluvial sands only deposited near the mouth of the rivers. Since the tidal inlet was reopened in 1898 during southeast gales, tidal conditions have changed and the relic tidal delta is experiencing active erosion and scouring of tidal channels (Lockhart *et al*. 1998). The Logan-Coomera coastal plain would experience daily tidal inundation if not for floodgates being installed.

It is now suspected that in southeast Queensland, sea level actually peaked 0.5–1 metres higher than present 6500 years ago, and then dropped back to current levels 3000–4000 years ago. If this were the case, it would explain why some sulfidic sediments are found at levels above current mean sea level.

Flood tidal delta

Marine or flood tide deltas are formed where high-energy water moving through the restricted estuary mouth during incoming tides, deposit sand on the inside of the sand barrier (Dalrymple *et al*. 1992). These generally contain medium-grain (shelf) sands and shells deposited by waves and tidal currents, often representing transgressive sand sheets overlapping muddy estuarine landward sediments.

The Logan River is the major depositional influence in the north section of the Logan–Coomera floodplain. The Logan River currently enters the Broadwater (tidal area between the coastal plain and the tidal inlet) north of Marks Hill, however deep stratigraphic mapping shows that the Logan River meandered over the floodplain and at one time entered the Broadwater just to the north of Cabbage Tree

Point. Holocene pyritic tidal delta sands and mud layers to a depth of 20 metres or more were found to the north of Cabbage Tree Point (T Graham *pers. comm.* 2000). Similar deposits were found at the mouth of Pimpama River. The theoretical process is modelled in Figure 4.

Flood tide delta sands are located on the coastal plain in the general area north from Woongoolba to the Logan River and east towards the tidal inlet.

Central basin mud

Central basins usually develop in the deepest part of the estuary where the fine fluvial river sediment (silt/clay particles mainly from floods) settles from suspension. The deposits are dark-grey muds, rich in estuarine shells and organic material.

The central basin mud deposits are found mainly in the southern section of the coastal plain along the full length of Pimpama River including the Hotham, Sandy and Behm Creeks. Found generally between 15 and 20 m depth at the mouth of Pimpama River and Behm Creek, the basin muds gradually become shallower towards the upper end of the catchment. Deep deposits to over 20 m are found west of Norwell.

Fluvial delta

Fluvial deltas develop where rivers enter estuarine water bodies and deposit their sediment load (Roy *et al*. unpublished). Sediments of terrestrial origin are deposited especially during flood times and fill the estuary from the upper reaches. These materials eventually fan out and move over the central basin mud. Depositional environments include river channel beds, levee banks, delta mouth bars and crevasse splays.

Fluvial delta deposits are found at depths between 3 and 6 m in the central southern section of the coastal plain.
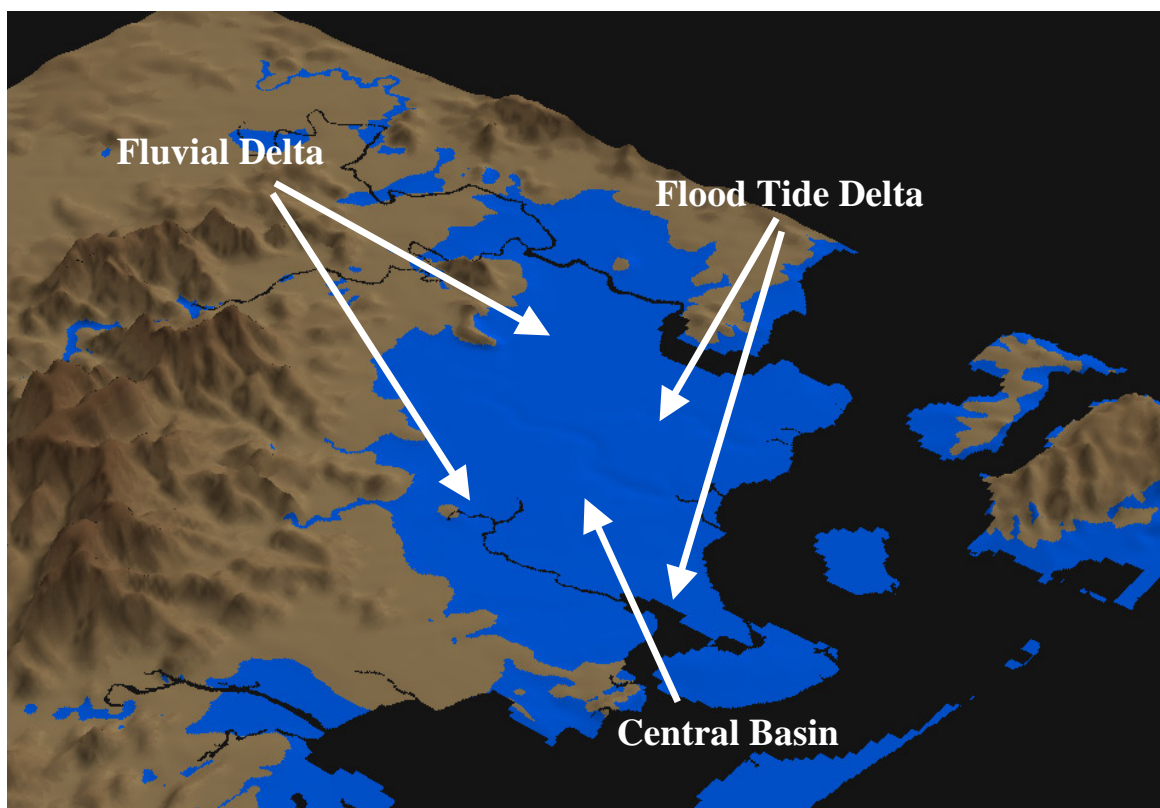
Figure 5. General estuary zones of the Logan–Coomera floodplain

7. *ACID SULFATE SOIL ASSESSMENT*

7.1 Pre-fieldwork planning and assessment

All available geological, geomorphological and topographic information for the study area was collated and assessed. With this background knowledge, aerial photograph interpretation was carried out with a stereoscope using recent colour photos at 1:25 000 scale and black and white photos from 1944 at scales of approx 1:40 000. This enabled the identification of landform and vegetation patterns that are likely to be associated with surface or buried sulfidic sediments thereby identifying appropriate sites for field assessment.

Colour topographic image maps at 1:25 000 scale were then used to identify the 5 m AHD contour line that represents a postulated landward limit of ASS occurrence needing to be field validated. The 1:25 000 scale Topographic Image Maps used have contour elevation data starting at 2.5 m with 5 m increments above the 5 m contour. The selected field assessment sites were marked on these maps at an approximate density of 16 sites per km^2 in accordance with 1:25 000 scale free soil survey mapping (Reid 1988).

7.2 Field survey methodology

Soil cores were taken to a maximum depth of 5 m (where possible) at each site selected in the pre-field phase. Early in the project the maximum sample depth was commonly 3 m but this was extended as new sampling equipment was designed. Site conditions or observations made during fieldwork sometimes led to the selection of alternate or additional sites. GeoCoastal (Australia) Pty Ltd drilled several deeper soil profiles in conjunction with NR&M to determine the stratigraphic characteristics of sediments in the Logan–Coomera area.

Sampling equipment

Acid sulfate soils vary widely in texture and wetness and tend to occur in situations where access is difficult. A variety of sampling equipment was therefore needed to obtain suitable soil cores (see Plates 1 to 7 in Appendix 1). Manual equipment used for sampling ASS includes spades, Jarret and sand augers, piston samplers, and gouge augers.

Mechanical sampling equipment used included spiral (cork screw) auger, vacuum vibro corers of 5 m and 6 m length and the Geoprobe®[1] (which uses direct push and percussion of a solid barrel with a removable sample liner). Typically, because drier (often non-pyritic) soils overlie wet pyritic sands and muds, a combination of manual and mechanical equipment is needed to extract an uncontaminated core.

7.3 Field sampling procedures

The field sampling guidelines which are set out in Ahern *et al.* (1998) and Ahern *et al.* (2000a) were closely followed to ensure reliability and uniformity of field and laboratory testing.

Over 725 soil profiles were described using the nomenclature of McDonald *et al.* (1990). Soil profile properties described include horizon depth, colour (Munsell 2000), mottles (including jarosite), texture, coarse fragments (eg. shell) and pH. Soil field pH tests were recorded at 0.25 m intervals, firstly in a 1:5 soil:water paste (pH$_F$), and secondly after the addition of 30% hydrogen peroxide (pH$_{FOX}$) (pH adjusted to the range 4.5–5.5). The level of effervescence produced during the pH$_{FOX}$ reaction was also recorded. A significant depression in pH caused by reaction with the peroxide is a good field indicator of the presence of pyrite.

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[1] Geoprobe is a registered trademark of Kejr Inc., Salina, Kansas.

It must be noted the field pH tests as an indicator of ASS should be used with caution and should always be supported, initially at least, with the appropriate laboratory analyses as per the NR&M *Guidelines for Sampling and Analysis of Lowland Acid Sulfate Soils (ASS) in Queensland* (Ahern *et al.* 1998) (which is obtainable from NR&M). Hey *et al.* (2000) provides a detailed assessment of the field test procedure and of the considerations needed when undertaking field tests to determine ASS risk.

A critical component of the soil profile description is the recognition of soil horizons. A soil horizon[2] is a layer whose morphological properties make it distinct from the horizon above and below it. The implication is that each layer will likely be homogenous in all its properties.

All profiles were sampled for laboratory analysis at the following intervals, except where these crossed horizon boundaries: 0–0.1 m, 0.2–0.3 m, 0.5–0.6 m, 0.8–1.0 m and then at intervals of 0.5 m. Samples were placed in sealed plastic bags and refrigerated immediately using portable fridge/freezers. Upon receipt at the laboratory, samples were dried, ground and analysed according to the standards set out in the *Guidelines for Sampling and Analysis of Lowland Acid Sulfate Soils (ASS) in Queensland.*

7.4 Laboratory analysis

The main assessment for pyrite content carried out on all samples is **Total Oxidisable Sulfur (TOS),** (Ahern *et al.* 2000b). This method assesses the amount of total sulfur (S_T) in all forms including pyrite (by X-Ray Fluorescence spectroscopy), and then subtracts the sulfur that is extracted by 4M hydrochloric acid. The latter (S_{HCl}) estimates the sulfur in non-pyritic forms such as that adsorbed on clay particles, in jarosite, and in water-soluble form. The remainder is the estimate of pyritic sulfur and hence is the potential of the soil to release acid if aerated under wetting and drying conditions, ie. $S_{TOS} = S_T - S_{HCl}$.

The **Peroxide Oxidation-Combined Acidity and Sulfate** (**POCASm)** (Ahern *et al.* 2000c) method was used as a secondary assessment of pyritic acidity to validate the TOS results on a selection of samples. These samples were selected because they have attributes which in effect mean that the TOS method alone may not give a complete assessment of the environmental risk posed by ASS. The POCASm method uses hydrogen peroxide to oxidise the pyrite in the sample to acid, and then compares the titratable acidity produced (the acid trail) with the actual sulfur content (or sulfur trail) in the same digested solution. The POCASm method gives a better estimate of potential acidity if there is inherent neutralising capacity in the sample. Additionally, it assesses actual acidity which, in some soils also poses an 'immediate' environmental threat. Results from the POCASm method include **Peroxide Oxidisable Sulfur (S_{POS}), Total Actual Acidity (TAA)** and **Total Potential Acidity (TPA)**.

