Acid sulfate soils and estuarine water quality of the Mackay district

Volume 1: Acid sulfate soil report

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Summary

This project, funded by the Natural Heritage Trust, details the *acid sulfate soils*[1] (ASS) and the estuarine water quality of six catchments in the Mackay district—those of the Reliance, McCreadys, Bakers, Sandy and Seaforth creeks and the Pioneer River. ASS were mapped at a scale of 1:50 000 from 586 *boreholes*, which were located using free survey techniques at spacings of 250 to 500 metres (m) depending on landform, or at very wide intervals in tidal areas where ASS were very consistent. Profiles were described in the field, and field peroxide oxidation tests were carried out at regular 0.25 m intervals down the profile, or from within horizons thinner than 0.25 m.

Soil samples for analysis were taken mainly at intervals of 0.5 m from each borehole. *Actual acid sulfate soils* (AASS) were analysed by the modified peroxide oxidation combined acidity and sulfate method (POCASm), which was replaced by the suspension POCAS method (SPOCAS) during the project. *Potential acid sulfate soils* (PASS) were analysed by the chromium reducible sulfur method (S_{CR}). Some 4030 samples were analysed to determine the actual and potential acid sulfate soil layers. Map units were allocated an AASS code (**A**) and/or PASS code (**S**), or a strongly acidic soil layer code (**a**), and a depth code number indicating the depth to these soil layers, based on the laboratory data. Colouring on the acid sulfate soil map highlights the depth to an actual or potential acid sulfate soil layer and associated level of risk. Fourteen sites in estuarine areas of the Mackay catchments were monitored on a fortnightly basis for pH, conductivity, dissolved oxygen and temperature.

Estuary geomorphology was compared with the estuarine classifications of Dalrymple et al. (1992) and it was concluded that the catchments of the Mackay district are either wave-dominated or tide-dominated estuaries, while some possess properties of both estuary types.

The study identified 9070 hectares (ha) of PASS, and 1178 ha of AASS. Mapping shows that 5750 ha (63%) of the ASS occur in the tidal areas up to the level of the highest astronomical tide (HAT). ASS are shallowest in the tidal zone and occur mainly in the upper metre of the profile. On other landforms such as floodplains, channel benches and dune fields they are deeper, mainly at depths between 2 and 5 m. Wetland areas underlain by strongly acidic AASS within the upper metre occur mainly in the Pioneer River catchment and are unique to the study area.

Analysis of AASS layers revealed that they are nearly fully oxidised, with oxidisable sulfur contents (% S) mainly less than the action level of 0.1% for a clay soil. Existing acidity concentrations (actual and retained) are also mainly less than the threshold level of 62 mol H^+/t. The (% S) varies significantly between the sandy and clayey PASS sediments. Throughout the six catchments, the mean value in the pyritic sands is from 0.16 to 0.35%, while in the clay PASS sediments it ranges from 0.62 to 1.10%, indicating that the mangrove muds pose the highest potential environmental risk.

Drainage of sugar cane and grazing lands underlain by ASS in the Mackay district requires only shallow drains, usually less than 0.5 m deep. As these do not have any effect on the underlying *watertables*, they have not had the significant impact on ASS in this area that agricultural drainage has caused in other areas in Queensland and New South Wales. The main causes of disturbance of ASS around Mackay are the filling of mainly former tidal lands for urban expansion, and the requirements of city infrastructure. However, at this stage, there is no evidence to indicate that these activities are causing the displacement and accelerated oxidation of ASS. In the area, ASS are also disturbed by minor, small-scale excavations for deep, urban stormwater drains, farm dams, sand and gravel extraction pits, aquaculture ponds and intake channels.

Water quality monitoring at all sites showed that pH, salinity, and dissolved oxygen levels are within acceptable limits for estuarine water, and do not indicate any off-site impacts from these disturbances.

1. Terms defined in the Glossary are presented in italics on first use.

Figure 1: Study area location diagram

1. Introduction

In recent times, coastal lowland areas around Mackay have become subject to increased development pressure as the city expands. Very little was known of the extent and distribution of acid sulfate soils (ASS) in the Mackay district and, more importantly, of the depths at which ASS occur. Additionally, little was known or understood about the level of disturbance of ASS in the area and the off-site effects of these disturbances on water quality, fish kills and mangrove dieback.

Therefore, to gain a better understanding of these factors in the Mackay district, the Department of Natural Resources and Mines (NR&M), in conjunction with Mackay City Council (MCC), and the Mackay Whitsunday Natural Resource Management Group (MWNRM), obtained funding from the Natural Heritage Trust (NHT) for a two-year ASS and water quality investigation.

The aims of the study were to map the extent of ASS at a scale of 1:50 000, and to monitor and determine estuarine water quality, particularly in areas where recent fish kills had occurred. This would indicate if ASS had been disturbed and if off-site effects were occurring. The information from this project will be used by state and local government to manage ASS in the Mackay district, and as a guide to developers and consultants.

1.1 Survey area

The proposed survey area extended from Shoal Point in the north, to Alligator Creek in the south. Townships to the north of Shoal Point, Seaforth, St Helens and Midge Point were also included as they were of interest to Mackay City Council (Figure 1). Before the field sampling program began, the catchments of the area between Shoal Point and Alligator Creek were identified. As it was unlikely that all these areas would be completed in the two-year NHT timeframe, in consultation with the community, mapping of the catchments and northern townships was prioritised in the following order: McCreadys Creek, Reliance Creek, Pioneer River, Bakers Creek, Seaforth, Sandy Creek, Alligator Creek, Midge Point and St Helens.

2. Methods

2.1 Acid sulfate soil field sampling, mapping and analysis

Field sampling

All available geological (Jensen et al. 1965) and topographic information covering the study area was reviewed before field work began. Colour aerial photographs from 1998, at a scale of approximately 1:25 000, were used for aerial photo interpretation (API) of the landscape, location of borehole sites, and mapping of soil boundaries. Orthophoto contour maps with a 1 m contour interval, at scales of 1:2500 and 1:5000, which were available for most of the survey area, were used to estimate the elevation of each site.

Free soil survey techniques were employed, with boreholes located at various spacings depending on the landform (Reid 1988). Boreholes were spaced at intervals of 250 to 500 m or more on landforms outside the tidal zone. Wider intervals were used in the tidal zone because the consistency of depth to ASS within the mangrove associations meant that intensive field sampling was not warranted, and due to time and budget constraints, it was more important to identify the areas underlain by ASS outside the tidal zone. As some tidal zone areas outside the catchments mapped by field survey were defined by API only, the reliability diagram on the map shows a range of intensities, from a broad scale of 1:100 000, to semi-detailed of 1:25 000.

Starting on the lowest-lying land of the tidal flats, boreholes were located progressively up the catchment until ASS were no longer encountered, or a landform boundary was identified that defined the extent of the *Holocene* ASS deposition. The soil profile was examined using various methods depending on the landform being sampled. Tapered gouge augers, 1.0 to 1.8 m long with 83, 75 and 50 mm diameters, were used to sample in mangrove areas and, occasionally, on supratidal flats (saltpans) that were wet and inaccessible to a four-wheel-drive vehicle. A theoretical maximum depth of sampling of 4.6 m was possible using the three gouge augers successively.

A trailer-mounted, vacuum-vibro soil-coring rig was used to obtain intact 50 mm cores of saturated sediments to a maximum depth of 6 m (Photograph 1). Depending on the type of sediments present, the drier overlying soil materials were first removed with a Dormer brand number 4 auger, Dormer sand auger, or a 75 or 100 mm diameter Jarrett brand auger. This soil was laid out in half-metre sections on a vinyl tarpaulin. When the soil materials were moist and soft enough, the vibro-corer was inserted into the augered hole to sample the deeper, saturated Holocene sediments. The cores were extruded into 2 m x 100 mm PVC trays and cut in half for recording soil properties and for sampling (Photograph 2). However, if the soil materials were too dry or hard, as in the *Pleistocene* clays, then hand-augering continued to a depth of 5 to 7 m. A total of 586 boreholes were examined, described and sampled for this project.

Photograph 1: Vacuum-vibro coring rig used for deep sampling of ASS

Photograph 2: Soil profile laid out on a tarpaulin in 1 m segments: note the gley, Pleistocene, heavy clay basement core sample in the PVC tray at the knife tip

The properties of the soil materials such as texture, colour, mottles, structure, soil moisture status, coarse fragments and segregations were described according to McDonald et al. (1990) and recorded in code format for each horizon on Department of Natural Resources and Mines field sheets. The soil was classified by the Australian Soil Classification (Isbell 1996), and other features of the land such as landform, slope and microrelief were also recorded. Mangrove and tree species were identified either from Lovelock (1993), Lear and Turner (1977), and Alcock and Champion (1989), or were sampled and identified by a local botanist.

Field pH (pH_F) and peroxide oxidised pH (pH_{FOX}) were measured with a portable pH meter (TPS Ionode WP84) at 0.25 m intervals in ASS sediments, at 0.5 m intervals in non-ASS materials, or within other soil horizons if they were less than 0.25 m thick. Soil samples were also taken at 0–0.1 m, 0.2–0.3 m, 0.5–0.6 m and 0.8–1.0 m intervals in the upper metre, and then at 0.5 m intervals throughout the rest of the soil profile, with approximately 500 grams of soil placed in sealed plastic bags. Soil samples were refrigerated in the field and transferred to a freezer for longer-term storage. Samples were either dried at 85°C for three days at Mackay, or sent frozen to the NR&M soil laboratory at Indooroopilly for analysis. Four thousand and thirty soil samples were analysed by the methods described below.

Soil analysis

Initially, actual acid sulfate soil (AASS) samples containing *jarosite*, or with a pH of 4 or less, were analysed by the modified peroxide oxidation combined acidity and sulfate method (POCASm) (Ahern et al. 2000). This was updated to the suspension POCAS method (SPOCAS) for the last 120 profiles (Ahern et al. 2004).

Analytes from the POCAS methods include:

- total actual acidity (TAA)
- total potential acidity (TPA)
- peroxide sulfur (Sp)
- 1M potassium chloride (KCl) extractable sulfur (S_{KCl}).

Total sulfidic acidity (TSA) is calculated from the acid trail (TSA = TPA-TAA), while the peroxide oxidisable sulfur (S_{POS}) is determined by the sulfur trail ($S_{POS} = S_p - S_{KCl}$). An additional analyte of the SPOCAS method is the 4M HCl extractable sulfur (S_{HCl}), which enables net acid soluble sulfur (S_{NAS}), otherwise known as retained acidity ($S_{NAS} = [S_{HCl} - S_{KCl}] \times 0.75$), to be calculated (Ahern et al. 2004).

The potential acid sulfate soil (PASS) samples were analysed by the chromium reducible sulfate (S_{CR}) method only (Sullivan et al. 2000).

All field and laboratory data were entered into the NR&M Soil and Land Information (SALI) database. Volume 2 of this report contains decoded descriptions of each profile, while Volume 3 contains a summary of the soil morphology and the soil analytical data for each profile.

Mapping unit categories

This section has been taken from Malcolm et al. (2002), with permission, and modified only to make it applicable to this study.

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.

The oxidisable sulfur content (% S) of the sample is used to calculate potential acidity. Soil colour, mottles and coarse fragments (such as shell) in the same horizon are noted, to cross-check with the % S result. Oxidisable sulfur contents that exceed the texture-based ASS *action criteria* (Ahern et al. 1998) of 0.03% for sands, 0.06% for loams to light clays, or 0.1% for light medium to heavy clays, are used as the determinants of PASS (Ahern et al. 1998).

The above rules have been built into the database and the % S result for each sample automatically ascribed a code (according to texture) if it exceeds the action criteria. The upper depth of the first horizon in which the action criteria have been exceeded has been assigned a 'depth to sulfide' code, such that:

- **S0** indicates that the action criteria were exceeded between 0 and 0.5 m.
- **S1** indicates that the action criteria were exceeded in the 0.5 to 1 m interval.
- **S2** indicates that the action criteria were exceeded in the 1 to 2 m interval.
- **S3** indicates that the action criteria were exceeded in the 2 to 3 m interval.
- **S4** indicates that the action criteria were exceeded in the 3 to 4 m interval.
- **S5** indicates that the action criteria were exceeded in the 4 to 5 m interval.
- **S5+** indicates that the action criteria were exceeded at depths greater than 5 m.

A **field pH value of 4 or less** is used as the determinant of AASS, so if such a pH was registered, the horizon was assigned a depth code similar to the depth to sulfide code, however, instead of an 'S', an 'A' prefix was assigned. For example, '**A0**' denotes an horizon with a pH of 4 or less, occurring between depths of 0.0 and 0.5 m.

As it is not uncommon to find AASS overlying PASS, in these cases the 'A' code and the 'S' code have been combined. For example '**A0S2**' denotes a soil layer with a pH of 4 or less, between depths of 0.0 and 0.5 m, overlying PASS at 1 to 2 m.

Because of 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 between 4 and 5 were recorded. In these cases, the same depth codes have been used preceded by a lower-case '**a**'. For example, '**a1**' denotes a profile registering a field pH between 4 and 5 at a depth of 0.5 to1.0 m, and '**a1S3**' denotes the same profile overlying PASS at 2 to 3 m.

Other map units used in the project are:

S—indicates the presence of ASS in tidal areas defined by API only. These map units were outside the catchments that were defined by intensive field survey, and were included to extend the ASS mapping to the map boundary. It was found early on in the survey that ASS could be reliably defined by API in these coastal catchments.

S_{LA}—(limited assessment) indicates land that was inaccessible to field survey because of its topography or thick vegetation, but was in a landscape position that indicated it had a high probability of being underlain by ASS.