A limited number of samples (mainly surface) were analysed by the **Chromium Reducible Sulfur (S_{CR})** method, recently modified by Sullivan *et al*. (2000). This approach gives a better approximation of pyrite content in highly organic sediments. This method measures reduced inorganic S compounds including pyrite (and other iron disulfides), acid volatile sulfides (AVS) and elemental S. The method can be made specific to the iron disulfide fraction with appropriate pre-treatments to remove AVS and elemental S fractions. It is unaffected by the presence of organic matter and has good precision and accuracy, especially at low levels. S_{CR} is the preferred method for low analysis sands and for highly organic or peaty soil because of its ability to measure reduced inorganic S.

Priority of laboratory methods
Where more than one analytical method was used to determine oxidisable sulfur (%S), then priority was in the order of Chromium Reducible Sulfur (S_{CR}), Peroxide Oxidisable Sulfur (S_{POS}) and then Total Oxidisable Sulfur (S_{TOS}) result. For example if the S_{TOS} laboratory result of a sample exceeds the action criteria, but the sample also has a S_{CR} result that is below the action criteria, then the S_{CR} result will take precedence and the sample will be deemed to be below the action criteria as it is assumed that organic sulfur was inflating the S_{TOS} result.

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[2] In traditional soil surveys, the term applies primarily to the material that has undergone some form of pedological development, and hence only the upper one to two metres are considered. In ASS mapping, a greater depth of material is described and so horizons with little or no pedological development are encountered. In this context, an important distinction is made between horizons and sedimentary facies. A facies can be considered to be one, or a group of horizons that have a distinct mode of deposition or source of sediment.

7.5 Database recording

All field and laboratory data has been entered into the NR&M Soil and Land Information Database (SALI), which was designed specifically for land resource surveys conducted by NR&M. Terminology and codes used in the database are fully compliant with the *Australian Soil and Land Survey Field Handbook* (McDonald *et al.* 1990). **Volume 2** provides the decoded field descriptions of the profiles described in the survey.

An important function of the database is to collate both soil profile morphology data and laboratory analysis results by horizons. All data from each soil profile can therefore be displayed in tabular format, and data from each horizon can be seen as a distinct 'layer' of information (see **Volume 3**).

7.6 Interpretation of field and laboratory data

The determination of which samples (and hence which soil horizons/layers) constitute an actual and/or a potential acid sulfate soil is based on an assessment of field morphological properties, field pH tests and laboratory results.

Potential acidity

The analytical result expressed as a percentage of oxidisable sulfur (%S) of the sample is used as the diagnostic test for potential acidity. Soil colour, mottles and coarse fragments such as shell in the same horizon are noted to cross check with the %S result. The %S values which meet or exceed the texture-based ASS action criteria (Ahern *et al.* 1998) of 0.03 %S for sands; 0.06 %S for loams to light clays, or 0.1 %S for medium to heavy clays were used as the determinants of potential ASS[3].

The above action criteria values are built into the SALI database and hence each %S result for each sample in each horizon is automatically ascribed a code (according to texture) if it exceeds the action criteria, ie. Ps for sands, Pl for loams and Pc for clays. The first horizon in which the action criteria is meet or exceeded is assigned a 'PASS code', which is a capital 'S' in combination with a 'Depth Code' according to where the depth of upper boundary of that horizon occurs. For example, if the upper boundary of the horizon occurs at 1.2 m the code would be **'S2'** as shown in Table 1.

Table 1.   Potential acidity depth codes

Depth interval	Depth code	PASS code
0.0–0.5 m	0	S0
0.5–1 m	1	S1
1–2 m	2	S2
2–3 m	3	S3
3–4 m	4	S4
4–5 m	5	S5
>5 m	5+	S5+

Actual acidity

A **field pH value of 4 or less** was used as the determinant of actual ASS. If a field pH of less than or equal to 4 is registered then the horizon is assigned a depth code similar to the 'depth to PASS' code. However instead of an 'S' prefix it will have an 'A' prefix and be a 'depth to AASS' code. For example a horizon with a pH of less than or equal to 4 and with an upper boundary of 0.2 m would be assigned **'A0'** as shown in Table 2.

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[3] The texture based ASS action criteria of 0.03, 0.06 and 0.1 %S for sands, loams to light clays and medium to heavy clays respectively only apply to disturbances less than 1000 tonnes. For disturbance >1000 tonnes, 0.03 %S applies regardless of texture.

Table 2. Actual acidity depth codes

Depth interval	Depth code	AASS code
0.0–0.5 m	0	A0
0.5–1 m	1	A1
1–2 m	2	A2
2–3 m	3	A3
3–4 m	4	A4
4–5 m	5	A5
>5 m	5+	A5+

The automatic database determination of AASS uses the field pH value rather than an analytical laboratory result, such as Total Actual Acidity (TAA), which was only completed in small numbers. The analytical result of TAA expressed as mol of hydrogen per tonne (mol H^+/t) is included in the laboratory results. The TAA values that exceed the action criteria [18 mol H^+/t for sands; 36 mol H^+/t for loams to light clays; or 62 mol H^+/t for medium to heavy clays] are the true determinants of AASS.

It is not uncommon to find actual acid sulfate soil overlying potential acid sulfate soil. In these cases the 'A' code and the 'S' code are combined. For example **'A0S2'** denotes a pH less than or equal to 4 occurs between 0 and 0.5 m and PASS occurs at 1 to 2 metres.

Strongly acidic soil

Due to the wealth of pH data obtained during the project and the importance of pH to agriculture, it was also decided to indicate areas where pH values of between 4 and 5 were recorded. In these cases the same depth categories were used preceded with a lower case 'a' as shown in Table 3. For example, a profile registering a field pH of between 4 and 5 at a depth of 0.5 to 1 m will be labelled **'a1'** and if this overlays PASS at 2–3 m it will be **'a1S3'**. Soils registering a field pH of between 4 and 5 are not always necessarily associated with sulfidic estuarine sediments. These may often be due to 'organic acidity' of surface or near-surface layers or the use of acidifying fertilisers.

Table 3. Strongly acidic soil depth codes

Depth interval	Depth code	Strongly acidic code
0.0–0.5 m	0	a0
0.5–1 m	1	a1
1–2 m	2	a2
2–3 m	3	a3
3–4 m	4	a4
4–5 m	5	a5
>5 m	5+	a5+

If a site has a strongly acidic horizon as well as an AASS layer with a PASS horizon below, the AASS horizon will take precedence so that the site code will reflect only the AASS and PASS code. The database also calculates the weighted average S_{TOS} %S to the depth of sampling. Volume 2 and 3 display selected morphological data, laboratory analysis results and calculated criteria for each soil profile.

Overriding potential determination of %S

Because most of the %S determination was conducted using the TOS method it is sometimes necessary to override a positive PASS result where it is thought to be positive due to organic matter. Though S_{CR} is the preferred method for measuring inorganic S, the S_{CR} method was not available until the later stages of project and is not possible to repeat all the analysis already conducted.

The following is not comprehensive, but does provide some of the decision process to override (alter the depth to code) a TOS result.
- Knowledge obtained from the morphological description such as field pH, reaction, colour, and soil type ie. podsol.

- Landscape position—an aerated soil, which is dry and fully oxidised.
- Referred from similar adjacent sites, which have had a negative S_{CR} result overriding a previous positive TOS result.
- Is the depth of 1st action level near the surface and is there a gap (of at least 1 horizon) between the upper action criteria (P) code/s and the next P code. The gap should comprise either below action level results or significantly lower %S results.

7.7 Mapping

Following the collation of field and laboratory data in the database, clear overlays to fit the 1:25 000 Topographic Image Maps are compiled which depict the location of each field site together with its accompanying PASS and/or AASS 'depth' code.

Lines are marked on the clear overlay which enclose areas (polygons) that contain field sites with similar AASS/PASS codes, that is land parcels that are relatively homogenous in terms of the depth to the first AASS and/or PASS layer. These polygons are referred to as 'unique mapping areas' (UMAs) and are coded according to the most common AASS/PASS depth code.

Given that the original site selection was based on a landscape interpretation process, each UMA therefore has a genesis based not only on the similarity of ASS laboratory results, but also on a commonality of landscape features such as surface elevation and landform/geomorphic type.

There is a significant variation across the landscape in AASS features because they are influenced by disturbances such as land levelling and drainage works, as well as soil texture. Areas with uniform PASS features are therefore commonly subdivided according to AASS variation. If a mapping unit has no PASS, then AASS codes may be used to delineate the mapping unit.

UMAs have been ascribed different colours according to their respective AASS/PASS depth code category, red being used for the shallowest depth. Where AASS occur, a yellow dot stipple is used in addition to the depth code colour.

Other categories such as the S_{DL} category deal with various types of disturbed land where ASS is likely to be present but ground truthing was not possible—see reference on the map supplied with this report.

It was also necessary to develop a category to cater for recent findings of Pleistocene age sulfidic sediments. These often occur at depths greater than 5 m below some quite impenetrable layers. Whilst for all intents and purposes these are still acid sulfate soils, they were generally considered outside the scope of this mapping project. Where these sediments were encountered they have been denoted with a superscript 'p' such as in **'S^{p}5'** (see map reference).

Laboratory analysis results showed varying levels of sulfides in some seasonally wet areas. These areas were associated with *Melaleuca* sp. and *Casuarina glauca* and were often underlain by PASS at depth. Although the Chromium Reducible Sulfur method showed many of these high surface results to be due to organic sulfur as opposed to pyritic sulfur, there were some that remained high. The scale of mapping did not always allow differentiation of these areas. A subscript 'w' has been used to flag wet areas associated with *Melaleuca* sp and *Casuarina glauca* eg. **'S2$_W$'**. Surface disturbance in these areas should be avoided without more detailed investigation.

The 1:25 000 scale map also shows the location of each field site. For more detailed information regarding interpretation of mapping codes, refer to **Appendix 2** of this report and the legend on the map provided.

Approximately 14 552 ha of land <5 m AHD was assessed between the Logan and Coomera rivers involving description and sampling of 725 boreholes. Outcrops of old residual landforms of Triassic and Silurian age that are greater than 5 m AHD are present on the eastern edge of the floodplain, namely Marks Hill (18 m), Cabbage Tree Point (14 m), Behms and Skopps Rd (17 m). They are not part of the estuarine Holocene sedimentary sequence and are not included in the 14 552 ha study area.

During the course of the project 7566 samples were taken for chemical analysis. Oxidisable sulfur (%S) results were obtained for 7028 of these samples using several analytical methods, including 6805 results by Total Oxidisable Sulfur (TOS), 403 results by Peroxide Oxidation Combined Acidity and Sulfate (POCASm) and 457 results by Chromium Reducible Sulfur (S_{CR}) analyses. The oxidisable sulfur values ranged from below detection levels to a maximum of 4.7 %S across mapping areas and soil texture groups. Average oxidisable sulfur values for sulfidic clays across all areas was 0.82 %S whilst for sulfidic loams the average was 0.38 %S and for sulfidic sands the average was 0.15 %S.