S_{DL}—indicates various types of disturbed land that were likely to be underlain by ASS and where field survey was not possible because of the nature of the disturbance. Examples of this included council facilities for disposal of waste as landfill, and aquaculture ponds.

LP—indicates land below an elevation of 5 m AHD *(Australian Height Datum)*, which field survey showed had little if any probability of being underlain by ASS.

LP5—indicates land above an elevation of 5 m AHD that had little if any probability of being underlain by ASS.

NA—indicates land not assessed by field survey, and therefore excluded from the defined ASS map units.

The previously quoted action levels are based on disturbances of less than 1000 cubic metres (m^3). For disturbances greater than this, the lowest action level of 0.03% for sands applies to all textures. Similarly for AASS, the treatment action levels are 18, 36 and 62 mol H^+/t for sand, loam and clay textures respectively. Again, if the 1000 m^3 is exceeded, the lower action level applies irrespective of texture.

Soil mapping

The distribution of ASS was mapped onto colour aerial photographs, based on interpretation of the field data and landforms on the photographs. Quite often, a distinct landform change was used to identify the limit of ASS. When this was not available, such as on river and creek flats, the boundary was determined using additional boreholes. Once analytical data were available, ASS areas were subdivided into units of the previously mentioned categories showing the AASS and/or PASS codings. PASS depth categories were coloured in shades of red, pink, orange and brown, with red denoting the shallowest depth. Where AASS were present, a yellow dot overlay was also used. Because of the highly variable nature of the sulfide content in the surface soil under wetlands with melaleuca forests, a subscript 'w' has been used to indicate these wet areas, as it was not possible to map them accurately at a scale of 1:50 000.

The location of each site is also shown on the map. Cartographers at NR&M Indooroopilly transferred the linework from the aerial photographs to a base map to produce the 1:50 000 ASS map. The 5 m contour from the 1 : 2500 and 1 : 5000 orthophoto mapping of the Mackay district is also shown on the ASS map.

Reporting

The reporting of this project has been divided into three parts:

Volume 1 presents the information on methodology, results and conclusions drawn from this study. The report is accompanied by a detailed 1:50 000 ASS map of the study area of Shoal Point to Alligator Creek, and that of Seaforth to Ball Bay.

Volume 2 presents descriptions and field pH measurements of all the boreholes described and sampled throughout the study area.

Volume 3 contains tabulated laboratory data with selected soil profile morphological properties including:

- ASS analyses of samples taken from each profile
- interpreted information, including the labelling of all samples that exceeded the ASS texture-based action criteria that national guidelines denote as 'requiring treatment'.

2.2 Water monitoring

Fourteen monitoring sites were selected in the Reliance, Eimeo, McCreadys, Apsley, Vines, Shellgrit, Bakers, Sandy and Alligator creeks and the Pioneer River (Table 1). Though each site was located within ASS areas of the estuaries, selection of the exact site was determined by access. Two of the sites selected were in deep stormwater drains because these had been excavated through ASS areas. The locations of the water monitoring sites are also shown on the ASS map.

From February 2002, monitoring was conducted every fortnight during the wet season, and at least once a month during the dry season. When it was possible, the water quality was measured after every large rainfall event.

At each site, pH, electrical conductivity (EC) and temperature were measured with a TPS Ionode WP84 pH-conductivity meter, while dissolved oxygen was measured with a YSI model 50B DO meter. Each meter was calibrated before use at the first site, and was checked again after the last site was monitored.

Because the incoming tide would produce similar results at each of the sites, while monitoring the outgoing tide would be more likely to indicate whether acid leachate was present, it was assumed that it would be better to monitor as late as possible on the outgoing tide.

Table 1: Water-monitoring site locations

Site no	Description
W1	Reliance Creek
W2	Bucasia stormwater drain
W3	Eimeo Creek boat ramp
W4	McCreadys Creek at Mackay golf course
W5	McCreadys Creek boat ramp
W6	Apsley Creek
W7	Vine Creek
W8	Pioneer River boat ramp
W9	Shellgrit Creek at Illawong Resort
W10	Bakers Creek at Mackay City Council drain outlet
W11	Bakers Creek at Bruce Highway
W12	Dunrock boat ramp
W13	Sandy Creek at Bruce Highway
W14	Alligator Creek at Bruce Highway

3. Acid sulfate soils: overview

3.1 Description and formation

This section has been taken from Malcolm et al. (2002), with permission, and has been modified only to make it applicable to this study.

'Acid sulfate soil' is a generic term given to sediments principally of marine origin that contain iron sulfides, mainly *pyrite* (FeS_2). The textures of these soils can range from sands to loams and clays. Over the last 140 000 years and, in particular, the last 10 000 years (the Holocene Epoch), sea level fluctuations (coinciding with periods of glaciation) have produced conditions along the Australian coastline conducive to the formation of pyrite. Dent (1986) states that 'pyrite accumulates in waterlogged soils that are both rich in organic matter and flushed with dissolved sulfate usually from sea water'.

The formation of iron sulfides occurs under *anaerobic* conditions when there is sufficient organic matter from decaying plant material in sediments to provide the energy for sulfide-forming bacteria. These bacteria use the organic matter, together with sulfate from sea water, and iron from freshwater sediment to produce the iron sulfides (pyrite), and bicarbonate ions. Flushing such as that provided by tidal regimes removes bicarbonate ions and assists in the formation of pyrite, as described by equation 1.

$$4SO_4{}^{2-} + Fe_2O_3 + 8CH_2O + {}^1/_2O_2 \rightarrow 2FeS_2 + 8HCO^{3-} + 4H_2O \quad (1)$$

sulfate ions + iron oxide + organic matter + oxygen → pyrite + bicarbonate ions + water

Identification of PASS and AASS

When iron sulfides are exposed to the atmosphere (e.g. through excavation and drainage), oxidation occurs, resulting in the production of sulfuric acid (H_2SO_4). Under these conditions, potentially toxic quantities of acid, iron, aluminium and heavy metals are released into the surrounding environment. Normally, AASS occur in upper layers more prone to oxidation, such as the zone of watertable fluctuation. They often overlie PASS, which remain in a reduced state below the watertable.

In the field, PASS are usually black or very dark grey to grey in colour (10YR2/0, 2.5Y2/0 to 5Y5/1) (Munsell Color 1975). They are typically wet, fine-textured soils (e.g. mangrove muds), but may be sandy or, more rarely, gravelly. AASS are usually lighter grey than PASS due to their oxidised state, and often show significant red and orange mottles indicating this. They are generally (but not exclusively) characterised by a yellow mottle called jarosite [$KFe_3(OH)_6(SO_4)_2$], which is strong evidence that sulfuric acid has been released (Photograph 3). 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 pyrite as the root has 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 less to form (Ahern & McElnea 2000). As there are few natural situations that cause pH to drop to these levels, jarosite is one of the better indicators of AASS.

Field pH and field pH peroxide tests also help identify AASS and PASS layers. 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 ASS. PASS usually have a pH_F of 3.5 to 7.5, and pH_{FOX} of 0.3 to 3.0, while AASS generally have a pH_F and pH_{FOX} of 4 or less. The equations below describe the oxidation process in more detail.

3.2 Oxidation of iron sulfides (pyrite)

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

$$FeS_2 + {}^{1}/_{2}O_2 + 2H^+ \rightarrow Fe^{2+} + S_2 + H_20 \quad (2)$$

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

$$S_2 + 30_2 + 2H_20 \rightarrow 2SO_4^{2-} + 4H^+ \quad (3)$$

The complete reaction of pyrite to ferrous ion (Fe II) and sulfate can be written as:

$$FeS_2 + {}^{7}/_{2}0_2 + H_20 \rightarrow Fe^{2+} + 2H^+ + 2SO_4^{2-} \quad (2) + (3) = \quad (4)$$

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 area.

The ferrous ion may in turn be oxidised to the ferric ion (which further reacts depending on the pH of the solution or soil). Low dissolved oxygen and extreme acidity can both cause fish kills. See equations (5), (6) and (7) below:

$$\underset{\text{ferrous}}{Fe^{2+}} + H^+ + {}^{1}/_{4}O_2 \rightarrow \underset{\text{ferric}}{Fe^{3+}} + {}^{1}/_{2}H_20 \quad (5)$$

In the absence of bacteria, the generation of Fe^{3+} from Fe^{2+} can be a rate-limiting step in the oxidation of pyrite, but *Thiobacillus ferrooxidans* can accelerate this reaction ten, to ten thousand times. Optimum conditions for its growth are a temperature about 30^0C and a pH of approximately 3. The reaction in equation (5) 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). This reaction produces additional acidity and removes dissolved oxygen from the waterways.

$$Fe^{3+} + 3H_20 \rightarrow Fe(OH)_3 + 3H^+ \quad (6)$$

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

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 16H^+ + 2SO_4^{2-} \quad (7)$$

Note: This reaction, equation (7), does not require oxygen to oxidise pyrite and can occur within an existing acid sulfate soil that has generated ferric ions, even when oxygen is denied by reflooding or deep burial. For this reason, existing AASS require liming even if they are being buried.

At different times, the acid levels in the solution will vary, and therefore one or more of reactions 4—7 may be operating. One of the important factors in moderating the pH is the buffering capacity of the soil, which depends on the type and quantity of clay minerals present, the form (fine or coarse) of any carbonates present, and the rate at which the chemical reactions occur. For example, if lime (as in fine shell remnants) is present, then it will neutralize some of the acid.

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

$$\underset{\text{1 mol pyrite}}{FeS_2} + {}^{15}/_{4}O_2 + {}^{7}/_{2}H_20 \rightarrow Fe(OH)_3 + \underset{\text{2 mol sulfate}}{2SO_4^{2-}} + \underset{\text{4 mol acid}}{4H^+} \quad (8)$$

3.3 Impacts

Oxidation of waterlogged sulfidic sediments has occurred naturally over time, such as when watertable levels have dropped during periods of extreme drought. Sulfuric acid release would, however, have been slow, and the natural buffering capacity in undisturbed landscapes would have reduced the likelihood of environmental damage. However, when large amounts of sulfidic sediments are artificially drained or excavated, 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 becomes extremely toxic to fish and vegetation, (though it is rarely concentrated enough to affect humans through short-term skin contact). The effects of ASS are widespread and can be divided into three broad categories—agronomic, engineering, and environmental impacts.

Agronomic impacts

ASS pose chemical, biological and physical problems for crops (Dent 1986). The sulphuric acid that is produced results in very low pH levels of less than 3. Under these conditions, heavy metals become soluble, causing aluminium, iron III, and manganese plant toxicities, and deficiencies of phosphorus, calcium and potassium. Farm productivity can also be reduced, as the availability of nutrients for pastures can be severely restricted if acidic conditions allow unpalatable acid-tolerant weeds such as *Phragmites* to invade paddocks (Photograph 4). Grazing animals living in these areas may consume too much aluminium and iron as a consequence (Sammut & Kelly 2000).

Photograph 3: AASS with prominent jarosite (yellow) mottles

Photograph 4: Acid-tolerant *Phragmites* species growing on a disturbed ASS area

Engineering impacts

In the undisturbed state, sulfidic clays act as super-saturated gels with very low bearing strength (Dent 1986), making them unsuitable for foundation support. The sulfuric acid produced after exposure of sulfidic sediments corrodes steel and concrete (Photograph 5). The iron in pyrite oxidises to form iron hydroxides, which can choke drains for significant distances downstream of the acid source (Photograph 6).

Photograph 5: Concrete infrastructure displaying pitting due to attack by acidified drainage water

Photograph 6: Iron oxides choking a drain

Environmental impacts

ASS disturbance has the potential to affect water quality and aquatic life significantly. Acid leached into waterbodies increases the solubility of aluminium and releases various forms of soluble and precipitated forms of iron. Aluminium in particular has severe effects on gilled organisms, causing death and disease of fish and crustaceans. Fish diseases include red spot (epizootic ulcerative syndrome), which occurs when the protective mucous covering the fish is removed by acid water, allowing a fungus to enter the skin and create large red ulcers on the body. (Photograph 7).

A decrease in the growth rates and productivity of aquaculture species such as oysters has also been attributed to acid released from disturbed ASS (White et al. 1996). Certain forms of the iron released when these soils are disturbed 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 lower the pH of poorly buffered soils such as those dominated by sand, restricting growth and killing intolerant native plants.

Photograph 7: Fish affected by red spot disease (epizootic ulcerative syndrome)

4. Geomorphology and acid sulfate soils

This section has been taken from Malcolm et al. (2002), with permission, and modified only to make it applicable to this study.

4.1 Background

In general, the sediments in which ASS form were laid down during periods of high sea level similar to those we know today. These high sea levels (which correlate with interglacial periods), have occurred twice in the last 150 000 years.

Although it is generally recognised that the majority of ASS occur in sediments deposited in the last 10 000 years, it is useful to look further back in time to gain a better understanding of this deposition. While the whole process relating to Pleistocene ASS is still to be clarified, landholders should assume that land can (and in some cases will) have ASS buried below apparently benign strata. The key features are the limits of sea level inundation, and the conditions for sediment deposition in these areas, which are explored below.

During the previous interglacial period within the Pleistocene epoch, 120 000 to 140 000 years before the present, evidence suggests that sea levels rose several metres higher than they are now (Pickett et al 1985). This caused the drowning of river valleys and low-lying coastal areas. In general, shorelines and floodplains were pushed many kilometres west, and estuaries similar to those of today were formed. After this high, the sea level receded and then fluctuated between 80 and 140 m below present levels during the most recent ice age (Chappell 1987). During this time, rivers and creeks cut deep channels through the previously deposited fluvial and estuarine sediments, removing some, and isolating others.

The most recent sea level rise (post-glacial marine transgression) began approximately 19 000 years ago. At this time, the sea level was estimated to be 140 m lower than it is now, with the shoreline up to 100 kilometres east of where it is today. At the beginning of the Holocene period (10 000 years ago), the sea level was approximately 25 m below its present level and still rising (Thom 1981). Present sea level was reached about 6500 years ago (Thom & Roy 1985).

The rapid rate of sea level rise during the Holocene epoch exceeded the rates of coastal deposition, and thus valleys and low-lying coastal areas were drowned just as they had been during the Pleistocene. Once sea level rise stabilised (termed '*still stand*'), new estuaries were formed and coastal deposition processes began filling the newly created subaqueous space (Graham & Larsen 1999). The depth of sediment deposited depended on the size of the local river system and the depth of down-cutting that had occurred during the low sea levels of the Pleistocene era.

4.2 Geomorphology of estuaries

Understanding the geomorphology of an area is an integral part of mapping ASS as it enables more educated placement of boreholes. The following provides a basic insight into the coastal processes that have resulted in the formation of ASS in the Mackay area.

Dalrymple et al. (1992) define 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 their coastal classification, ideal estuaries can be divided into three energy zones:

- an outer zone dominated by marine processes (i.e. waves and tidal currents)
- a low-energy central zone where incoming marine energy is balanced by river energy
- an inner, river-dominated zone.

Depending on which influence is stronger, estuaries can be further classified as either wave- or tide-dominated. In wave-dominated or barrier type estuaries (WDEs), wave energy at the mouth of the system is relatively high. In combination with tidal currents, this causes sediment to move alongshore and onshore into the mouth of the estuary, forming a barrier such as a spit or submerged sandbar which then prevents 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, while in the upper reaches (dominated by river energy), fluvial sediments are deposited as bay-head or fluvial deltas. The area of neutral or minimal energy (central basin) between the two is generally filled with finer sediment such as clays and silts, which results in a clearly defined tripartite (coarse—fine—coarse) distribution of sediments within the estuary. 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.

Tide-dominated estuaries (TDEs) occur when tidal-current energy exceeds wave energy at the river mouth (Dalrymple et al. 1992). They are typically funnel-shaped, and tend to occur in areas with very large tidal ranges (e.g. the South Alligator River in north-western Australia), although they can also form in areas with smaller tidal ranges if wave action is also limited. Elongate sandbars that dissipate wave energy develop in the lower and seaward estuarine reaches, which are therefore dominated by marine sands. As in WDEs, fluvial energy decreases with distance downstream.

In the upper reaches, which are dominated by river currents, sandy and gravelly fluvial–tidal sediments are deposited and fluvial deltas often develop. However, as tidal energy penetrates further upstream than wave energy, the area of neutral or lowest energy—where tidal and fluvial energies are equal—is not as pronounced as in WDEs (see Dalrymple et al. 1992, figures 4 and 7), so there is little or no tripartite sediment distribution in TDEs. Mud-filled central basins can develop early on during the transgression behind the marine sand tidal delta sills (Roy 1984), and can be buried later by sandy tidal or fluvial sediments as the basin becomes shallower. Sands therefore occur along the estuary channels, with muddy sediments being restricted to tidal flats and marshes along the margins of the estuary (Dalrymple et al. 1992).

The estuaries in the study area are mainly wave-dominated with well defined sand barriers (e.g. McCreadys, Eimeo, Bakers and Seaforth creeks and the Pioneer River) (Photograph 8). However, several of the estuaries protected from wave and wind action by headlands (e.g. Reliance, Sandy and Alligator creeks) are considered to be more typical of TDEs (Photograph 9). Because of the large tidal range in the Mackay district (typically 3–6 m), the WDEs also display some of the features of TDEs, such as higher tidal-current energy at the channel mouth, very wide estuary mouths, and sandy tidal channels due to increased tidal-current energy. They also lack permanent lagoons behind the sand barrier, because of the high tidal range.

As TDEs also have wide, open mouths, but no sand barrier or spit, tidal-current energy dominates in their lower reaches, with strong tidal exchange and well developed sandy tidal deltas.

Photograph 8: Typical wave-dominated estuary of McCreadys Creek in the Mackay district

Photograph 9: Typical tide-dominated estuary of Reliance Creek in the Mackay district

5. Results

Of the nine catchments and coastal township areas targeted for ASS mapping, six were completed during the two years of the project. The mapped area consists of the catchments of Reliance Creek, McCreadys Creek, the Pioneer River, Bakers Creek and Sandy Creek, and the Seaforth–Ball Bay area. A total of 14 290 ha of land was mapped during this project, of which 9139 ha were identified as being underlain by ASS. This includes 1178 ha of AASS and 9070 ha of PASS. (There are 69 ha of AASS not underlain by PASS.) Significantly, 3003 ha of land below an elevation of 5 m AHD (mapped as LP) is not underlain by ASS.

The LP5 land was not mapped to any great extent, and is shown on the map only when confirmed by boreholes and soil analysis. It is therefore not considered further in the following discussion of results. Table 2 presents a summary of the areas of AASS and PASS found in each of the depth category mapping units, as well as the other mapping units used (e.g.. LP, S_{DL} and S_{LA}).

Table 2: Area (ha) of AASS (red) and PASS (black) for each depth category; other ASS mapping units; and LP land for each catchment

Depth (m)	Reliance		McCreadys		Pioneer		Bakers		Sandy		Seaforth		Total	
	AASS	PASS	AASS	PASS	AASS	PASS	AASS	PASS	AASS	PASS	AASS	PASS	AASS	PASS
0–0.5	150	1 353	28	154	178	320	65	261	89	161		275	510	2 524
0.5–1	15	537	84	469	110	408	127	498	44	69	9	17	389	1 998
1–2	15	252	7	287	38	484	101	431	35	422		2	196	1 878
2–3	11	160	13	142		405	41	203	13	159		6	78	1 075
3–4		114		19		210	26	156		86		37	26	622
4–5		4		64		78	9	137		35		39	9	357
0.5				64		10		19		48		12		153
Map unit														
S_{DL}		32		15		76		110		12		8		253
S_{LA}						20		103		82		5		210
Total ASS	191	2 452	132	1 214	326	2 011	369	1 918	181	1 074	9	401	1 208	9 070
LP		548		316		586		1 008		479		66		3 003
LP_5		318		224		1 452		94		53		76		2 217
Total land		3 318		1 754		4 049		3 020		1 606		543		14 290

The results of the ASS mapping, soil analyses and water quality monitoring for each catchment area are discussed in the following sections, in catchment order from north to south (Reliance Creek to Sandy Creek), followed by the Seaforth to Ball Bay area.

5.1 Reliance Creek catchment area

Catchment geomorphology

The Reliance Creek catchment area is a small estuary confined by coastal hills formed from Cretaceous and Permian volcanic rocks. The Eimeo and Dolphin Heads estuaries, which are also included in this catchment area, are described later in this section (Figure 2). The central basin area of Reliance Creek penetrates only 5 km inland before the creek line is deflected westwards by the steep hills to the south. Unlike the other coastal creeks, Reliance Creek is a north—south orientated estuary, with a wide, almost straight, drainage channel discharging straight into the ocean. On the eastern side of the creek mouth, extending westward from Shoal Point, there is only a weakly developed coastal sand spit that does not restrict tidal exchange. As the high tidal energy levels at the creek mouth probably prevent further migration of this sand spit to form a barrier, the Reliance Creek estuary is considered a TDE.

Reliance Creek is also protected from the dominant south-easterly wind and wave action by the low hills of Shoal Point, the most northerly point on the coastline. This headland offers protection from currents, trapping north-migrating sand so that extensive sand flats up to 2 km wide at low tide have formed out from the mouth of Reliance Creek. The creek therefore has excellent tidal exchange, with the drainage depression becoming a series of exposed sandbars at low tide, with narrow, meandering, shallow channels that continue out over the sand flats.

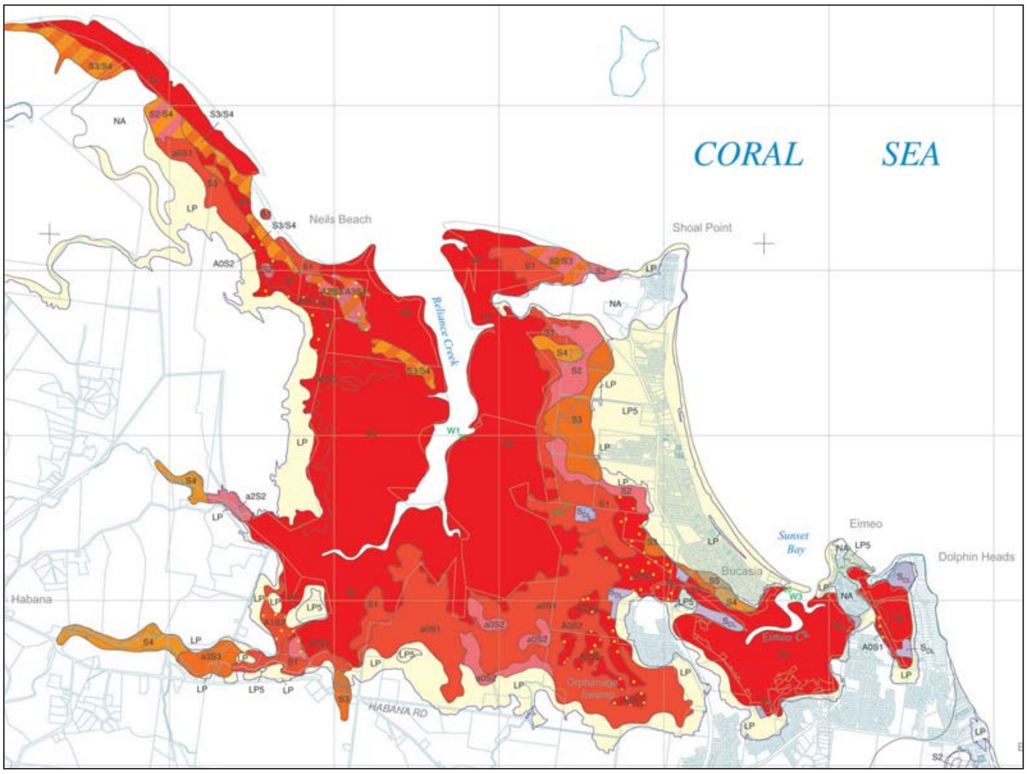


Figure 2: Reliance Creek catchment area

The central creek channel is surrounded by dense mangrove forests that extend up to 1.5 km inland. They are fringed by supratidal (saltpans) and extratidal (marine couch) flats before the limit of the tidal zone is reached. Mud layers, 1.5 to 3.5 m thick, have been laid down over former tidal or fluvial sands in this part of the central basin. In the south-eastern area of the central basin, forests of long-leaved paperbark (*Melaleuca leucadendra*) have established where thin (<0.3 m) alluvial clay deposits have been laid down over the saltpans and marine couch flats. Channels of the tidal flats still penetrate into and around these paperbark forests so that in certain areas they appear as forested 'islands' on the tidal flats. Mangrove muds up to 5 m thick have been laid down in this central basin area.

From the headwaters of the central basin, Reliance Creek continues to the west as a narrow valley through the surrounding hills, 10 km inland to Farleigh and The Leap. This large catchment area has enabled the creek to cut down deeply into the bedrock, and the resultant channel has been infilled with Holocene estuarine gravels, sand, and mud lenses as far inland as the Habana Road. Subsequent fluvial delta development has buried these sediments with 3 to 4 m of recent alluvial deposits. A similar scenario was encountered on two other tributaries of Reliance Creek.

Behind the headland of Shoal Point and the Pleistocene sand ridge extending down to Bucasia, a unique landscape has formed. In this area, a Holocene dunefield up to 3 km long and 1 km wide has been laid down over sandy estuarine sediments. Some of the sand ridges are still evident, although most of the area has been modified for growing sugar cane. The dunes are orientated in a general north-westerly to south-easterly direction in response to the dominant south-easterly winds, with the sands most likely sourced from the current coastline.

The Eimeo and Dolphin Heads creek catchments are also included as part of the Reliance Creek catchment area. Eimeo Creek Basin was once joined by a narrow neck of extratidal flats at Bucasia; however, filling for the Bucasia shopping centre has now separated the two basins and prevented movement of tidal waters. The Dolphin Heads Basin just to the east of Eimeo Creek is separated from it by low hills. Both basins are barrier estuaries that are protected by coastal sand barriers or sand spits, with only narrow channel entrances. These two basins are unique in that they are confined on all other sides by low hills that rise up immediately from the edge of the tidal zone. As neither of them has a permanent watercourse at the bay head because of the steep surrounding topography, there are no bay-head deltas. They therefore consist almost entirely of a central basin with only a limited flood-tidal delta at the sand spit.

The central basins are almost completely covered with dense mangrove forests, with only narrow saltpans along the landward margins. As they are low energy zones, they are filled entirely with mangrove muds more than 4 m thick (depth examination was limited by hand-sampling equipment). As with all estuaries in the Mackay region, there is no subaqueous space or permanent waterbody behind the sand barrier because of the high tidal range on this part of the Queensland coast. Both estuaries still have moderate exchanges and are drained at low tide, with only pools of water remaining in the drainage line. This strong tidal exchange maintains the open entrances to the estuaries. Extensive sand flats trapped in behind the two headlands have also built up seawards from the estuaries and are exposed at low tide.