The ASS mapping defined several mapping categories over the 14 552 ha of land assessed. Potential acid sulfate soils (PASS) were defined as soils with field pH (pH_F) >5, and oxidisable sulfur (%S) results meeting or exceeding the texture-based ASS action criteria (see Table 1 in Appendix 2). Strongly acidic soils contained pH_F >4 and ≤5, with %S results less than the action criteria. Low probability soils had pH_F >5 and %S results less than the action criteria. Actual acid sulfate soils (AASS) contained pH_F ≤4. AASS are likely to be a significant source of acidity with respect to surface and ground waters. Of the 14 552 ha of land assessed, the following categories were identified (see Table 4):

- Potential acid sulfate soils   ~27% of total area (3947 ha)
- PASS with strongly acidic soil layers   ~22% of total area (3158 ha)
- PASS with actual acid sulfate soil layers   ~27% of total area (3902 ha)
- Actual acid sulfate soils   ~6% of total area (886 ha)
- Low probability soils   ~5% of total area (724 ha)
- Low probability soils with strongly acidic soil layers   ~13% of total area (1935 ha)

Table 4.   Area (ha) represented within each of the acid sulfate soil mapping units

		Depth to[1] Actual Acid Sulfate Soil (pH_F ≤4)				Depth to[1] Strongly Acidic Soil (pH_F >4 to ≤5)					Non Acidic soil pH_F >5	Total Area
		A0	A1	A2	A3	a0	a1	a2	a3	a4		
Low Probability (LP)						1935					724	2659
Actual ASS		378	447	61								886
Depth to[1] Potential Acid Sulfate Soil[2]	**S0**	794									2111	
	S1	784	43			520	8				72	
	S2	1886	54			1952					321	
	S3	88	217			469	58			23	81	11007
	S4			36		126						
	S5										34	
	S+						2				79	
	S_{DL}[3]										1249	
Total Area		4788				5093					4671	14552

[1] Depth categories of actual, strongly acidic and potential ASS conditions indicate the depth to the layer where the first occurrence of these conditions occurs, that is, 'A', 'a' or 'S' 0, 1, 2, 3 or 4 indicate 'depth to' categories of 0–0.5, 0.5–1, 1–2, 2–3, and 3–4 m respectively.

[2] A potential ASS is one where the %S value meets or exceeds the texture-based action criteria (Ahern *et al.* 1998) of 0.03 %S for sands; 0.06 %S for loams to light clays, or 0.1 %S for medium to heavy clays.

[3] S_{DL} area is subjected to development and contains varying amounts of PASS and some small low probability areas.

In terms of pH, approximately 33% (4788 ha) of the assessed area is mapped as an actual acid sulfate soil with pH_F values ≤4; approximately 35% (5093 ha) is strongly acidic with pH_F values >4 and ≤5; and the remaining area of 32% (4671 ha) has pH_F values >5 (see Figure 6).
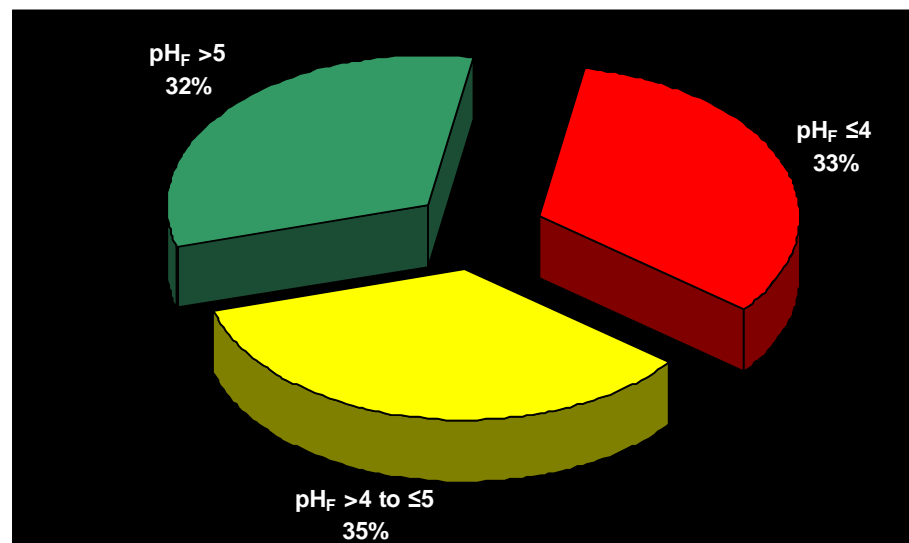
Figure 6.   Distribution of soil pH_F over 14 552 ha of assessed land

The data above is based on the areas of map units that have been coded to reflect the actual and potential acidity properties obtained from each borehole within each unit. A map unit coded A0S0 will comprise a dominance of boreholes that have been classified A0S0. Few map units however are homogenous, so that some units will contain boreholes classified differently to the map unit code. It is also the case that the density of boreholes will vary from one map unit to the next. When examining a parameter like acidity, it is therefore useful to examine to what degree the area data from map units compares to actual borehole data. This is done in Table 5, where it can be seen that the borehole data suggests that there is a greater preponderance of actual (55%) and highly acidic soils (26%) than is indicated by the map unit data.

Table 5.   Number of boreholes in each of the actual and potential acidity codes

		Depth to[1] Actual Acid Sulfate Soil (pH_F ≤4)				Depth to[1] Strongly Acidic Soil (pH_F >4 to ≤5)					Non Acidic soil pH_F >5	Total Area
		A0	A1	A2	A3	a0	a1	a2	a3	a4		
Low Probability (LP)						4	1	1			13	19
Actual ASS		74	15	7	1							97
Depth to[1] Potential Acid Sulfate Soil[2]	**S0**	64	2			8	1				37	609
	S1	60	8			22					22	
	S2	91	18	4		92	3				38	
	S3	23	13	4	1	53		2			15	
	S4	3		2		1					4	
	S5	1				1				1	1	
	S+	8										
	S$_{DL}$[3]											
Total Area		401				190					134	725

[1] Depth categories of actual, strongly acidic and potential ASS conditions indicate the depth to the layer where the first occurrence of these conditions occurs, that is, 'A', 'a' or 'S' 0, 1, 2, 3 or 4 indicate 'depth to' categories of 0–0.5, 0.5–1, 1–2, 2–3, and 3–4 m respectively.

[2] A potential ASS is one where the %S value meets or exceeds the texture-based action criteria (Ahern *et al*. 1998) of 0.03 %S for sands; 0.06 %S for loams to light clays, or 0.1 %S for medium to heavy clays.

[3] S_{DL} area is subjected to development and contains varying amounts of PASS and some small low probability areas.

Of the 11 007 ha of PASS area identified, 88% contained a PASS layer within the first two metres of the soil surface. Figure 7 shows the areas of PASS according to the depth of the first soil layer that exceeds the relevant action criteria.
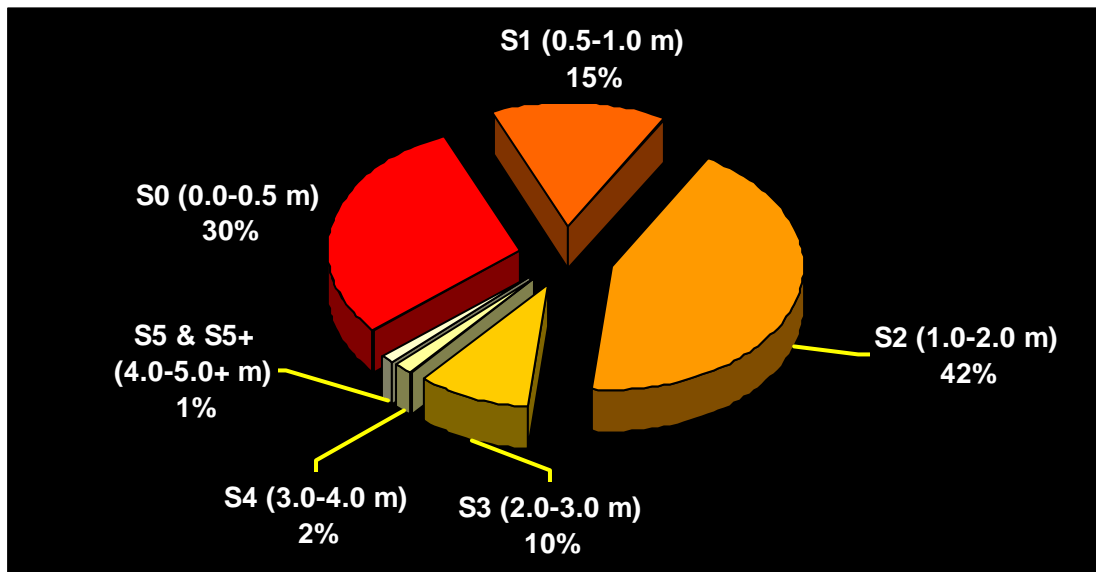
Figure 7. Proportions of the assessed area with potential acid sulfate soils according to depth intervals to the first PASS layer

The total mapping area of 14 552 can be further divided according to the distribution of pH_F values (Table 4 and Figure 8). For example soils within the 'S0' depth interval (0.0 to 0.5 m) totalling 2905 ha can be further divided into 794 ha of AASS (pH ≤4) and 2111 ha with pH >5. The number of soils with pH ≤4 in this category is expected, as the 'S0' mapping units generally occur in the lowest part of the landscape where watertables are highest, thus minimising the depth of the oxidised layer. Conversely, the depth interval 'S2' (1.0 to 2.0 m) occurs higher in the landscape and predictably has a larger area of AASS (pH ≤4) and strongly acidic soil (pH >4 to ≤5) than the pH >5 area.
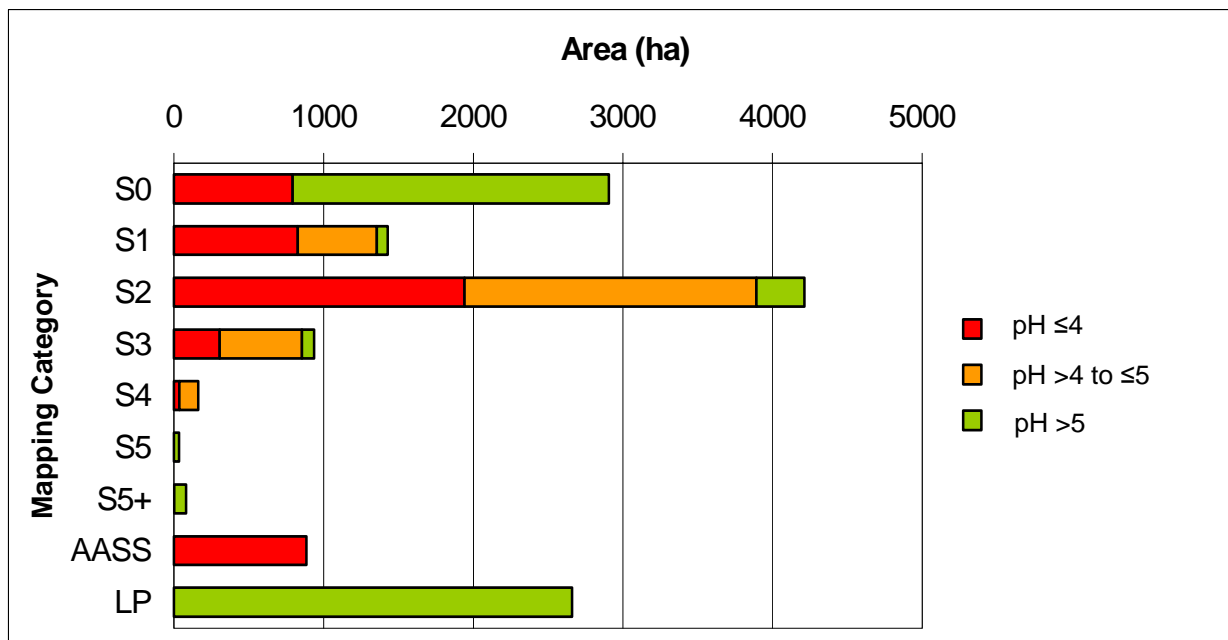
Figure 8. Proportions of the assessed area by depth intervals and pH

Table 6 provides a summary of the interval depths, the total number of samples, texture divisions, percentages and the average and median %S. Total samples are divided into PASS and non-PASS samples with average, median and maximum %S given for each of the texture divisions for the PASS samples.