Acid sulfate soils

The Reliance Creek catchment area contains 2459 ha of ASS, with 191 ha of AASS and 2452 ha of PASS, which were defined from 85 boreholes. As outlined in the geomorphology section, 86% (2110 ha) of ASS in this catchment area occurs within the tidal zone, showing the significance of this landform in relation to these soils. The largest area of ASS outside the tidal zone (168 ha) occurs under the Holocene sand dunes between Shoal Point and Bucasia. There are also 106 ha underlying the valley flats of Reliance Creek and its tributaries, with a further 77 ha buried by the sand dunes on the north-western margin of the estuary mouth.

Table 3 shows the areas of AASS and PASS for each of the depth categories, and the areas of disturbed and limited assessment lands. Most of the AASS (150 ha) occurs in the upper half metre of the profile (**A0**) on the saltpans, marine couch flats and melaleuca backplains. Smaller areas of AASS underlie some of the valley flats (30 ha) and sand dunes (11 ha).

Table 3: Area (ha) and proportion (%) of AASS and PASS for each depth category, disturbed and limited assessment lands in the Reliance Creek catchment area

ASS	0–0.5 m	0.5–1.0 m	1–2 m	2–3 m	3–4 m	4–5 m	5m+	S_{DL}	S_{LA}	Total
AASS	150	15	15	11	-	-	-	-	-	191
%	78	8	8	6						100
PASS	1 353	537	252	160	114	4	-	32	-	2 452
%	55	22	0	7	5	<1		1		100

LP: 548 ha

The largest area of PASS (1353 ha) is also the shallowest, and occurs in the upper half metre of the profiles (**S0**) in the wetter mangrove areas of the intertidal flats. There are also significant areas of PASS (537 ha) at depths of 0.5 to 1.0 m (**S1**) under the less frequently inundated mangrove forests and saltpans, and 1 to 2 m (252 ha) below the marine couch flats, melaleuca backplains and low-lying areas of the Bucasia dunefield (**S2**). Below these depths (2—5 m) the PASS occur on varying landforms, with each depth category accounting for only 7% or less of the total area of PASS. As a result of either excavations or filling, there are also 32 ha of disturbed lands underlain by ASS.

Within the catchment area, there are 548 ha of land below an elevation of 5 m AHD that are not underlain by ASS (**LP**). These are the foot slopes of the surrounding hills and rises, which are underlain by more than 5 m of unconsolidated clay and sand sediments. In many cases, the extent of Holocene ASS deposition is defined as the change in landform between the tidal zone (up to the level of the HAT) and these colluvial foot slopes. These clay sediments continue under the Holocene basins and represent the gley, Pleistocene, heavy clay basement over which estuarine sediments were deposited as the sea level rose.

Analyses of the AASS indicated that they are almost fully oxidised, with % S mainly between 0.01 and 0.12%, except in one profile where the level in one layer is 1.4%. Only three of the 28 samples analysed exceed the action level for treatment (0.1% for a clay soil, or 0.06% for a loamy soil). Actual acidity levels vary from <10 (below the level of quantification) to 46 mol H^+/t, with a mean of 29 mol H^+/t, which are all below the action level of 62 mol H^+/t for a clay soil. Levels in the single samples of sand-textured and sandy loam-textured AASS tested are also below their respective action levels (18 and 36 mol H^+/t), with actual acidities of <10 and 12 mol H^+/t respectively. Retained acidity levels, measured in one profile only (site 506), are from 3 to 15 mol H^+/t, resulting in overall existing acidity levels (actual plus retained) of 33 to 51 mol H^+/t.

The % S content of the PASS layers varies considerably between the clay and sand texture groups (Figure 3), ranging from 0.03 to 0.72% in the sands with a mean of 0.16%, to 1% in the clays, with a range of 0.03 to 3.20%. Levels in the four samples in the loam group are low to moderate (0.09—0.69%), with a mean of 0.35%.

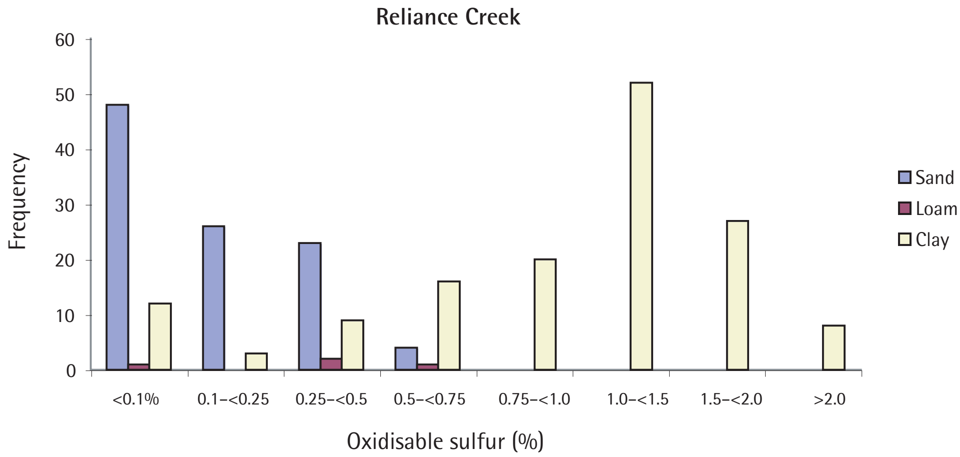


Figure 3: Frequency of samples within the oxidisable sulfur ranges for the sand, loam and clay texture groups, for the profiles of the Reliance Creek catchment area

Detailed descriptions of landforms

Central basin—intertidal flats

The mangrove forests of the central basin are mapped predominantly as **S0**, with the PASS at or just below the surface. In a few of the sites sampled in the wetter areas of the intertidal flats, which are dominated by the red mangroves (*Rhizophora stylosa*), and tall stilted mangroves with interwoven aerial roots (*Rhizophora apiculata*) (Photograph 10), the % S content of the surface soil is moderate (0.17—0.35%). However, in contrast with the other catchments, many of the areas of yellow mangrove (*Ceriops tegal*) adjoining these mangrove forests of the creek lines are also **S0**, with the PASS occurring slightly deeper at 0.3 to 0.5 m. Only on the margins are there small **S1** areas with PASS between 0.5 and 1.0 m (Photograph 11).

Photograph 10: Typical red mangrove forest displaying interwoven aerial roots of a wetter S0 area next to a drainage line

Photograph 11: Classic yellow mangrove forest in the Mackay district in a less inundated S1 map unit

The soils of the mangrove forests are Sulfidic, Intertidal Hydrosols. They consist of very dark, to dark grey (10YR3/1; 2.5Y3/0, 4/0), silty light or light medium clays, occasionally with few to common (2–20%) orange or brown mottles in the topsoil, usually overlying dark grey pyritic sands between 1.5 and 3.3 m. Overall, the central basin mud deposits are significantly thicker than those of McCreadys Creek. Occasionally, no sands were encountered up to the maximum depth of the gouge auger (3–4 m). The % S content of the muds varies from 0.17 to 3.2%, while that of the sands ranges from 0.27 to 0.85%.

Central basin—supratidal and extratidal flats

The saltpans or supratidal flats (Photograph 12) are either **S0** or **S1**, with the PASS occurring between 0.35 and 0.80 m. Dark grey (10YR4/1; 2.5Y5/2; 5Y4/1), mottled B2 horizons are present in all profiles. Jarosite has developed at one site, in a layer with a pH of 5.3 to 5.7. Most of the saltpans are also mapped as **a0** units, as part of the upper 0.5 m of the profile has a pH of 4.3 to 4.6. The % S content of the muds varies from 0.51 to 2.0% (no sand lenses were encountered). These soils are classified as Sulfidic, Supratidal Hydrosols. The Reliance Creek Basin is quite shallow under some of the saltpans where the heavy gley clays of the Pleistocene basement occur at depths of only 1.5 to 3.1 m. The basement under all catchments stands out markedly from the overlying Holocene sediments, as it is gley-coloured (5GY, 5G or 5BG 4/1, 5/1, 6/1), sometimes mottled, and has the significantly heavier texture of medium to heavy clay (see Photograph 2).

Areas of the marine couch (*Sporobolus virginicus*), or extratidal flats, are quite extensive in the Reliance Creek tidal zone, particularly in the south-eastern area of the central basin near Bucasia (Photograph 13). These flats are mainly **A0S1**, **A0S2**, **a0S1** or **a0S2**, with the PASS occurring between 0.6 and 1.8 m. The profiles are well developed, with mottled, dark grey or grey (10YR4/1, 5/1; 2.5Y5/0, 5/2) B2 horizons in the upper 0.5 m, often with few to many (2—50%) yellow jarositic mottles. The pH of the AASS layers is either less than 4.0, or from 4.2 to 4.9, resulting in either **A0** or **a0** mapping units. These soils are mainly Sulfuric, Extratidal Hydrosols. The AASS layers are almost fully oxidised, with very low % S (0.04—0.1%), and actual acidity levels of 15 to 35 mol H^+/t. One area is mapped as **A0** as it consists only of an AASS directly overlying the shallow gley clay basement at 1.4 m. The underlying PASS consist of layers of muds and sands. The % S content of the clays is high (usually 0.5—2.7%), while that of the pyritic sands is only 0.21 to 0.33%.

Photograph 12: Typical salt pan or supratidal flat in the Reliance Creek catchment area

Photograph 13: Extensive marine couch or extratidal flats in the Reliance Creek catchment area

Central basin—melaleuca forests

Long-leaved paperbark forests occur on the thin layers of alluvium only in the south-eastern corner of the Reliance estuary directly to the west of Bucasia, which is known as the Orphanage Swamp (Photograph 14). As there is no major watercourse in this area that can deposit sufficient alluvium to form a fluvial delta, alluvial–colluvial wash from the surrounding hills has laid a thin veneer over the margins of the tidal flats.

Most of the profiles described in these areas have well developed, dark grey to grey (10YR5/1, 6/1; 7.5YR5/0) silty light or light medium clay subsoils, with many (20—50%) prominent red and brown mottles, and few to common (2–20%) yellow jarositic mottles. The subsoil is also usually extremely acid, with a pH of 2.9 to 3.9 in the upper 0.5 m, making it an AASS. The % S content of these layers ranges from 0.01 to 0.12%, while actual acidity levels vary from 15 to 45 mol H^+/t. These horizons overlie silty, light clay PASS between depths of 1.0 and 1.3 m, and these areas are mapped mainly as **A0S2**. Below 2 m, the deeper PASS sediments often consist of alternating layers of sands and muds, 0.1 to 0.5 m thick, to depths greater than 5 m. The % S content in the sands ranges from 0.10 to 0.52%, while that of the silty light clays is much higher at 0.7 to 1.7%. Most of the profiles are classified as Sulfuric, Redoxic Hydrosols.

Bay-head deltas

As outlined earlier, there is bay-head delta development only on the floodplain of Reliance Creek and the valley flats of two smaller creeks nearby (Photograph 15). The depth to PASS increases with distance inland along these creek flats. On the flats adjoining the tidal areas it occurs at 1.7 to 2.2 m (**S2** or **S3**). These areas also have AASS, or strongly acidic layers with jarosite, 0.3 to 0.7 m thick, overlying the PASS at depths of 0.9 to 1.4 m (**A1**, **A2** and **a2**). Further inland, the PASS are deeper, occurring between 2.7 and 3.9 m (**S3** or **S4**), and though AASS are not present, the overlying sediments are occasionally strongly acidic (e.g. **a3S3** map unit). The PASS sediments can be very gravelly at times, containing many or very many (20—90%), small to large (2—60 mm), rounded gravels that prevented sampling to 5 m in all cases.

The ASS are overlain by 0.8 to 2.9 m of black, or very dark grey (10Y2/1, 2/2, 3/1, 3/2) light medium to medium heavy clay, overlying mottled dark grey or grey (10YR4/1, 5/1; 2.5Y5/0) estuarine or alluvial clays. The % S content of the AASS layers is mainly very low (0.01–0.09%), except in the one previously quoted layer where it is very high (1.4%), with actual acidities of 25 to 45 mol H^+/t. The % S content of the clay PASS sediments is from 0.33 to 1.80%.

Photograph 14: Melaleuca (long-leaved paperbark) forests within the tidal zone on thin layers of alluvial sediment overlying ASS

Photograph 15: Valley flat underlain by ASS at 2.8 m (S3) on a tributary of Reliance Creek

Coastal sand dunes

On the west side of the mouth of Reliance Creek, the sand dunes have been stranded in or at the back of the mangrove forests due to further infilling of the estuary. These dune areas consist of three or more parallel sand ridges representing former beachfronts. All overlie PASS between 1.5 and 3.5 m, with the depth varying between the dune crest and swale (**S2/S3 to S3/S4**). One of the dunes with a thin layer of an AASS is mapped as **A2S3/A3S4**. These compound map units have been used to indicate the difference in depth to the ASS between the dune crest and swale. Soils on these dunes are mainly Orthic Tenosols, with weakly developed colour B horizons (10YR4/4, 5/4), grading into C horizons of pale sands (10YR6/2, 6/3, 7/4) at 1.2 m. There are up to 2.5 m of aeolian sands overlying gravelly delta sands, or estuarine sands or muds. The % S content of the pyritic sands is from 0.03 to 0.72%, while that of the muds is much higher at 1.1 to 3.2%.