Table 6.   Depth intervals displaying texture, number of samples and %S average, median and maximum

	Texture	Number of samples	% of total samples	%S Average	%S Median	%S Maximum

Depth 0.0–0.5 m

	Texture	Number of samples	% of total samples	Average	Median	Maximum
Total samples		1347	100	0.06	0.04	
	Sands	34	3			
	Loams	383	28			
	Clays	930	69			
PASS		161	12	0.23	0.14	
	Sands	1	1	0.04	0.04	0.04
	Loams	71	44	0.24	0.13	1.49
	Clays	89	55	0.23	0.15	1.27
Non–PASS		1186	88	0.04	0.04	

Depth 0.5–1.0 m

	Texture	Number of samples	% of total samples	Average	Median	Maximum
Total samples		1240	100	0.18	0.03	
	Sands	102	8			
	Loams	278	23			
	Clays	860	69			
PASS		254	20	0.77	0.62	
	Sands	14	6	0.15	0.06	0.66
	Loams	62	25	0.49	0.37	2.51
	Clays	175	69	0.93	0.92	3.84
Non– PASS		986	80	0.03	0.03	

Depth 1.0–2.0 m

	Texture	Number of samples	% of total samples	Average	Median	Maximum
Total samples		1421	100	0.35	0.07	
	Sands	211	15			
	Loams	397	28			
	Clays	813	57			
PASS		721	51	0.67	0.53	
	Sands	110	15	0.19	0.14	0.80
	Loams	237	33	0.49	0.42	3.80
	Clays	374	52	0.92	0.90	2.70
Non– PASS		700	49	0.02	0.02	

Depth 2.0–5.0 m

	Texture	Number of samples	% of total samples	Average	Median	Maximum
Total samples		2254	100	0.41	0.23	
	Sands	780	35			
	Loams	483	21			
	Clays	991	44			
PASS		1894	84	0.49	0.30	
	Sands	671	35	0.15	0.10	1.15
	Loams	439	24	0.34	0.28	4.73
	Clays	784	41	0.86	0.81	2.70
Non–PASS		360	16	0.03	0.02	

Depth 5.0+ m

	Texture	Number of samples	% of total samples	Average	Median	Maximum
Total samples		547	100	0.35	0.18	
	Sands	194	36			
	Loams	72	13			
	Clays	281	51			
PASS		431	79	0.43	0.44	
	Sands	145	34	0.11	0.07	0.84
	Loams	51	12	0.27	0.19	3.84
	Clays	235	54	0.68	0.63	2.73
Non–PASS		116	21	0.02	0.02	

The red columns in Figure 9 show the percentage of samples collected in each depth interval that contained PASS. The dashed blue columns indicate the percentage of the total samples collected in each depth interval. The figure clearly shows that the probability of finding PASS on the Logan–Coomera floodplain dramatically increases below 1.0 m from the surface.
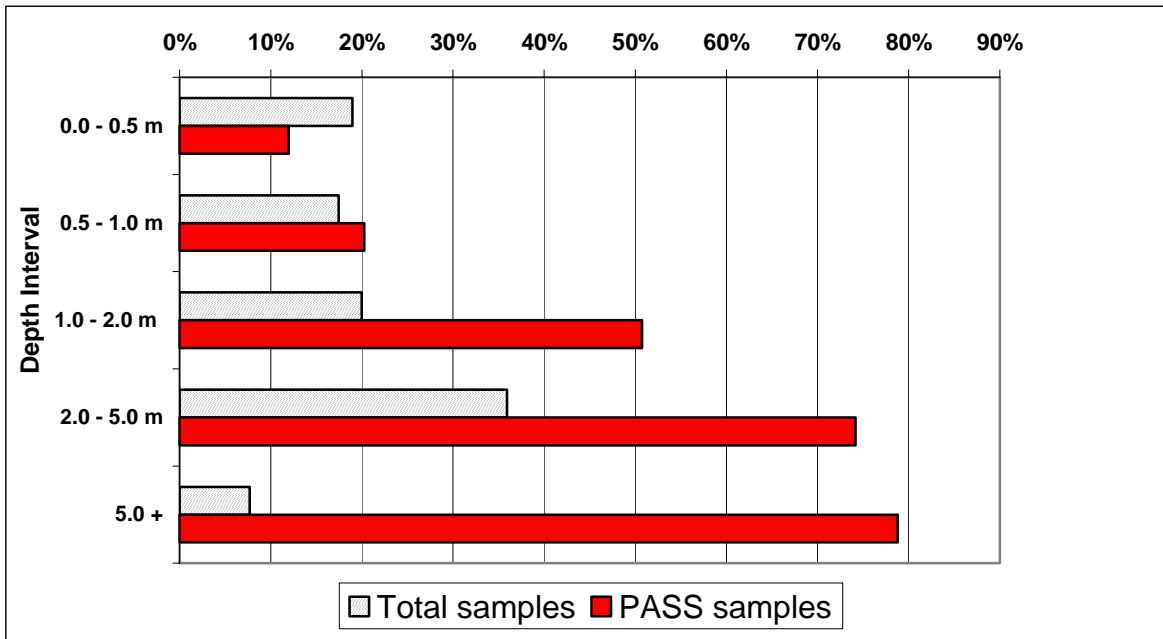
Figure 9. Percentage of samples collected in each depth interval, indicating total samples and PASS samples

Figure 10 shows the total number of samples collected for each texture group and the number of these samples that are PASS. In the upper two metres, the sequence of decreasing texture frequency is clays, loams to sands for all samples, and the same for PASS samples. The proportion of sands to the other textures increases with depth so that below two metres the sequence is clays, sands and then loams. That is, below two metres sand content increases, and loam content decreases, relative to the first two metres.
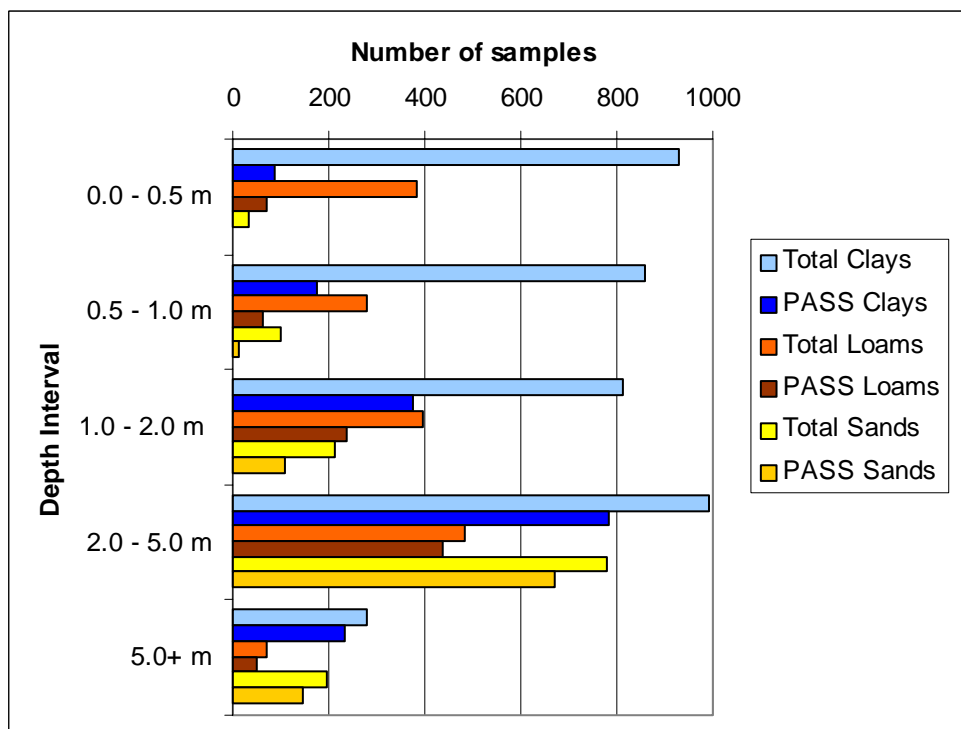
Figure 10. Sequence of texture group frequency for all samples and those with PASS by depth intervals

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The formation of pyrite in marine sediments occurs in low energy zones and therefore clays and loams will generally contain higher concentrations of pyrite than sands. This can be seen in Figure 11 where average %S values increase from sands to loams to clays for all depth intervals. Maximum %S values for all textures increase from the surface to two metres then gradually decrease with increasing depth. These values can also be seen in Table 6.
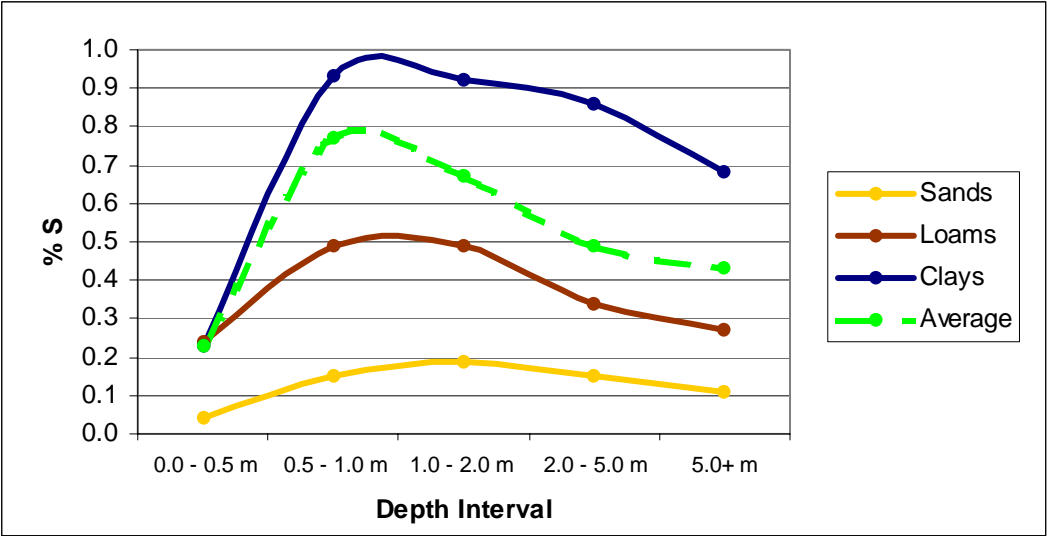
Figure 11. Average %S values for PASS samples by texture groups and depth intervals

9.   *MANAGEMENT PRINCIPLES OF ACID SULFATE SOILS*

9.1   Background

The sustainable management of coastal areas and waters requires a deliberate approach to problems associated with ASS. This implies that individual landowners develop management plans to properly manage these problem soils on their land—but such efforts will be suboptimal (despite goodwill) if the cumulative nature of man-induced impacts from ASS are not approached as a total-area issue. Often the cumulative impacts of many small discharges of acid can be just as damaging as a large release of acid from a single source or event.

All stakeholders benefit from a cooperative assessment of the situation. Government departments and agencies provide supportive advice and information (of which this report is a clear example)—but there is also a growing set of regulations/legislation that places responsibility for any environmental harm with the landowner. Changes in land use can trigger changes in ASS. This applies to urban developments as well as the agricultural industry. In very practical terms, a landowner needs to manage their property to minimise risk; this applies as much to existing cane farms as it does to new developments.

Agriculture needs to modify the landscape if it is to be efficient. This is not usually a problem, but when farms are established on ASS then this can inadvertently set in train adverse consequences. It is prudent for those landowners to examine their existing situation; if remedial management is needed then action is better earlier than later.

9.2   Factors to be considered in managing new disturbances

Where new developments are being established and if these are located in acid sulfate soil areas then the landowner needs to be very wary. Disturbing or dewatering ASS can initiate the oxidation process, which releases large volumes of sulfuric acid and causes the mobilisation of toxic levels of iron, aluminium and heavy metals. The result is a dysfunctional environment both *in situ* and in downstream areas. Often ASS are best left undisturbed, both on economic and environmental grounds.

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 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.

In a new disturbance, any potential or existing acidity should be fully treated and appropriate management strategies adopted according to the site specific conditions. For ASS disturbances, all pollutants [for ASS this usually involves acid, water soluble iron, aluminium and sometimes heavy metals] must be contained and managed within the site boundary and treated to acceptable levels prior to discharge to a natural/external water body. As pH affects the solubility of the main ASS pollutants, pH control of all site water bodies is essential. When water discharge is licensed or approved in the management plan then discharge must only occur when pH is in the approved range (usually 6.5–8.5, depending on site specific conditions).

Once ASS have been disturbed at a site, then potential exists for soluble forms of aluminium (which can be most toxic to fish around pH 5.2; Sammut *et al*. 1996) to be mobilised and released. Because aluminium species in solution are pH dependent and the chemistry is complex in natural waters, raising the pH well above pH 5.2 (eg. pH >6.5) ensures a substantial reduction in the total soluble aluminium concentration and a change in the ionic species present.

Use of stream, river or estuarine water as a primary agent to neutralise acidity is currently **not acceptable** as this removes bicarbonate from the water, which may adversely affect shell formation on crustaceans and the health of benthic communities. On all except minor disturbances, site management plans should incorporate complete bunding of the site to control run off water using non-ASS material in the walls of the bund.

9.3   Management strategies

Not all management strategies are appropriate to the specific situation. Selection of an appropriate management strategy will depend on the physical and chemical characteristics of the ASS, the hydrological circumstances and the environmental sensitivity of the site. Where a significant disturbance of ASS is being proposed, a soil scientist or engineer experienced in ASS management should be consulted.

As ASS can vary in their physical and chemical characteristics, they do not all respond to mitigation strategies in a consistent way. To avoid costly errors, both environmentally and financially, soil investigations at a high intensity should be undertaken to map the distribution of ASS prior to developing mitigation strategies. Such detailed investigations are necessary not only to understand the risks associated with disturbing these soils, but also to determine the most feasible mitigation options.

The chief areas of concern on existing canelands are: the bund walls and spoil heaps containing ASS; flap gates; and deep, frequent drains that lower the watertable and efficiently export acid and/or contaminants. Most of these existing situations can be improved by:
- selective application and incorporation of modest quantities of lime or other neutralising agent to spoil heaps, paddocks, and sides of drains. These will need renewing annually where substantial acid producing potential exists in the soil;
- treating spoil with lime when cleaning out clogged drains;
- resisting the temptation to deepen drains—broad and shallow is environmentally friendly, easier to mow/keep clean and can move as much surface water if designed correctly;
- if deep drains exist, using temporary boards to keep the watertable high once the major surface water is removed;
- reducing the number of drains and using laser levelling to remove excess surface water (it is important that laser levelling does not expose an acid layer);
- not ploughing too deeply or deep ripping if an ASS layer is close to the surface;
- lime slotting between the paddock and drain is currently being trailed in the Pimpama area and may prove useful (Cook *et al*. 2002);
- using specially designed weed cleaning buckets for drains to minimise disturbance of drain sediments, which can contain monosulfides (monosulfides are black oozy sediments that oxidise rapidly on exposure to oxygen producing large quantities of acid (Bush *et al.* 2002)).

The *Soil Management Guidelines* (Dear *et al*. 2002) define risk-based management strategies for acid sulfate soils and provides guidance on how to achieve best practice environmental management of ASS. The *Soil Management Guidelines* outline preferred management strategies, and other more higher risk management strategies. The information that follows is based on that described in the *Soil Management Guidelines*. The *Soil Management Guidelines* should be consulted for further information.

Avoidance strategies

Avoiding the disturbance of ASS is always the most preferred option as ASS are benign when left in a waterlogged, undisturbed environment. Avoidance, by not disturbing or not developing in areas affected by ASS is often the most environmentally responsible and cheapest option. A detailed assessment of the distribution of ASS in an area is recommended to avoid disturbing ASS.

If this assessment indicates serious ASS on the proposed site, then total avoidance should be the first option ie. the most sensible option may be to find an alternative site. Selection of alternative, non-ASS sites is preferred to remediation of impacts caused by disturbance of ASS. If groundwater levels are not affected by earthworks, undisturbed *in situ* PASS can be covered with clean fill.

Minimisation of disturbance

If total avoidance is not feasible, than alteration of proposed activities to minimise disturbance is the next best option. Strategies to minimise disturbance of ASS include:

- Redesign earthworks layout—redesign works to minimise the need for disturbance of ASS;
- Shallow disturbances—viable in situations where ASS are located deeper in the profile;
- Redesign existing drains—shallower, wider drains are generally preferred over deep, narrow drains; and
- Minimise groundwater fluctuations—activities that result in groundwater fluctuations and particularly lowering of the watertable should be avoided.

Neutralisation

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.

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.

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 agricultural lime (aglime), $CaCO_3$. Aglime has a slightly alkaline pH (~8.2) and reacts with any acid produced, raising the soil pH to safer levels. According to Ahern and Watling (2000), aglime is preferred due to the lower risks of contaminating surrounding waterways or groundwater.

The solubility of iron and aluminium is controlled in part by pH. Therefore, measures to control the pH of soil and of all site water bodies are expected in any management plan. 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.

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.

Calculations of fine aglime requirements to effectively treat soils can be obtained from Table 7 [adapted from Table 4 of the QASSIT guidelines (Ahern *et al*. 1998)]. 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.

Soils require neutralisation with an agent at 1.5 to 2 times the theoretical acid production potential. This 'safety factor' is used because in more 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.

Table 7.   Conversion rates for calculating liming requirements on acid sulfate soils.

Oxid. Sulfur (S%)	moles H⁺/kg (S% x 0.6237)	moles H⁺/t or moles H⁺/m³ (S% x 623.7)	kg H₂SO₄/tonne or kg H₂SO₄/m³ (S% x 30.59)	kg CaCO₃/tonne soil or kg CaCO₃/m³ 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/cm³ or 1 tonne/m³; bulk density generally ranges between 0.7–2.0, but can be as low as 0.2 for peats. Where bulk density is >1 g/cm³ (or 1 tonne/m³), then the correction factor for bulk density will need to be used. This increases lime requirements (eg. if BD=1.6, then 1 m³ of soil with 624 mol H⁺/tonne (1.0 %S) will require 75 kg lime/m³ instead of 47 kg). Correction factors for lime purity, neutralising value and effective neutralising value may also be required.

Using chemical calculations, a soil with 1 %S as pyrite would produce 30.59 kg H_2SO_4/tonne of soil— this would require 31.2 kg/tonne of soil of pure aglime ($CaCO_3$) to neutralise the potential acidity. Incorporating a safety factor of 1.5 gives a lime requirement of 46.8 kg/tonne of soil to neutralise the acid.

Soils may be neutralised on a temporary treatment pad or alternatively the soils may be neutralised where 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.

A guard layer of neutralising agent should be spread onto the soil surface of the treatment pad prior to the placement of soils. 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.

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 verification testing 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. Supervision of earthworks is the key to success (see Dear *et al*. 2002, for further details).

Caution needs to be taken in relation to over-liming of canelands, because this can cause some fertility problems as sugarcane tends to prefer slightly acid soils.

As mentioned above, the preferred ameliorant is aglime—other forms of alkaline materials suitable for soil amelioration, with a low solubility, include dolomite $(Ca,Mg)CO_3$, magnesite $MgCO_3$ and burnt magnesite MgO. Other agents with low solubility include 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).

10. CONCLUSIONS

The investigation reported here is part of a larger project covering the occurrences of ASS in the coastal sugarcane growing regions of southern Queensland.

Approximately 14 552 ha of land less than 5 m AHD was assessed between the Logan and Coomera rivers involving description and sampling of approximately 725 boreholes. During the course of the project 7566 samples were collected for laboratory analysis. Oxidisable sulfur (%S) results were obtained for 7028 of these samples using several analytical methods, including 6805 results by Total Oxidisable Sulfur (TOS), 403 results by Peroxide Oxidation Combined Acidity and Sulfate (POCAS) and 457 results by Chromium Reducible Sulfur (S_{CR}) analyses. The oxidisable sulfur values ranged from below detection levels to a maximum of 4.7 %S across mapping areas and soil texture groups. Average oxidisable sulfur values for sulfidic clays across all areas was 0.82 %S whilst for sulfidic loams the average was 0.38 %S and for sulfidic sands the average was 0.15 %S.

The ASS mapping defined several mapping categories over the 14 552 ha of land assessed. Potential acid sulfate soils (PASS) were defined as soils with field pH (pH_F) >5, and oxidisable sulfur (%S) results meeting or exceeding the texture-based ASS action criteria (see Table 1 in Appendix 2). Strongly acidic soils contained pH_F >4 and ≤5, with %S results less than the action criteria. Low probability soils had pH_F >5 and %S results less than the action criteria. Actual acid sulfate soils (AASS) contained pH_F ≤4. AASS are likely to be a significant source of acidity with respect to surface and ground waters.

The areas mapped in the different categories are:
- Potential acid sulfate soils   ~27% of total area (3947 ha)
- PASS with strongly acidic soil layers   ~22% of total area (3158 ha)
- PASS with actual acid sulfate soil layers   ~27% of total area (3902 ha)
- Actual acid sulfate soils   ~6% of total area (886 ha)
- Low probability soils   ~5% of total area (724 ha)
- Low probability soils with strongly acidic soil layers ~13% of total area (1935 ha)

Of the 14 552 ha of land assessed approximately 76% or 11 007 ha was mapped as a potential acid sulfate soil. Soils in this category contain at least one layer with an oxidisable sulfur (%S) greater that the relevant action criteria.

In terms of pH, actual acid sulfate soils (pH_F ≤4) occur in 4788 ha or 33% of the total mapping area. It is important to note that these soils are currently undergoing oxidation predominately in the top metre of the soil—which means that the cane is growing in soils with a pH_F of ≤4.0, and additional acid is being released each year, thereby worsening the situation. These soils pose an immediate environmental threat *via* acidification of soils and adjacent waterways. Liming treatment is suggested for these localities. Strongly acidic soils (pH_F >4 and ≤5) cover a further 5093 ha or 35% of the study area. The remaining area of 32 % or 4671 ha area has a pH_F >5. Of the 4788 ha of AASS, 81% of these also overly PASS.

As has been discussed in this report, activation of ASS on one property may well affect adjoining properties (or downstream enterprises). A regional or even a property-cluster approach has real benefits. The maps produced by this project are in GIS format and can therefore be used as the basis for any subsequent (more detailed) investigation. Access to the existing individual borehole data can be arranged and this can provide guidance as to the best localities for supplementing the data. Although the map produced by this investigation (at a scale of 1:25 000) is of sufficient detail to identify the areas concerned, the assessment of risk at a detailed level is beyond the scope of this investigation. The field techniques and sampling equipment associated with this project can however be of benefit to any subsequent work.

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12.   DEFINITIONS AND CONCEPTS USED IN THIS DOCUMENT

Acid Sulfate Soil (ASS) – soil or sediment containing highly acidic soil horizons or layers affected by oxidation of iron sulfides (*actual acid sulfate soils*) and/or soil or sediment containing iron sulfides or other sulfidic material that has not been exposed to air and oxidised (*potential acid sulfate* soils).
Note: The term acid sulfate soil generally includes both actual and potential acid sulfate soils. Actual and potential acid sulfate soils are often found in the same profile, with actual acid sulfate soils generally overlying potential acid sulfate soil horizons.