Shoal Point—Bucasia dunefield

The Holocene dunefield between Shoal Point and Bucasia on the eastern side of the central basin is unique, as the PASS sediments are composed entirely of pyritic sands. This area is mapped as **S2**, **S3** or **S4**, as the dunefield, though modified, is still fairly undulating with some low dunes remaining. The sandy PASS occur between depths of 1.6 and 3.7 m and continue to beyond 5 m. The % S content of the pyritic sands is low (mainly between 0.03 and 0.19%), with only one moderate level of 0.35% in one of the profiles. A separate ASS area on a sand sheet to the south of Bucasia is mapped as **S3**, **S4** and **S5**, with the PASS occurring between 2.8 and 4.1 m. The PASS again consist mainly of pyritic sands, with % S levels of 0.02 to 0.4%. There are also two 0.2 m lenses of light clay PASS in the sands with 0.7% S. The overlying aeolian sands are fine, usually with a colour B horizon (10YR5/3, 6/3, 6/4) in the upper metre of the profile. These soils are classified as either Orthic Tenosols or Arenic Rudosols.

Water quality monitoring

Figures 4, 5 and 6 show estuarine water pH and electrical conductivity for the three sampling sites in the Reliance Creek catchment area. (Dissolved oxygen and temperature data are tabulated in the Appendix.) The Reliance Creek (W1) and Eimeo Creek sites (W3) have normal estuarine water pH (7.1—8.3) and salinity (30—53 dS/m), with the latter decreasing after rainfall and runoff. Over the monitoring period, the dissolved oxygen levels varied from 5.1 to 7.9 mg/L, which is also within the normal range for estuarine waters.

Data from the Reliance Creek drain (W2), which crosses a tidal flat to the west of the Bucasia sewerage treatment plant, are much more variable. Salinity varies markedly between runoff events, and is very low (5—9 dS/m) immediately after rainfall. It also increases to 50 dS/m as salt water enters the drain on the tide.

This drain, which is up to 2 m deep, has been excavated across a tidal flat and melaleuca backplain, and the excavated PASS material has been left beside the drain. As these two areas are underlain by ASS between 0.8 and 2.0 m, the drain represents a disturbed site within the catchment. However, over the monitoring period, the pH of the water in it was between 6.5 and 8.4, while the dissolved oxygen levels were between 4.2 and 11.1 mg/L, both of which are within the acceptable range for water quality. Since the absence of iron staining on the drain wall supports the pH data by indicating that the amount of acid leachate has not been significant, it appears that little if any acid leakage is occurring at this site.

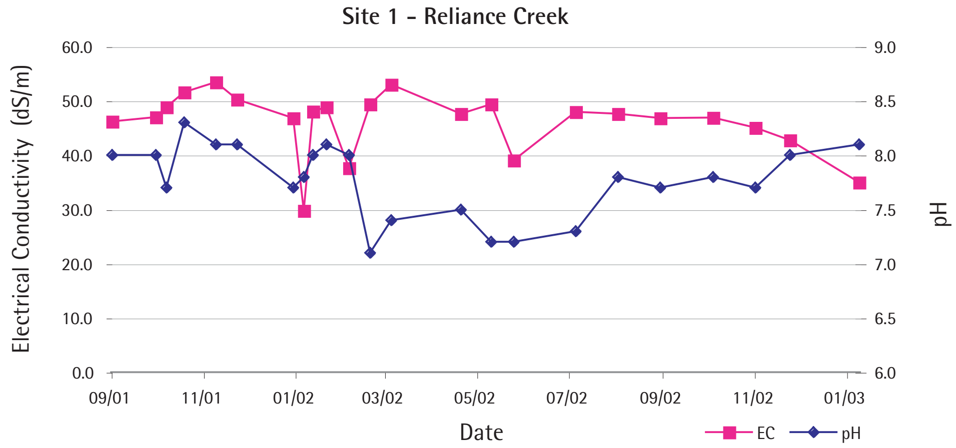


Figure 4: pH and EC of estuarine waters of Reliance Creek

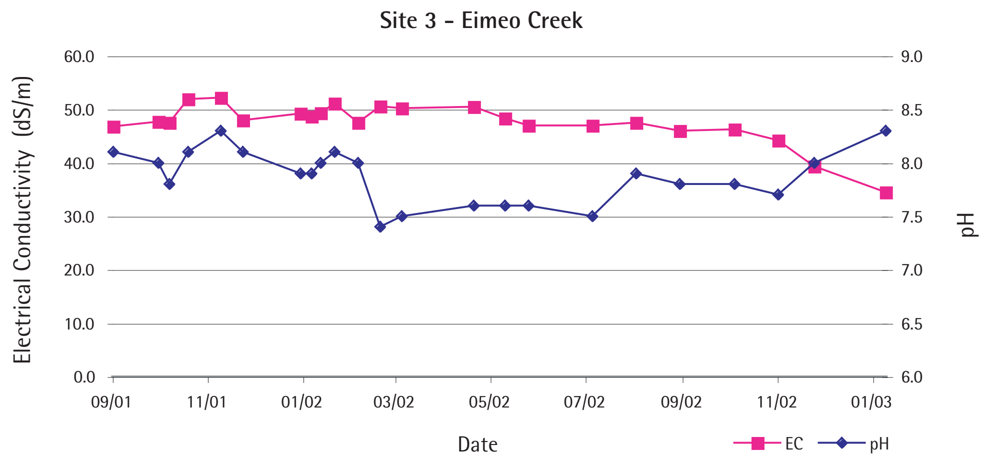


Figure 5: pH and EC of estuarine waters of Eimeo Creek

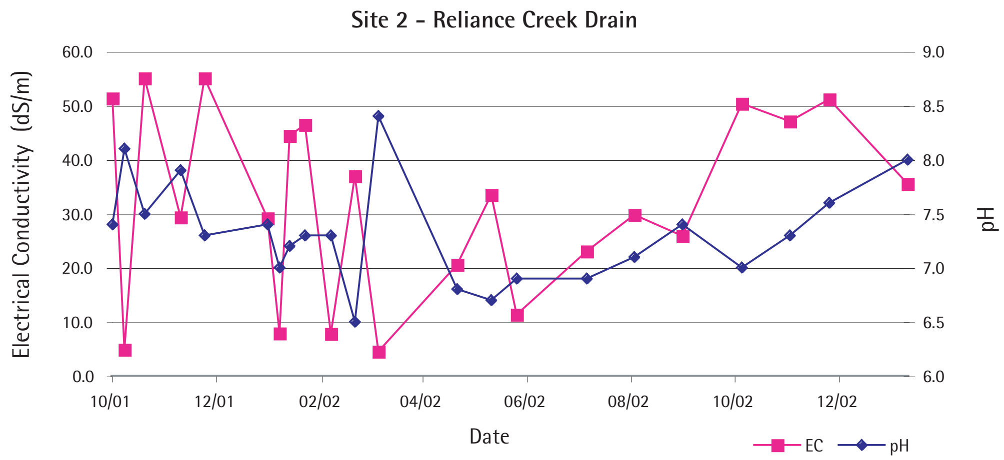


Figure 6: pH and EC of estuarine waters from the Bucasia stormwater drain

5.2 McCreadys Creek catchment area

Catchment geomorphology

The McCreadys Creek catchment is a small coastal drainage system that extends only 5 km inland. It is a basin confined by the rises and low hills formed on intermediate and acid volcanic rocks (Campwyn Beds) to the north, and Mesozoic microdiorite rocks to the west and south (Figure 8). A large Pleistocene sand sheet, on which the suburb of Andergrove is built, joins the microdiorite rises in the central-south of the catchment. This sand sheet is interpreted as representing a former coastal dune system during the interglacial, higher sea levels of the Pleistocene epoch. The dunes have subsequently been eroded and flattened, so they now appear as a domed sand mass. The soil profile is also significantly more developed on this older sand mass, with strong, red-brown, colour B horizons.

The south-eastern part of the basin is separated from the Bassett Basin of the Pioneer River catchment further to the south by low, Holocene sand dunes along Keeleys Road and Slade Point Road, although during the early Holocene the two basins would have been continuous. It is likely that the Pioneer River once entered the sea behind the headland of Slade Point. The McCreadys Basin is further protected on its eastern side by the steep-walled, parabolic, Holocene sand dunes that extend from Mackay harbour to the northern tip of Slade Point. Behind this, a sand spit extending southwards from Blacks Beach affords the basin complete protection, with the mouth of the creek entering the sea around the southern tip of the Blacks Beach spit.

The McCreadys estuary is therefore a wave-dominated or barrier type estuary dominated by a narrow tidal creek that meanders through dense mangrove forests in the central basin area. At the bay-head delta, the floodplains of the drainage lines are gradually extending into the central basin, covering the estuarine sediments with clay and silt alluvial sediments and forming black cracking clay soils (Vertosols) up to 1.4 m deep. The estuary has two basin areas separated by the Andergrove sand sheet. The western basin is drained by McCreadys Creek and its tributaries, while the southern basin section between Andergrove and Slade Point is drained by Apsley Creek.

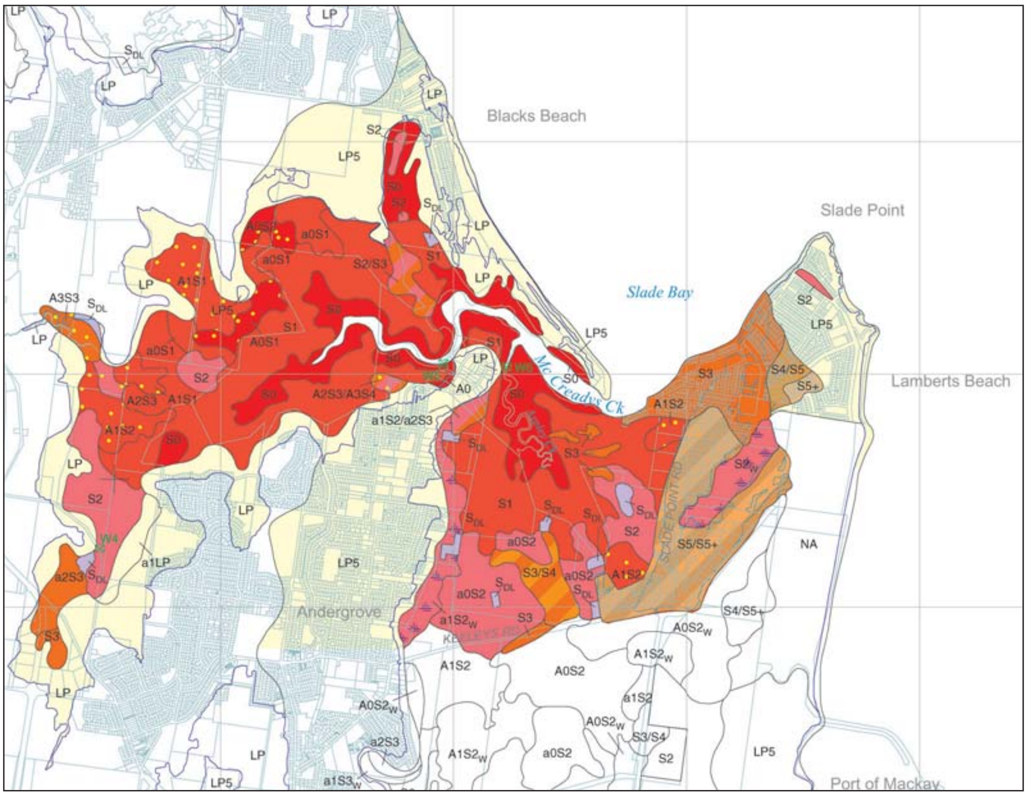


Figure 7: McCreadys Creek catchment area

Acid sulfate soils

In the McCreadys Creek catchment, 1216 ha of ASS were defined from 83 boreholes. There are 133 ha of AASS and 1214 ha of PASS. Of this total area, 638 ha (53%) occur within the tidal zone, indicating the significance of this area in relation to ASS. Outside the tidal zone, the largest area of ASS occurs under the sand dunes and melaleuca swamp of Slade Point (231 ha). Smaller areas underlie the alluvium of McCreadys Creek and its tributary (104 ha), and the floodplains and swamps around Keeleys Road (80 ha).

Table 4 shows the areas of AASS and PASS for each of the depth categories, and areas of disturbed and limited assessment lands. The AASS occur mainly in the upper metre of the soil profiles (**A0** and **A1**) on the saltpans and marine couch flats of the tidal zone, and on the melaleuca flats of the adjoining floodplains. These lands make up over 100 ha (86%) of the total area of AASS in the McCreadys Creek catchment area. Only very small areas (7—13 ha) underlie the floodplains or sand dunes, at depths of 1 to 3 m.

Table 4: Area (ha) and proportion (%) of AASS and PASS for each depth category, disturbed and limited assessment lands in the McCreadys Creek catchment area

ASS	0–0.5 m	0.5–1.0 m	1–2 m	2–3 m	3–4 m	4–5 m	5m+	S_{DL}	S_{LA}	Total
AASS	28	84	7	13	-	-	-	-	-	132
%	22	64	5		9					100
PASS	154	469	287	142	19	64	64	15	-	1 214
%	13	38	24	12	2	5	5	1		100

LP: 316 ha

Over 50% (623 ha) of the PASS also occurs within the upper metre of the soil profile (**S0** and **S1**) in the mangrove forests and fringing saltpans of the tidal zone. A significant area of land (287 ha) with PASS at 1 to 2 m (**S2**) occurs under the marine couch flats adjoining floodplain areas of the bay-head delta and melaleuca wetlands. A further 289 ha of deeper PASS sediments at 2 to >5 m underlie the upper reaches of the floodplains or the Holocene sand dunes. In the area there are only 15 ha of disturbed lands, which are mainly excavations for dams or sand and gravel pits. There is also a further 316 ha of land below an elevation of 5 m AHD that is not underlain by ASS (LP map units). These are the foot slopes of the surrounding rises and hills that are underlain by more than 5 m of unconsolidated clay and sand sediments. The boundary between these foot slopes and the tidal zone indicates the limit of Holocene ASS deposition.

Analysis of the AASS revealed that they are almost fully oxidised, with % S contents of <0.01 to 0.14%. All (except for one sample) have a clay texture, and only five of the 36 samples analysed exceed the action level (0.1%) for treatment for clay sediments. The actual acidity levels of these soils vary from <10 to 64 mol H^+/t, with a mean of 25 mol H^+/t, and all but one are below the action level of 62 mol H^+/t. Retained acidity (measured in only one profile) ranges from 28 to 40 mol H^+/t.

The % S content of the PASS varies throughout the catchment, but most markedly between textures. In the clays, the average is 0.89% (0.02—5.20%), while in the sands it is only 0.27% (0.02–1.20%). All clays with levels below 0.1% occur in the surface soils in the mangrove tidal areas, or in the very top of buried PASS. There are only seven samples in the loam category (sandy loam to clay loam), and in these the average is 0.59% (0.45–0.79%). Figure 8 shows the number of samples in each % S range in the clay, loam and sand texture categories.

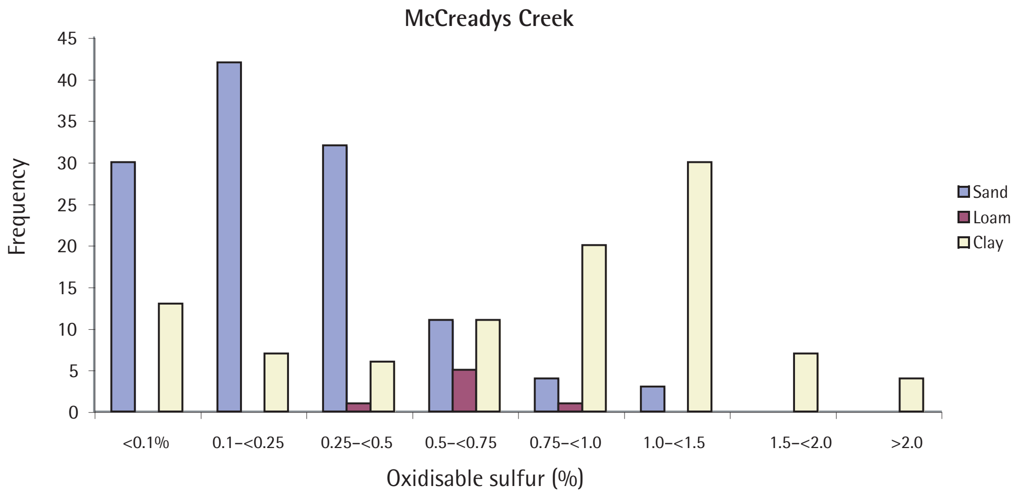


Figure 8: Frequency of samples within the oxidisable sulfur ranges for the sand, loam and clay texture groups, for the profiles of the McCreadys Creek catchment area

Detailed descriptions of landforms

Central basin—intertidal flats

The mangrove forests of the central basin are mapped as either **S0** or **S1**, with the **S0** areas occurring in the wetter areas around creek lines with red mangrove (*Rhizophora stylosa*) forests. The PASS occur either on, or just below, the surface. Inland from the creek lines, the mangrove forests are dominated by the yellow mangrove (*Ceriops tegal*), with associates such as the rib-fruited mangrove (*Bruguiera exaristata*), large-leaved orange mangrove (*B. gymnorrhiza*), milky mangrove (*Excoecaria agallocha*) and grey mangrove (*Avicennia marina*). The PASS under these mangrove forests occur between 0.5 and 1.0 m (**S1**). However, in the tongue of yellow mangroves that extend up towards Blacks Beach behind the sand spit, the % S levels in the surface 0.1 m are just over 0.1% (0.11—0.17%), increasing the area of **S0** away from the main drainage channel. Soils of the mangrove forests are Sulfidic, Intertidal Hydrosols with 1.3 to 2.5 m of very dark or dark grey (2.5Y3/0, 4/0; 5Y4/1), silty light clay or mangrove mud, overlying dark grey pyritic sands. The % S content of the muds is mainly between 0.15 and 2.5%.

Central basin—supratidal, extratidal and melaleuca flats

Bare saltpans (supratidal flats), or grasslands of marine couch (extratidal flats) occur in places behind the mangrove forests. These areas either directly abut the non-ASS areas (**LP**) of the Andergrove and Blacks Beach sand sheets and rises formed on volcanic rocks, or transition into the alluvial, bay-head deltas. The edge of the tidal zone at the highest astronomical tide level in many places indicates the limit of Holocene ASS deposition.

The saltpans are also mainly **S1** areas, with lesser areas of **S0** and **S2** as the PASS occur at depths of 0.2 and 1.5 m. The % S content of the PASS underlying the saltpans is between 0.36 and 1.50%. As this landform is drier than the intertidal flats, a B2 horizon has developed in the upper 0.5 m of the soil profile, which has dark to light grey colours (10YR3/1, 5/1; 2.5Y6/2; 5Y4/1, 6/1), and common to many (10—50%), yellow, brown or orange mottles. One saltpan area is mapped as **a0S1**, as the pH in the upper 0.5 m of the profile is between 4.2 and 4.7. These soils are Sulfidic, Supratidal Hydrosols.

The profiles on the adjoining extratidal and melaleuca flats are even more developed, with AASS having formed in some locations (**A0S1**, **A0S2**, **A1S1** and A1S2). The subsoil is a similar pale grey, with common to many (10—50%) orange, brown, and red mottles, and only very few or few (<2—10%), fine (<5 mm), yellow jarositic mottles and a pH of 4 or less. Other areas have a strongly acidic pH only in the upper metre of the profile, so that some of the map units are also classified as **a0**. Actual acidity contents vary from <10 to 64 mol H^+/t. These soils are classified as Sulfuric, Extratidal Hydrosols.

The PASS layers occur mainly at depths of 0.6 and 1.5 m (**S1** or **S2**), and are always dark grey (2.5Y3/0, 4/0), silty light clays, with % S levels of 0.34 to 2.10%. The muds overlie dark grey (2.5Y4/0, 5/0) pyritic sands at depths of 0.9 to 1.8 m. The % S levels in these sands are only low to moderate (0.03–0.89%). Below 3.8 m, the pyritic sands sometimes overlie the gley, heavy clay Pleistocene basement.

Sand barrier and coastal sand dunes

There are no ASS underlying the Blacks Beach sand spit, which is characterised by a series of low sand dunes and is mapped as either **LP** or **LP5**. In the swales, up to 1.5 m of aeolian sand overlie the non-pyritic, coarser, tidal delta sands, while there is a consistent gravelly layer between depths of 4.0 and 4.5 m.

Several relict sand dunes stranded in the mangrove forests, mainly to the east of Apsley Creek, are underlain by PASS between depths of 2 and 3 m (**S3**). Another quite large dune extending southward into the mangroves from the Pleistocene sand sheet to the south of Blacks Beach is underlain by PASS at 1.3 to 2.3 m (**S2/S3**). These dunes represent former shore lines where there was sufficient wind energy to deposit sand over the mangrove muds. Soils of these dunes are young, with only minimal profile development, and are classified as either Arenic Rudosols, or Orthic Tenosols when a weakly developed B horizon has formed.

Two small dunal areas that join onto the northern tip of the Andergrove sand sheet also have either an AASS or a strongly acidic soil layer overlying the PASS. These are classified as **A2S3/A3S4** and **a1S2/a2S3** map units and, in the swales, the PASS occur between 1.7 and 2.3 m.

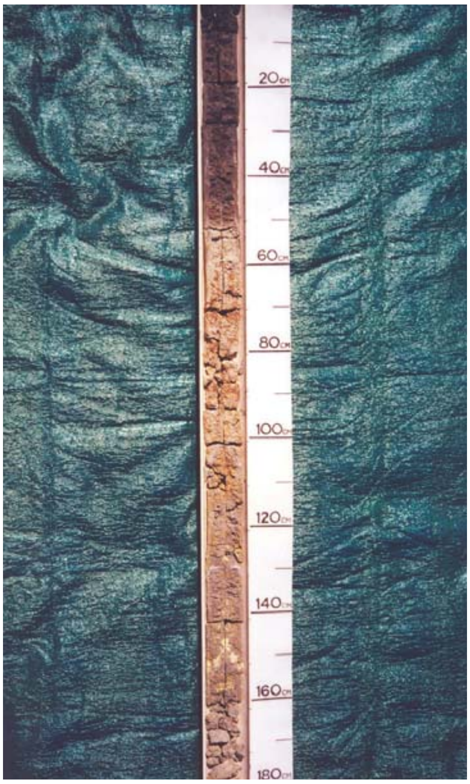
Bay-head deltas

The bay-head deltas occur on the lower reaches of the floodplains of McCreadys Creek and its tributary where alluvium has been deposited over former estuarine areas (Photograph 16). The depth to PASS increases with distance upstream, from 0.8 to 2.0 m (**S1** or **S2**) on the flats adjoining the tidal zone, to 2.2 to 2.7 m (**S3**) further inland. AASS layers often overlie the PASS, though at times they are almost fully oxidised with only 0.01 to 0.12% S remaining. Their actual acidity varies from 10 to 42 mol H^+/t, and the layers occur at depths of 0.30 to 2.25 m (**A0** to **A3**). Strongly acid soil layers also occur in the upper part of the profile (**a0** and **a2**), sometimes with jarositic mottles. As only thin layers of mangrove muds (1.0–1.5 m deep) have been deposited in places along the margin of the basin, PASS layers are not always present. These sediments have oxidised to the extent that only an AASS or a strongly acidic soil layer (**A0** or **a1LP** map unit) remains directly overlying the gley, Pleistocene basement. The soils of the floodplains of McCreadys Creek are mainly Aquic, Black Vertosols because of the presence of intermediate volcanic rocks (microdiorite) in the catchment (Photograph 17). They consist of 0.4 to 1.4 m of black (10YR2/1, 2/2; 7.5YR2/0) medium clay, with a strong, fine (2–5 mm), lenticular structure. This recent alluvial soil overlies dark grey (10YR4/1, 5/1) AASS layers with very few or few (2–10%), fine (<5 mm), yellow jarosite mottles at depths of 0.5 to 2.5 m, or fully oxidised, grey, mottled layers lacking jarosite, but with an extremely acid pH of less than 4. The AASS are usually underlain by PASS, which are very dark grey or dark grey (2.5Y3/0, 4/0) silty light clays or fine sands. The ASS sediments underlying the bay-head deltas are also relatively thin, with the gley, Pleistocene basement occurring between 1.3 and 5.0 m.

The muds generally contain 0.8–1.3% S, with 5.2% the highest level recorded for all clay PASS samples from McCreadys Creek. The levels in the sandy PASS lenses are much lower, mainly between 0.08 and 0.30%, but again, two with levels of 1.1 and 1.2% are the highest recorded for all sandy PASS sediments sampled.

Photograph 16: Black Vertosol on a bay-head delta in McCreadys Creek catchment, underlain by ASS at a depth of 1.7 m (A2S3)

Photograph 18: Slade Point urban lands on former Holocene sand dunes underlain by ASS below depths of 4.5 m (S5)



Photograph 17: Black Vertosol of McCreadys Creek underlain by a classic ASS profile

Slade Point coastal dunes

The final area where ASS were encountered in the McCreadys Creek catchment is under the low dunes of Slade Point, directly inland of the very steep, coastal, parabolic dunes (Photograph 18). These gently sloping, more rounded dunes are now urban and industrial areas, and the dunes have been modified to some extent for urban development. The PASS under them are very deep, between 4 and 6 m (**S4**, **S5** and **S5+**), and always consist of pyritic sands, occasionally containing thin (1 cm) lenses of light clay, with low % S levels, mainly between 0.05 and 0.16%. The dunes consist of 1.2 to 2.0 m of pale aeolian sands overlying thick layers of brown, coarse, fluvial sands with common (10–20%), fine to medium (2–20 mm), rounded gravels of acid to intermediate volcanic rocks and quartz. Because they lack profile development, these soils are mainly Basic, Arenic Rudosols.

The northern part of Slade Point is mapped as **S3**, as it appears to be mainly a formerly swampy area interspersed with very low sand ridges. The swamps have been filled and the area levelled, with the PASS occurring consistently between depths of 2.4 and 2.8 m. Again they consist mostly of pyritic sands, but this time with more light clay lenses up to 10 cm thick. One site also has a mud layer below 4.5 m that is more than 1 m thick. The % S content of the sands is only 0.08 to 0.19%, while that of the muds is 0.51 to 0.94%.

Melaleuca wetlands

Two melaleuca wetland areas occur in the McCreadys Creek catchment. The first, a large wetland of long-leaved paperbarks in a north-east trending, closed depression between two of the sand ridges in the centre of Slade Point, is underlain by pyritic sands at a depth of 1.8 m **(S2w)**; however, the % S levels in this sandy PASS are very low, varying from only 0.03 to 0.10%. In the other area (a long, thin wetland adjoining the Andergrove sand sheet to the north of Keeleys Road **(a1S2w)** % S levels in the upper clay and sand PASS horizons are higher, at 0.19 to 0.37% respectively. (Sampling was limited to a gouge auger.)