Actual Acid Sulfate Soil (AASS) – soil or sediment containing highly acidic soil horizons or layers affected by the oxidation of soil materials that are rich in iron sulfides, primarily sulfide. This oxidation produces hydrogen ions in excess of sediment's capacity to neutralise the acidity, resulting in soils of pH of 4 or less. These soils can usually be identified by the presence of jarosite.

Potential Acid Sulfate Soils (PASS) – soil or sediment containing iron sulfides or sulfidic material, that have not been exposed to air and oxidised. The field pH of these soils in their undisturbed state is pH 4 or more, and may be neutral or slightly alkaline.

Action Criteria – In Queensland, action criteria define when ASS disturbed at a site will need to be managed. Action criteria are based on the sum of existing plus potential acidity. This is usually calculates as equivalent sulfur (in %S units) or equivalent acidity (in mol H^+/tonne). As clay content tends to influence a soil's natural buffering capacity, the action criteria are grouped by three broad categories—coarse, medium and fine. For disturbances of 1 to 1000 tonnes of material, the action criteria are:

Coarse textured material (sands to loamy sands)	0.03 %S (18 mol H^+/tonne)
Medium texture material (loams to light clays)	0.06 %S (36 mol H^+/tonne)
Fine textured material (medium to heavy clays)	0.1 %S (62 mol H^+/tonne)

Note that where disturbances exceed 1000 tonnes, the action criteria of 0.03 %S (18 mol H^+/tonne) applies, regardless of soil texture.

Aglime – A neutralising agent used to treat acidic soils; by composition, it is commonly 95–98% pure calcium carbonate $CaCO_3$; it is insoluble in pure water, with a pH of ~8.3; application rates will depend on the purity and fineness of the product.

AHD (Australian Height Datum) – The datum used for the determination of elevations in Australia. The determination uses a national network of bench marks and tide gauges, and sets mean sea level as zero elevation.

Anaerobic – Conditions whereby oxygen is excluded, usually by waterlogging.

Borehole – The actual hole created when an auger or push-tube is inserted into the soil body; the portion removed (the core) will demonstrate the soil profile.

EIS (Environmental Impact Statement) – *or* EIA (Environmental Impact Assessment) – The EIS is the written report generated from the EIA which is the study commissioned by the proponent of a project to identify and quantify any/all impacts (both on- and off-site) that the proposed project may have on the existing environment.

Groundwater – Subsurface water in the zone of saturation, including water below the watertable and water occupying cavities, pores and openings in underlying soil and rock.

Groundwater flows – The natural or artificially produced movement of groundwater in the zone of saturation.

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

Jarosite – An acidic pale yellow iron sulfate mineral: $KFe_3(OH)_6(SO_4)_2$), is the most conclusive indicator of AASS. Jarosite is a by-product of the acid sulfate soil oxidation process, formed at pH less than 3.7; commonly found precipitated along root channels and other soil surfaces exposed to air.

Pyrite – Pale-bronze or brass yellow, isometric mineral; FeS_2; the most widespread and abundant of the sulfide materials.

Pleistocene – A period of time extending from 1.8 million years ago to about 10 000 years ago, an epoch of the Quaternary period.

Quaternary – A geological time period extending from 1.8 million years ago to present time; incorporates both the Pleistocene and Holocene epochs.

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

Chemical acronyms used for analytical procedures"

POCAS – Peroxide Oxidation-Combined Acidity and Sulfate method

pH_F – Field pH (pH of soil and deionised water)

pH_{FOX} – Field pH after oxidation (pH of soil and hydrogen peroxide)

pH_{KCl} – pH of a 1:5 solution of soil and 1M KCl

S_{CR} – Chromium Reducible Sulfur

TAA – Total Actual Acidity

TPA – Total Potential Acidity

TOS – Total Oxidisable Sulfur

TSA – Total Sulfidic Acidity

Hand Operated Sampling Equipment

Jarret Auger

The Jarret auger has a 100 mm (4 inch) diameter and will penetrate the soil surface approximately 200 mm before the auger head is filled. It is suitable for use on a range of soil textures in the dry and moist state but will not retrieve dry sands. Where the soil type is suitable, it may be possible to auger 5–10 metres using the Jarret auger and a series of 1-metre extension rods (Plate 1).

Augers for sands and soft sediments

Sand augers are useful for sampling in very sandy friable soils however in our experience, the 'Dormer No. 4 Auger' is more versatile as it successfully recovers most moist sands and soft muds. To obtain an adequate volume of sample, a 75 mm diameter, single slot tube is commonly used. These augers penetrate to a depth of about 30 cm before filling the auger. The auger is then reinserted to obtain further samples from the same sample hole (Plate 2).

Tapered gouge auger

The tapered gouge auger is designed to take undisturbed samples from very soft material with a significant clay content. Typically, the auger is an open-faced, stainless steel tube that tapers from a diameter of 50 mm at the top, to 20 mm at the bottom. The auger is pushed into the soil, turned to cut the core and then withdrawn. It can be used at the surface or down an augered hole however re-sampling is limited due to hole collapse. The open face tube allows easy removal of soil from the auger, and the tapered end improves sample retention for wet soils. The tapered gouge auger produces a highly representative sample of the profile. Once the gouge auger has been pushed down once, it cannot be pushed down into the same hole again, as the tapering effect will lead to cross-contamination in the next soil sample (Plate 3).

Push tube with tapered tip

The push tube consists of a 50 mm diameter PVC or stainless steel tubing that is pushed into the soil surface to obtain a sample. This technique is good for a range of soil textures but is generally not used for saturated sands, as sample loss can be a problem. However, adding a sealable cap before extraction may improve retention by reducing suction. This is a particular problem in dry clays and saturated sands.

Piston sampler

The Piston sampler is similar in principle to a large yabbie pump. It is used to obtain undisturbed samples in saturated sands or soft muds below the watertable. The piston sampler is a push tube with a manual suction and piston mechanism to improve retention. As the stainless steel tube is pushed down, the piston is pulled up then held while the tube is withdrawn. The piston sampler is limited by the length of the piston due to wall collapse on withdrawal. Using a suitable sized poly pipe for casing will reduce the incidence of wall collapse and can increase the depth of excavation on saturated sands. However, care is needed to avoid contamination (Plate 4).

Mechanical Sampling Equipment

There are many limitations associated with the sampling of coastal soils. Sand below the watertable is difficult to sample, while sites containing gravel layers are the most challenging and best sampled using an excavator. Moreover, the greater the sampling depth below the watertable, the more difficult sampling is likely to be. To overcome this difficulty, specialised mechanical equipment has been developed for ASS sampling. A brief outline of the benefits and limitations of conventional and specialised drilling equipment appears below.

Hydraulic push tube

A hydraulic push tube is normally mounted on the rear of a 4WD vehicle or trailer. The steel push tube usually has a diameter of 50 mm and has a hardened tapered tip that is hydraulically pushed into the soil.

Although the equipment performs well in loams, clay loams and some clays, sticky clays are difficult to remove from the tube, and wet sands are likely to fall out (Plate 5).

Spiral (cork screw) auger

The spiral auger is of similar design to a posthole auger. The spiral auger has serious limitations as it is difficult to obtain a sufficient amount of clean, uncontaminated sample. Cleaning is also laborious and the spiral auger is therefore generally unsatisfactory for ASS sampling.

Hollow flight screw auger incorporating an internal split tube sampler

The hollow flight auger is useful for undisturbed sampling. It uses a hollow screw auger with an internal sampler that can be withdrawn regularly. The internal sampler is fitted with a 'split tube' that obtains suitable cores, though compression of muds and sample loss of sands below the watertable does occur. A 'catcher' often improves retention on saturated sands.

Backhoe/excavator

Backhoes and excavators provide an excellent view of the soil profile and are very good at recovering gravels. Sampling can be easily obtained at measured intervals down the excavated face. A backhoe or excavator is advantageous for sites containing abundant shell as it allows a larger sample to be collected without shattering the shell. This overcomes a common problem with most sampling techniques as visible shell should be removed prior to laboratory analysis. Once below the watertable however, wall collapse is a substantial problem compromising effective sampling and personal safety. Work place safety issues must be addressed when excavating pits. The possibility of hydrogen sulfide gas poisoning should be a consideration when entering a pit.

Wash bore drilling combined with a driven Standard Penetration Test (SPT) split tube sampler

This form of equipment is used mainly for engineering purposes rather than for detailed soil investigations as it is difficult to log and sample the profile adequately. It is often used for deep drilling on saturated sands where a bentonite and polymer solution is continually pumped under pressure to hold the borehole walls intact. Sample contamination can be a substantial problem due to mobilisation of fine sediment within the profile. Some well-equipped drilling rigs can also use a Standard Penetration Test (SPT) sampler or a thin walled 50 mm diameter tube (designated U50—undisturbed, 50 mm diameter) when wash boring. 'Gemco' is one of the brands commercially available in Australia.

Core sampling employing a vacuum and vibration technique

The Vacuum-Vibro Corer (based on principles used by some off-shore drilling rigs) has been developed and modified by NR&M to more effectively sample wet sands, muds, and soft soils commonly encountered in ASS environments (Plate 6).

The VVC consists of a 60 mm diameter, 5–6 m stainless steel tube which is mounted on the back of a trailer, 4WD utility or truck. Using both vibration and vacuum the tube is inserted into the soil to obtain a continuous, intact sample. The tube, containing the sample is then winched up whilst the vacuum is maintained. A combination of compressed air and vibration is then used to extrude the sample into a clear, plastic sleeve. The sample can then be described and sampled easily.

If the upper profile is hard and dry, a hydraulic push tube or manual augering device may be required until soft moist material is encountered at depth.

Geoprobe

The Geoprobe is a track mounted, self-propelled all-terrain vehicle that improves accessibility to notoriously difficult ASS sampling sites. The Geoprobe is a hydraulically powered percussion machine that can sample to depths of up to 30 m. The Geoprobe obtains continuous soil samples that are contained in 1.2 m removable clear polymer liners. The samples can be logged immediately or sealed and frozen for later logging. The Geoprobe retrieves soft sands and muds with minimal compaction (Plate 7).