Water quality monitoring

The following graphs (Figures 9, 10 and 11) show the pH and salt concentration of the water measured at the three monitoring sites in the McCreadys Creek catchment. (Dissolved oxygen and temperature data are tabulated in the Appendix). As site W4, opposite the golf course, is in the upper reach of McCreadys Creek and subject only to the higher spring tides, the electrical conductivity reflects the changes in salt concentration between the wet and dry seasons. The salt content is very low after rainfall and runoff, but increases to higher levels over the dry season as a result of occasional influx and evaporation of salt water. The pH measured was always between 6.5 and 8.3, indicating that over the period of measurement there were no acidification events. An absence of iron staining at this site also supports this data, as do the dissolved oxygen levels of 4.4 to 11.8 mg/L (see Appendix). This has been the site of two fish kills in recent years.

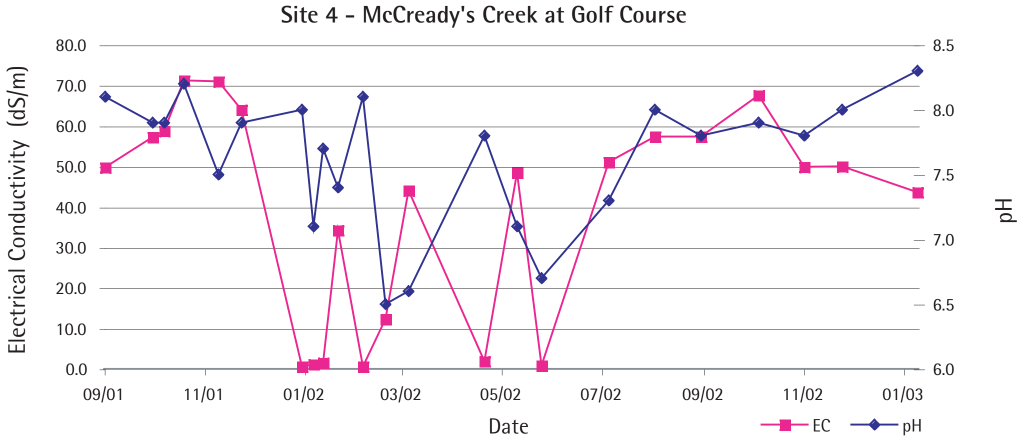


Figure 9: pH and EC of estuarine waters of McCreadys Creek at the Mackay golf course

As the McCreadys Creek boat ramp (W5) and Apsley Creek (W6) monitoring sites are in areas of the estuary subject to strong, daily tidal flows, the salt content of the water is much less affected by runoff during the wet season than that at the golf course site. Electrical conductivity is between 45 and 50 dS/m during the dry season, decreasing to 25 to 35 dS/m after significant rainfall. The pH at these two sites is mainly between 7 and 8—typical for estuarine waters. This also indicates there was no acidification of the McCreadys Creek estuary from disturbance of ASS over the period of monitoring. Dissolved oxygen levels of 4.7 to 7.7 mg/L for these two sites are also with the acceptable range for estuarine waters.

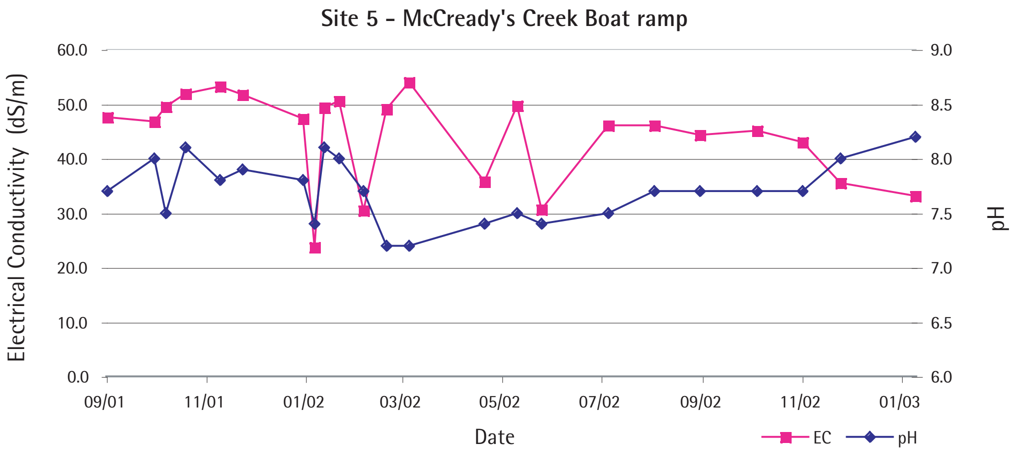


Figure 10: pH and EC of estuarine waters of McCreadys Creek at the boat ramp

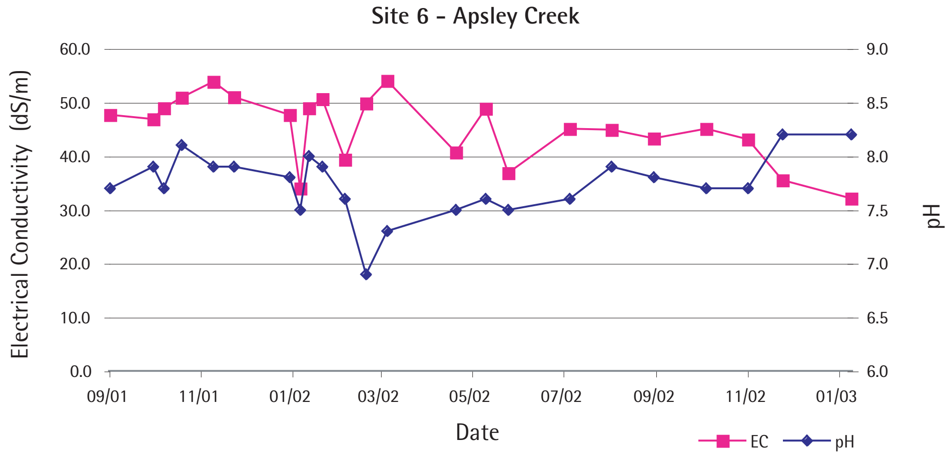


Figure 11: pH and EC of estuarine waters of Apsley Creek

5.3 Pioneer River catchment area

Catchment geomorphology

The Pioneer River valley is the major drainage and floodplain system of the Mackay district. It consists of a vast, flat floodplain that has infilled a basin between the low hills just to the north of the river itself, and the hills bordering Alligator Creek in the south. It is about 20 km wide and represents a completely different landform from that in the north of the survey area, which consists of short coastal streams bounded by hills.

The Pioneer River valley extends some 75 km inland to the coastal ranges of the Great Dividing Range. To the south of the Pioneer River, which runs along its northern edge, the floodplain is also drained by Bakers, Sandy and Alligator creeks. Bakers and Sandy creeks are considered to be former channels of the Pioneer River (Gourlay & Hacker 1986; Holz & Shields 1985). In this study, these four drainage lines are treated as separate catchments.

During the Pleistocene epoch, these drainage lines cut narrow, deep, gorge-like valleys into the floodplain. As the sea level rose and stabilised during the Holocene, these narrow valleys infilled with estuarine muds, sands and gravels. Recent alluvium has since been laid down over the top of the estuarine sediments, forming the channel benches and vegetated islands which stand 3–5 m below the main Pioneer floodplain (Photographs 19 and 20). The creek lines now meander around these channel benches and islands in the new valley floor.

Photograph 19: Low-lying channel bench of the Pioneer River underlain by ASS at 2.6 m (S3)

Photograph 20: Channel Bench of the Pioneer River: note the bank on the left which shows the elevation of the older, higher-level Pioneer floodplain and undulating topography of the channel bench

The contrast in soils between these two landforms is also marked. The older, Pleistocene-aged soils of the Pioneer floodplain are leached and weathered sodic duplex soils with 'tough' heavy clay subsoils; whereas, on the channel benches, the soils are 'softer' non-sodic clays, loams and sands, anywhere from 1.5 to more than 5 m thick. Deep augering along the edge of the older elevated floodplain just inland of the channel benches consistently revealed an absence of ASS, even to an elevation well below mean sea level (0 m AHD). All channel benches are, however, underlain by ASS layers of varying thickness.

The Pioneer River estuary is a WDE with a well developed sand spit or barrier extending southwards from Mackay harbour to East Point at the river mouth. As the river has a large catchment area with massive flood discharges, its channel is 700 m wide at the mouth, enabling a strong tidal exchange, more typical of a TDE, to occur (Figure 12).

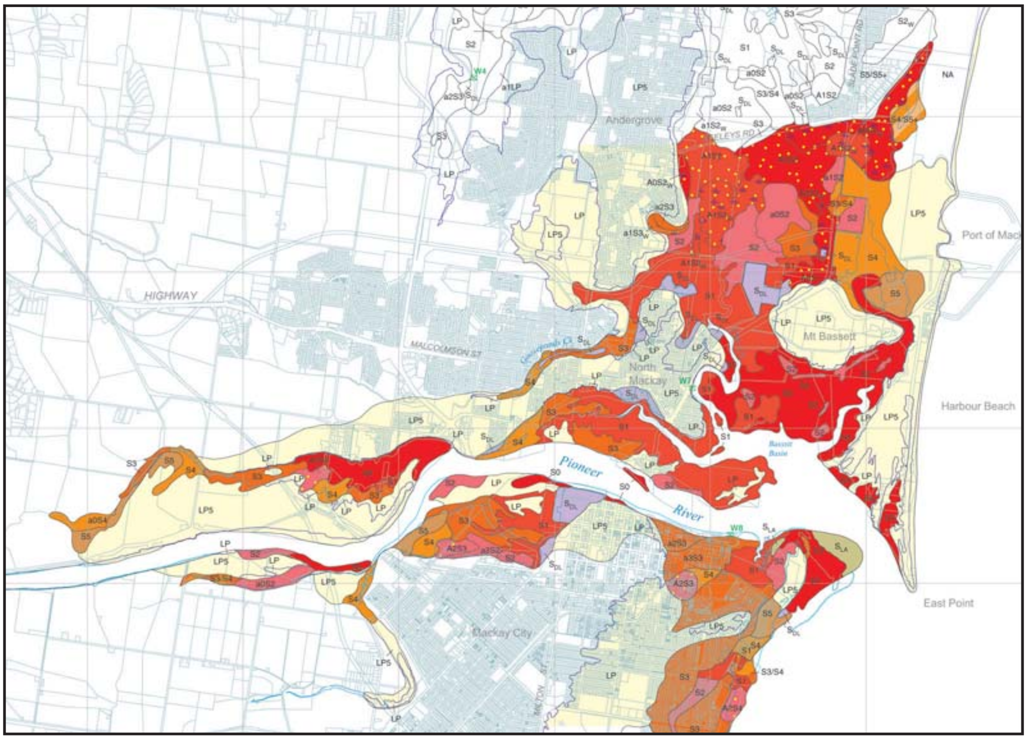


Figure 12: Pioneer River catchment area

A lobed central basin, which has been infilled with clay sediments, has formed behind the East Point sand spit. It comprises the tidal zone mangrove forests of the Bassett basin fish habitat reserve, and the melaleuca wetlands of the Keeleys Road area. This latter area consists of melaleuca swamps and other melaleuca forests formed on thin layers (<0.3 m) of alluvium deposited on top of former estuarine sediments. This area joins directly onto the Apsley Creek section of the McCreadys Creek catchment, which would have at one time been a continuous tidal system between the Pioneer River and McCreadys Creek.

On the south side of the Pioneer River, opposite the Bassett Basin, is a former mangrove area, similar to that of the basin itself. It used to extend the entire length of the coastline behind the coastal sand dunes, joining onto the tidal area to the east of the airport; however, except for a small area around Sandfly Creek, it has been almost completely filled for the urban and industrial areas of East Mackay.

Along both sides of the Pioneer River, after the mangrove forests of the Bassett Basin, are the previously mentioned channel benches, which continue upstream for another 10 km. These areas represent the bay-head delta development of the Pioneer River.

Acid sulfate soils

The Pioneer catchment area has 2011 ha of ASS, determined from 158 boreholes. There are 326 ha of AASS, mainly under the melaleuca forests and marine couch flats of the Keeleys Road area, and 2011 ha of PASS. Of this area, 1023 ha (51%) occur within the tidal zone. Outside the tidal zone, the largest areas of PASS are found under the melaleuca forests (117 ha), channel benches (276 ha), and East Mackay and Mackay harbour urban lands (390 ha). Table 5 shows the areas of AASS and PASS for each depth category, and the areas of disturbed and limited assessment land.

Table 5: Area (ha) and proportion (%) of AASS and PASS for each depth category, disturbed and limited assessment lands in the Pioneer River catchment area

ASS	0–0.5 m	0.5–1.0 m	1–2 m	2–3 m	3–4 m	4–5 m	5m+	S_{DL}	S_{LA}	Total
AASS	178	110	38	-	-	-	-	-	-	326
%	55	34	11							100
PASS	320	408	484	405	210	78	10	76	20	2 011
%	16	20	24	20	10	4	1	4	1	100

LP: 586 ha

Most of the AASS (288 ha or 83%), occur in the upper metre of the soil profile (**A0** and **A1** units) on the extensive marine couch flats, melaleuca backplains and swamps in the Keeleys Road area. Smaller areas (a total of 38 ha), underlie the channel benches of the Pioneer River and East Mackay urban lands at depths of 1 to 2 m (**A2** units).

There are almost equal areas (320–484 ha) of PASS in the upper four depth layers from **S0** to **S3**. In the shallowest areas (**S0–S1**), which are in the mangrove forests and tidal zone, there are 728 ha. The largest area (484 ha) occurs in the **S2** areas (between 1 and 2 m deep) under the marine couch flats, melaleuca backplains, and wetlands and channel benches in the lower estuarine reaches. There are significant areas (405 ha) in the **S3** units (between 2 and 3 m), and 210 ha in the **S4** units (between 3 and 4 m) under the channel benches, valley flats and East Mackay urban lands.