Plate 1. Jarett soil auger

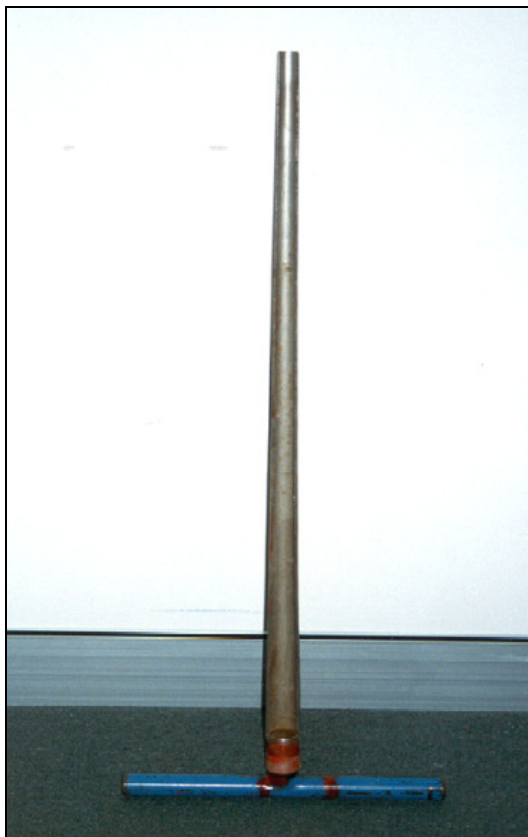

Plate 2. Dormer soil and Dormer sand augers
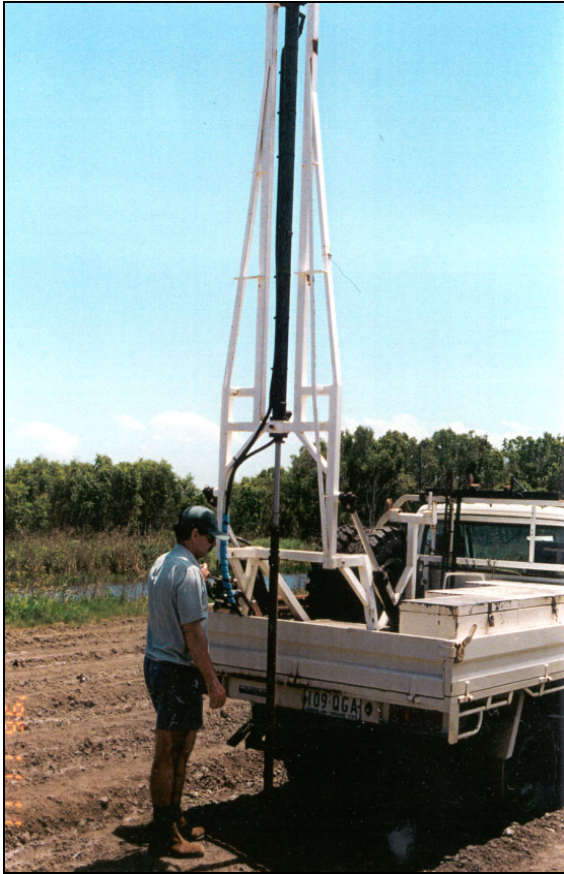

Plate 3. Dormer tapered gouge auger

Plate 4. Piston sampler

Plate 5. Hydraulic push rig

Plate 6. Vibro suction corer

Plate 7. Geoprobe

> **Note:** *This document should be provided with all NR&M mapping products and referred to in the printed acid sulfate soils reports accompanying mapping products. It should be included with digital product packages (CD ROMs etc) to provide information essential for the correct use of ASS maps and reports produced by NR&M, and to limit liability for misuse of NR&M products.*

DISCLAIMER:

While every care is taken to ensure the accuracy of this product, the Department of Natural Resources and Mines (NR&M) makes no representations or warranties (expressed or implied) about its accuracy, reliability, completeness or suitability for any particular purpose and disclaims all responsibility and all liability. Any representation, statement, opinion or advice, expressed or implied from this product is made in good faith and on the basis that the State of Queensland, its agents and employees are not liable (whether by reason of negligence, lack of care or otherwise) to any person for any damage, expense or loss whatsoever which has occurred or may occur in relation to that person taking or not taking (as the case may be) action in respect of any representation, statement or advice referred to above.

1.   Background

Acid sulfate soils (ASS) are marine or estuarine sediments that contain iron sulfides, commonly pyrite. When exposed to air by disturbance or drainage, the iron sulfides oxidise producing significant quantities of sulfuric acid (battery acid). This acid results in the release of toxic quantities of iron, aluminium and heavy metals from the soil. These pollutants can seep into waterways, killing fish, other aquatic organisms and vegetation. Concrete and steel structure may also be severely corroded, requiring replacement.

Environmental harm from ASS has been well documented, particularly in New South Wales, and there is significant and growing anecdotal evidence of fish kills and other environmental damage in coastal areas of Queensland affected by ASS. As part of the Queensland Department of Natural Resources and Mines (NR&M), the Queensland Acid Sulfate Soils Investigation Team (QASSIT) has undertaken a number of projects to map the location and extent of ASS in coastal Queensland.

This document is aimed at ensuring the correct use and interpretation of maps and data published by NR&M as a result of these projects. NR&M ASS maps are available in hard copy and electronic forms at a range of scales – 1:100 000, 1:50 000, 1:25 000. The variation in map scale relates directly to borehole or site intensity, and hence reliability of map boundaries. This document also provides a general description of the field sampling and mapping procedures used by NR&M. Users of mapping products do not always understand the limitations of the data (particularly in relation to mapping scale), and the serious consequences that can result from using the information out of context or attempting to extrapolate beyond the data limits. To pre-empt such misuse, it has been necessary to include a cautionary statement such as the one below, with all products.

Example of paragraph in an ASS report:
> *"Users of mapping products such as ASS maps must be aware of the limitations implied in the scale of mapping undertaken. At a scale of approximately 1:25 000, the mapping is suitable for use in regional farm management and development planning. Individual property planing or developments will require more detailed ASS investigations at scales of at least 1:10 000, depending on the type and location of development. Map unit boundaries may be updated as additional field and laboratory data becomes available. End users of NR&M mapping products should become acquainted with the methodologies used and the limitations of the product."*

It must be emphasised that users of mapping products should seek competent advice before undertaking action—whether exploratory or remedial action. Often the consequences associated with disturbed ASS can still be producing adverse effects 30 years after an event (Cook *et al*. 1999).

2. *Mapping Acid Sulfate Soils*

ASS are relatively common in Queensland coastal areas and are generally found in lowlying areas less than 5 m Australian Height Datum (AHD), and mapping exercises tend to also concentrate on these localities. Field sampling and mapping of ASS is more technically challenging than standard agricultural soil mapping. For example, ASS are three-dimensional bodies of sandy or muddy sediments, of varying depth and pyritic concentration. These sediments may be covered with more recent, non-estuarine sediments (alluvium), and they may also be oxidised to some depth, depending on natural or man-made watertable fluctuations.

ASS which have already undergone some oxidation and display existing acidity (pH ≤4) are termed **actual ASS (AASS)**. ASS which have not yet been oxidised are termed **potential ASS (PASS)**. Often actual ASS immediately overlie potential ASS, and the lower level of watertable fluctuation is usually the boundary between the two (Smith *et al*. 2000).

Due to the potentially hazardous properties of ASS, it is necessary to target mapping according to likely occurrence, and potential future disturbance of ASS. As a result, mapping scale may vary across a single map from 1:100 000 to 1:25 000, depending on the likelihood of finding ASS in the area. A greater likelihood of finding ASS generally necessitates a greater mapping intensity.

The basis for field sampling and mapping of ASS has been:
- Identification of landform types associated with Holocene estuarine deposition; principally via stereoscopic air photo interpretation (API); and
- Surface elevation below 5 m AHD (based on maximum Holocene sea levels).

Identification of PASS and AASS

In the field, PASS are usually grey to dark olive grey in colour (5Y41 to 5GY31 in the Munsell soil colour chart). They are typically wet, fine textured soils (eg. mangrove muds), but may also be sandy or more rarely, gravely. When PASS remain in their undisturbed, natural, waterlogged state, they are environmentally 'benign'. However, if exposed to oxygen, the iron sulfides in the PASS will oxidise, and sulfuric acid will be produced. Basically, the PASS becomes AASS.

AASS are usually browner (10YR51 to 2.5Y33 in the Munsell soil colour chart) than PASS because they have been partly or fully oxidised. They often show significant red and orange mottles, indicating their oxidised state. AASS generally contain a straw-coloured mottle called jarosite, $KFe_3(OH)_6(SO_4)_2$, which is strong evidence that sulfuric acid has been produced, since jarosite requires very acidic conditions (pH <3.7) to form and stay visible.

Field pH (pH_F) and field pH peroxide (pH_{FOX}) tests also help identify AASS and PASS layers. In the pH_{FOX} test, the addition of hydrogen peroxide to an ASS sample triggers accelerated oxidation of pyrite, liberating the acid that would form slowly under natural oxidising conditions. The strength of reaction to peroxide and the pH decrease from pH_F to pH_{FOX} are key indicators of PASS. PASS usually have pH_F values greater than 4 (usually around neutral) and pH_{FOX} <3, and show a strong reaction to peroxide. AASS generally have a pH_F and pH_{FOX} below 4. For more detailed information on conducting and interpretation of field pH tests, refer to Hey *et al*. (2000).

Site description and sampling

Site description, sampling, field testing and laboratory analysis is carried out in accordance with the latest version of the *Guidelines for Sampling and Analysis of Lowland Acid Sulfate Soils (ASS) in Queensland* (Ahern *et al*. 1998) (referred to as the *Queensland Sampling Guidelines*). A range of manual and mechanical sampling equipment specially designed to cater for the recovery of intact cores from saturated sands, soft plastic muds and other ASS material is used. Soil cores are generally between 2 and 6 metres

in depth and preferably extend to the depth of the non-marine sediment layers. Traverses of deeper boreholes are used in key areas, to improve understanding of the coastal geomorphology, and develop a clearer picture of the historical development of ASS.

Morphological descriptions of each site are recorded according to the nomenclature of McDonald *et al*. (1990) and site locations are recorded in standard Australian Map Grid coordinates to an accuracy of 3 metres. All data is stored in NR&M's Soil and Land Information [SALI] database.

Samples (weighing approximately 0.5 kg) are collected at 0.5 m intervals down the soil profile, or within each soil or sedimentary layer. Samples are bagged, labelled and frozen in the field in preparation for future laboratory analysis. Field tests (pH_F and pH_{FOX}) are conducted at 0.25 m intervals down the soil profile in the field and results are tabulated. Upon arrival at the laboratory, samples are either frozen or oven-dried at 85°C for 48 hours for laboratory analysis.

Decoded site descriptions and chemical data are usually supplied in the appendices of the project reports. They show the texture and other characteristics of each soil layer, which layers have PASS, AASS or pH between 4 and 5, and the results of laboratory analysis.

Mapping categories

For initial mapping, all sites assigned with map unit codes are overlaid or printed onto topographic maps. Homogenous areas are then delineated according to the following criteria:

- **Presence of or 'depth to' AASS layer**—defined as soil pH less than or equal to 4
- **Presence of or 'depth to' PASS layer**—defined as any soil layer in which the oxidisable sulfur (S%, a measure of pyrite content) exceeds the appropriate *action criteria* (see below)
- **Presence of or 'depth to' to acidic layer**—defined as layers with pH >4 to ≤5; this level of acidity can be due to natural organic acidity or past oxidation of ASS

Note: 'Depth to' categories are shown only at 1:50 000 and 1:25 000 mapping scales. The density of boreholes in 1:100 000 mapping does not provide sufficient reliability to allow this level of detail, so these maps only indicate the presence of ASS, with no 'depth to' categories shown.

Action criteria

Action criteria refer to the amount of existing and potential acidity in the soil that triggers the need for management if the soil is disturbed. Action criteria vary according to soil texture (Table 1). For more details regarding action criteria refer to the *Queensland Sampling Guidelines* (Ahern *et al*. 1998).

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

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

ASS are chemically very complex soils, making analysis and interpretation particularly difficult. It is always important, but especially so for detailed investigations, that the correct type of analysis is carried out on ASS samples. The Chromium Reducible Sulfur (S_{CR}) method is the preferred method for low analysis sands and for highly organic or peaty soils because of its specificity to reduced inorganic sulfur (ie. pyrite). Analysis by the Peroxide Oxidation Combined Acidity and Sulfate (POCAS) method and the more recent Suspension POCAS (SPOCAS) method gives best results for samples containing amounts of shell or carbonates, or those showing existing acidity. The Total Oxidisable Sulfur (TOS) method is a useful low cost method to analyse ASS. On occasions, analysis by all three methods may be necessary. For more information regarding laboratory analysis and interpretation of ASS chemical data refer to McElnea and Ahern (2000).

3. Limits of Various Mapping Scales

The scale of mapping has important ramifications with respect to the context in which maps are used. Map scale relates directly to site density, and hence reliability of map boundaries. For an indication of the reliability of each map unit, users should refer to the **intensity diagram on the map, or the UMA scale code** (in the UMA database), which is calculated from the number of boreholes present within each unit— as indicated in the box below. The UMA database is maintained as part of the geographic information system (GIS) files, and includes data on individual map units, referred to as Unique Map Areas (UMAs). This includes the identity of the sites that occur in the UMA and a statement about its reliability.

The mapping scale of each UMA is calculated using the following formula: $(\sqrt{ha}/\text{no. sites}) \times 10^4$

For example, if there are four sites in a UMA of one square kilometre (ie. 4 sites per 100 ha), then the scale is: $(\sqrt{100}/4) \times 10^4 = \sqrt{25} \times 10\,000 = 50\,000$

In practice, the nominated scale covers a range of site densities. For QASSIT ASS maps:
- 1:100 000 implies approximately 1 borehole per 100 ha
- 1:50 000 implies approximately 1 borehole per 25 ha
- 1:25 000 implies approximately 1 borehole per 6.25 ha

The scale of a map is clearly marked on the map and accompanying information in the map key or in a supporting publication is provided on how the map may be used. Map users need to be aware of the limitations of interpretation from these mapping scales. The information is only intended for use and in presentation with information at that scale. Should digital information be integrated with data or a more intensive scale, then the legend of the printed map should make it clear that the ASS theme is only accurate to the relevant scale. Figure 1 below shows how variations in borehole density can determine the overall mapping outcome. The higher number of 1:50 000 and 1:25 000 boreholes can enable the identification of smaller more detailed units.
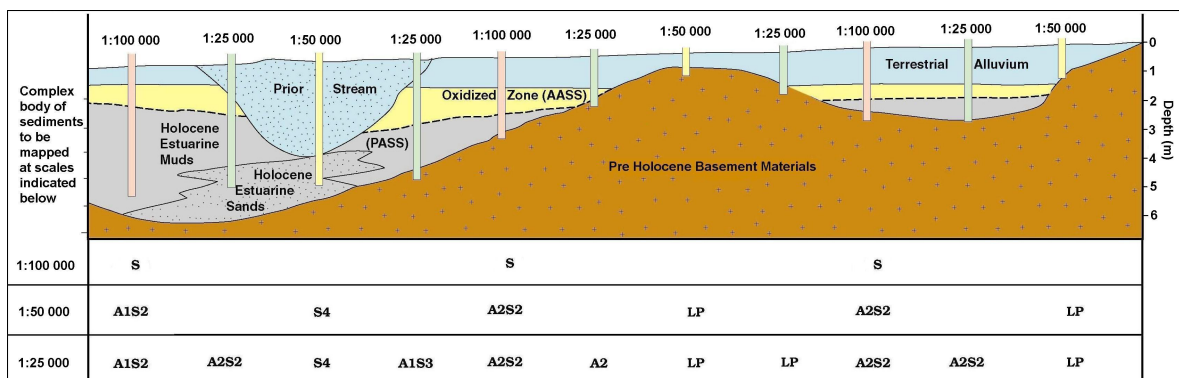

Figure 1. Borehole density diagram showing additional detail available for mapping at each scale.

The site intensity of 1:100 000, 1:50 000 and 1:25 000 maps is not appropriate for individual developments. Individual developments will require even more detailed ASS investigations at scales of at least 1:10 000, depending on the type and location of the development. ASS investigations for individual developments should be conducted according to the *Queensland Sampling Guidelines*.

1:100 000 Scale Mapping

At 1:100 000 scale, only the presence or absence of ASS is indicated. No information is given about the depth to ASS, and whether AASS or PASS are present. This scale of mapping is not appropriate for use on an individual property basis. Not only are boundaries not sufficiently accurate at the property level, it is not possible to make decisions about ASS management simply on the basis of its presence. Factors such as 'depth to ASS' and the amount of existing and/or potential acidity are needed for such decisions. For local authorities considering development applications, we advise that the only use of 1:100 000 mapping in these contexts should be as a mechanism to signal the need for further assessment. For example, a decision to prohibit an activity based solely on 1:100 000 scale map information would not be appropriate.

1:50 000 Scale Mapping

Mapping at 1:50 000 scale indicates the presence or absence of AASS and PASS and also gives an indication of depth to AASS and PASS. Although unsuitable for individual property planning, 1:50 000 is a useful scale for regional property management and development planning. It must be remembered though, it is based on approximately one quarter of the data used for 1:25 000 mapping. Therefore 1:50 000 scale map units are likely to be larger and contain more variability than 1:25 000 scale units (hence a lower level of confidence).

1:25 000 Scale Mapping

Due to increased site intensity, mapping at 1:25 000 scale indicates the presence or absence of AASS and PASS and the depth to AASS and PASS, with more detailed delineation and improved reliability of map units. This additional information can improve ASS management decisions regarding current or future land use. 1:25 000 is a reliable scale for individual property planning, however individual developments will require more detailed ASS investigations.

4.   Map Legends and Map Unit Codes

The maps use colour to indicate the various categories of AASS and PASS. For relatively undisturbed areas mapped at 1:50 000 or 1:25 000 scale, the main mapping categories depict the varying depths to the first AASS and/or PASS layer. Map units represent areas where the depth to the first AASS or PASS layer is relatively uniform. These are coloured using shades of red, pink, orange and brown, with red indicating the shallowest depth (eg. S0 unit is coloured red, indicating that PASS occur 0 to 0.5 m below the surface). The base colour of individual map units is attributed according to the shallowest ASS layer, regardless of whether this represents 'actual' or 'potential' acidity. If AASS is present in the unit, this is represented by an overlay of yellow dots.

Each map unit is labelled with a map unit code, which indicates the characteristics of the unit. The basic codes used are:
S   potential acid sulfate soil (PASS)
A   actual acid sulfate soil (AASS)
a   acid layer with pH >4 to ≤5

Each symbol (S, A, or a) is then followed by a numeric depth code ranging from 0 to 5. For eg.
S0   indicates PASS between the soil surface and 0.5 m depth
S1   indicates PASS at 0.5 to 1.0 m depth
S2   indicates PASS at 1.0 to 2.0 m depth
S3   indicates PASS at 2.0 to 3.0 m depth
S4   indicates PASS at 3.0 to 4.0 m depth
S5   indicates PASS at 4.0 to 5.0 m depth

S5+ indicates PASS at depths greater than 5.0 m

Combined Codes. The codes above may be used alone or in combination ie:

A1 AASS (pH ≤4) occurs at 0.5–1 m depth; no PASS present

S4 PASS occurs at 3–4 m depth; no AASS present

A1S3 AASS occurs at 0.5–1 m depth; PASS occurs at 2–3 m

a0S2 pH 4–5 layer occurs within 0.5 m; PASS occurs at 1–2 m

Mixed Units. These are shown with both colours striped to indicate areas where the depth to ASS is too variable to be accurately mapped at the operative scale (eg. A1/A2).

Other Codes. For disturbed, urban or industrial lands or other areas where little or no field checking could be achieved, the maps show where ASS is likely to occur based on geomorphology and elevation data. Codes used are:

S Land mapped at 1:100 000 scale where ASS occurs within 5 m of the surface.

S$_{LA}$ Limited field assessment, but reasonable probability of ASS occurring due to landscape position. Current land use prevents disturbance or access is restricted eg. National Parks and Reserves.

S$_{DL}$ Limited field assessment in disturbed lands likely to contain ASS eg. canal estate, marina, aquaculture, quarry, urban or industrial lands.

S^P Indicates pyritic sediments of Pleistocene age. Found only recently, these sediments often occur in deep sandy soils (eg. Podosols) below quite impenetrable 'coffee rock' layers, at depths greater than 5 m. While these are still acid sulfate soils, they were generally considered outside the scope of the mapping project.

$_W$ Indicates seasonally wet or swampy areas often associated with *Melaleuca spp.* and *Casuarina glauca* communities. ASS typically occur at depth. These areas show varying levels of sulfides near the surface, possibly due to organic sources of sulfur (see note on organic soils below). Subscript 'w' is used in conjunction with other codes such as S$_{LAW}$ or S2$_W$.

> Note: Soil disturbance in any areas designated one of the 'S' codes above—with no depth shown— should be avoided without more detailed investigation.

Codes for areas with low probability of ASS.

LP Areas below 5 m elevation with low probability of ASS occurring

LP5 Areas above 5 m elevation with low probability of ASS occurring

NA Land not assessed

Borehole locations and data. For all scales, each fully described and sampled site is shown as a dot on the map. Site numbers are also shown at 1:50 000 and 1:25 000 scales.

5. Modification of ASS Codes Allocated by SALI-Chem

There are situations where the mapping codes, which are automatically assigned by NR&M's soil chemistry database program [SALI-Chem], need to be modified in the light of supplementary data if they are to provide the most accurate information.

- *Modification of 'depth to' codes*. For each site, in order to allocate 'depth to' codes for AASS, PASS and acid soil layers (**A0**, **S2**, **a1** etc), SALI-Chem applies the appropriate action criteria (depending on soil texture) to the available laboratory data. The depth code assigned is based on the **upper depth of the horizon from which the sample was taken**. In some instances, these mapping codes may require modification to more accurately represent the site in question. For example, a soil horizon described in the field may stretch across depth categories (ie. from 0.4 m to 0.9 m depth), but upon later viewing of laboratory results, the sample from 0.5-0.6 m returns a result below the action criteria, while the sample from 0.8-0.9 m exceeds the action criteria. The database would automatically code this soil as an '**S0**' profile, based on the **upper depth of the sampled horizon** (0.4 m). The mapping officer may choose to re-code the profile to '**S1**', in order to reflect the observation that PASS was found only between 0.5 to 1.0 m (and not between the surface and 0.5 m).

- *Organic soils.* In soil chemistry terms, ASS are characterised by **inorganic acidity from sources such as pyrite.** However, sometimes a laboratory (or field) analysis will yield a natural pH of less than 4 despite the absence of significant levels of pyrite. This is most often caused by organic acidity, which is usually less hazardous, and typically occurs in surface or near-surface layers of Podosols, Organosols or Hydrosols. Where there appears to be no AASS influence near the surface, these soil units will be mapped as '**a**', rather than '**A**'.

  Organic matter can also contain significant amounts of sulfur which may trigger an 'S' code (in SALI-Chem) if samples are analysed by TOS or POCAS methods. Only Chromium Reducible Sulfur (S_{CR}) analysis can distinguish between pyrite and organic sulfur sources. As S_{CR} is not done for every site, the results from some surface organic soils have been discounted if the actual depth of PASS is obviously deeper than the surface layers. Data from adjacent sites, particularly those where S_{CR} analysis is available, may be used to adjust depth codes to reflect the perceived true depth (or absence) of PASS.

- *Jarosite and pH's > 4.0.* Although jarosite usually occurs in conjunction with soil pH below 4 (resulting in an '**A**' coding), at some sites where jarosite is common (greater than 10%), natural pH may remain above 4.0 ('**a**' coding). This is believed to be due to natural variability within the soil matrix. Because the presence of jarosite is a reliable indicator of AASS, the site can be recoded from '**a**' to '**A**'.

6.   Updating of Map Unit Boundaries

Soil maps are based only on the information available at the time of mapping. QASSIT may update boundaries for soil units on both digital and printed maps, as additional field and laboratory data becomes available. Map users should ensure that they have the most up-to-date mapping information available.

7.   References

For further information on QASSIT mapping projects, please contact QASSIT:
Phone: (07) 3896 9819
Fax: (07) 3896 9782
Address: Block C, 80 Meiers Road, Indooroopilly Qld 4068

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