Only small areas of PASS (78 and 10 ha respectively) occur in the **S5** and **S5+** units, which underlie the more elevated channel benches or former coastal dune areas at Mackay harbour or East Mackay. Most of the disturbed lands are the result of filling activities around the margins of the urban and commercial areas of Mackay, or at landfill sites.

Finally, there are 586 ha of land in the Pioneer catchment below an elevation of 5 m AHD, that are not underlain by ASS (**LP** units). These are on the older, slightly more elevated alluvial plain areas around North and East Mackay, and within some of the channel benches. There are also significant areas of land above 5 m AHD on the channel benches and valley flats that are underlain by ASS.

Analyses of AASS layers showed that they are almost fully oxidised, with only very low or low levels (0.01–0.17 %) of oxidisable sulfur remaining. Only five of the 35 samples of AASS analysed exceed the action levels for treatment. Of these, all are clay sediments, except for one sandy AASS layer. Their actual acidity levels (retained acidity was not measured) vary from <10 to 127 mol H^+/t, with a mean of 41 mol H^+/t. However only five of these samples exceed the action level of 62 mol H^+/t for a clay soil, with the mean still well below this threshold limit. The six loamy or sandy AASS also have actual acidities below their respective action levels of 36 and 18 mol H^+/t.

The % S contents of the PASS vary across the catchment, but most markedly between textures. In the clays, the average is 0.84% (0.01–4.3%), while that of the sands is 0.24% (0.02–2.7%). In most of the clay-textured samples, the level is higher than 0.50%, whereas in most of the sandy samples, it is less than 0.25%, highlighting the large difference between the pyritic sands and mangrove muds. A significant number of clay samples, mainly from the surface soils of the mangrove forests, or occasionally from the very top of a buried PASS layer, have less than 0.1% S. Of the eight samples in the loam category (sandy loam to clay loam), the average is 0.34% (0.03–0.82%). Figure 13 shows the number of samples within the various % S ranges for the clay, loam and sand texture categories.

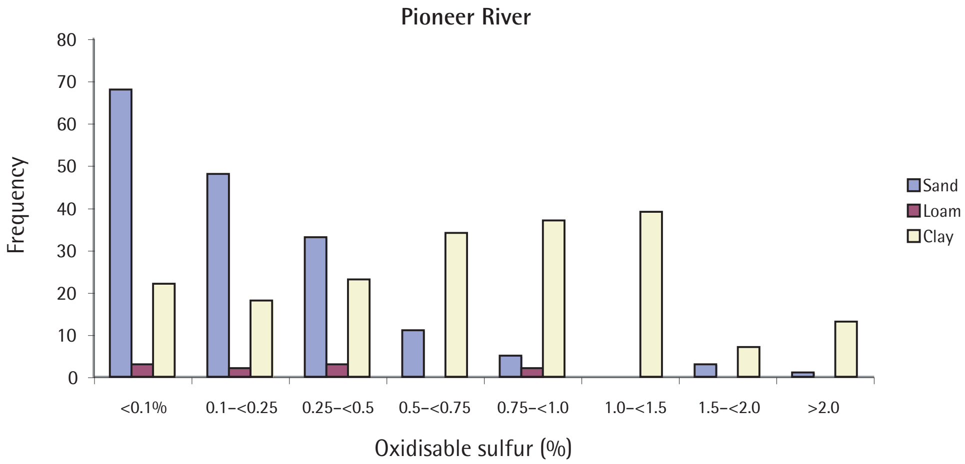


Figure 13: Frequency of samples within the oxidisable sulfur ranges for the sand, loam and clay texture groups, for the profiles of the Pioneer River catchment area

Detailed descriptions of landforms

Central basin—intertidal flats

The mangrove forests throughout the Pioneer River catchment are either **S0** or **S1**, with the PASS consistently occurring in the upper metre of the profile. In the mangrove areas jutting into the East Point sand spit, the % S content of the surface soil is from 0.19 to 0.48%. However, in most other **S0** areas, it is only 0.02–0.09%, with significantly higher levels starting at depths between 0.2 and 0.4 m.

The soils of the mangrove forests are Sulfidic, Intertidal Hydrosols, with black to very dark grey (10YR2/1, 3/1, 3/2), silty, light clay surface soils overlying very dark or dark grey (2.5Y3/0, 4/0), PASS C horizons of silty clay. The **S1** areas often have very dark grey, or dark grey (10YR3/1, 4/1), mottled, silty, light clay B2 horizons extending to depths of 0.3 to 0.9 m. These layers are usually free of pyrite. The mangrove muds always overlie sandy PASS sediments between 0.9 and 2.6 m. The % S content of the muds, excluding the surface soils, is mainly between 0.3 and 1.7%, while in the pyritic sands it varies from 0.11 to 0.67%.

Sampling was not possible on the many small sand dunes stranded within these tidal flats to the south of Mt. Bassett. They are mapped as **S2**, with the mapping unit interpreted from the increase in elevation.

Central basin—extratidal flats, melaleuca forests and wetlands

Outside the intertidal flats, the Keeleys Road area is one of the largest, continuous areas underlain by ASS in the entire study area. It consists of melaleuca swamps (Photograph 21) and backplains (Photograph 22), marine couch flats and occasional sand dunes or sand sheets. Across the area, the PASS occur consistently between depths of 1.5 and 2.0 m (**S2** map units), except where the sand dunes and sheets have been laid down (S3 and **S3/S4**). It is also the most extensive area of AASS in the study area. The melaleuca swamps are mainly **A0S2**$_{W}$ and **A1S2**$_{W}$, with an AASS layer in the upper metre of the profile. Jarosite is usually present and the pH_F is between 3.8 and 4.0. This extremely low pH also continues in the upper PASS layers. In the surface soils of these swamps, the oxidisable sulfur contents (0.21–0.27%), exceed the action level of 0.1% for a clay soil. In another small melaleuca swamp in a former embayment jutting into the Andergrove sand sheet, a strongly acid soil layer (pH_F 4.2–4.5) is mapped as **a1S3**$_{W}$.

Photograph 21: Melaleuca forest of the wetlands area at Slade Point Road, Mackay

Photograph 22: Melaleuca forest on local alluvium overlying PASS at 1.7 m (A1S2). Extremely acid pH is due to organic acids produced by the melaleuca trees

The long-leaved paperbark forests on the slightly elevated backplains are either **a0S2** or **A1S2**, as the pH_F varies from 3.2 to 5.0 in the upper metre of the profile. Jarosite rarely occurs in the AASS layers, and there is a measurable amount (0.32%) of oxidisable sulfur in the surface soil at only one site. The marine couch flats, however, are mainly **S2** with a pH_F greater than 5 throughout the profile, except for a large **A0S2** unit where it is 3.5 to 3.8 in the upper metre.

The soil profile of all these areas is similar, consisting of a dark surface layer, 0.1 to 0.2 m thick, with a light clay texture, overlying a dark grey or grey (10YR4/1, 5/1, 6/1; 5Y5/1, 6/1), mottled, light clay B2 horizon, sometimes with jarosite. This, in turn, overlies dark grey (2.5Y3/0, 4/0), light clay, PASS layers between 1.0 and 1.5 m. Across this area (except under sand dunes) the clay PASS layers change abruptly to pyritic sands, consistently between 1.3 and 1.8 m. They usually continue beyond 5 m, or occasionally are underlain by coarse, gravelly, fluvial sands, or the gley, Pleistocene, heavy clay basement between depths of 2.2 and 4.5 m.

These profiles are classified as Sulfidic or Sulfuric, Redoxic Hydrosols. The AASS layers are almost fully oxidised, with % S concentrations of 0.01 to 0.12%, compared with those of the underlying PASS clay layers, which are mainly between 0.45 and 1.20%. The actual acidity of the AASS varies from <10 to 108 mol H^+/t. The % S content of the pyritic sands is mainly lower at 0.02 to 0.32%; however, in one of the melaleuca swamps it reaches maximum levels of 4.3% and 2.7% in the mud and sand layers respectively, illustrating the high variability of pyrite content even within a profile.

Coastal sand dunes and Mackay harbour modified lands

To the east of the melaleuca wetlands is the industrial area of the Mackay harbour, where ASS buried beneath the sand dunes continue to within 200 m of the coastline. The harbour area is mapped as either **S4** or **S5**, with PASS occurring between depths of 3.2 and 4.3 m. The straight lines of the mapping indicate where former wetlands have been filled, while closer to the coast, the sand dunes have been levelled to create land suitable for buildings and harbour infrastructure. To the south of the harbour, there are no ASS underlying the East Point sand spit up to the maximum depth of coring (6 m). The area is mapped as **LP** and **LP5.** To the north of the harbour, an area of sand dunes is mapped as **S4/S5+** as the dunes are higher than normal with a 2 m difference between the dune crest and swale. The PASS layers underlying these lands are mainly pyritic sands with occasional thin clay lenses and % S concentrations of 0.03 to 0.40%. The very high, coastal parabolic sand dunes between the harbour and Slade Point were not assessed because they were difficult to access.

Bay-head delta—channel benches and valley flats

The channel benches along the north and south banks of the Pioneer River are mapped mainly as **S3**, **S4** and **S5**, as they are underlain by PASS between 2.3 and 4.6 m. AASS layers overlying the PASS occur in only one map unit (**A2S2**), with an actual acidity of 94 mol H^+/t, while in another map unit in the upper reaches of Fursden Creek, the surface soil is strongly acidic (**a0S4**). Nearly all profiles consist of 1.8 to 4.6 m of black to dark brown (10YR2/1, 2/2, 3/3, 4/3), sandy to silty clay, recent alluvial sediments directly overlying black or very dark grey (2.5Y2/0, 3/0), silty light clay PASS layers. The upper PASS clay layers vary in thickness from 0.2 to 2.3 m and are consistently underlain by sandy PASS lenses. These in turn are usually underlain by gravelly, coarse fluvial sands, which are most likely former stream bed deposits of the Pioneer River. The % S levels of the clayey PASS materials are mainly between 0.5 and 2.0%, while those of the sands are significantly lower at 0.02 to 0.40%.

The topography of these channel benches is quite undulating as they are traversed by many former stream channels and associated relict levees. In particular, the Fursden Creek channel bench and the one opposite it on the south bank are very undulating and it is possible that the PASS may extend further out than is shown on the map. As the land rises sharply by 2–5 m from the outer boundary of these soils, the PASS may have been beyond the depth of the sampling equipment used.

ASS also occur under the valley flat of Goosepond Creek, which is not a channel bench but a narrow valley of a creek that has that has cut down into the older, elevated alluvial plain of the Pioneer River. This valley flat is mapped as **S3** and **S4**, as thick, silty light clay PASS layers occur between 2.3 and 3.8 m. PASS may have been excavated from the artificial lakes constructed along this valley flat between Malcolmson Street and Evans Avenue.

East Mackay modified lands

The urban areas of East Mackay consist mainly of filled tidal flats that join the Pioneer River floodplain at the eastern edge of the business area. The filled areas have up to 3 m of gravelly coarse sands directly overlying sandy or clayey PASS. Most of this area is mapped as **S3**, with PASS occurring between depths of 2 and 3 m, except along the former and existing frontal dune areas where it is deeper than 3 m, and is mapped as **S4**, **S5** and **S5+**.

There is also a small remnant tidal area at the southern end of Binnington Esplanade that is **S1**. However, as urban development is planned here in the near future, this area will soon be filled to the level of the surrounding houses, and will therefore most likely also become an **S3** area. A former mangrove-lined creek channel to the south-west of this tidal flat is mapped as **S2**, as the PASS are consistently shallower at 1.8 m.

AASS or strongly acid soil horizons occur in those areas of East Mackay where the ASS are covered by natural alluvium on the original backplains. These areas are mapped as **A2S3**, **a2S3** or **a3S4** as the pH_F of these soils varies from 3.4 to 4.9. However, jarosite mottles are always present in these layers which are almost fully oxidised, with % S contents of only 0.01 to 0.11%. Actual acidity levels are all below the action levels for the mainly clay sediments, which vary from <10 to 40 mol H^+/t. Actual acidities of the two sand and loamy AASS layers are also only 10 and 14 mol H^+/t respectively. Another area to the north of the Ocean International Resort is mapped as **A2S4**, but the AASS here are former clay and sand PASS excavated from a tidal area to the east of the airport and used to fill this area. These too are almost fully oxidised, with % S levels of 0.01 to 0.07%, but with higher actual acidity contents of 18 to 83 mol H^+/t.

The % S levels in the clay PASS materials throughout this area are mainly between 0.4 and 1.3%, with a very high maximum of 3.3%, while those in the pyritic sands are much lower, mainly between 0.03 and 0.5%, but also with a very high maximum of 1.7%. These PASS sediments are either black, very dark or dark grey (2.5Y 2/0, 3/0, 4/0), while there are often 2–10% of rounded gravels of quartz and basic and acid igneous rocks in the pyritic sands. Tree branches are also commonly encountered in the clay sediments, with wood cores up to 10 cm thick recovered in some profiles. A former sand ridge running along Evan Street is underlain only by gravelly, fluvial sands (to the depth of coring) and is therefore mapped as **LP**.

Water quality monitoring

The quality of the estuarine water of the Pioneer River was measured at two sites, in Vine Creek (W7) at North Mackay, and at the Pioneer River boat ramp (W8) at East Mackay. The pHs of 7.2 and 8.2, and electrical conductivities of 25 and 50 dS/m respectively (Figures 14 and 15) over the monitoring period are typical of estuarine water. The pHs do not indicate any adverse effects from ASS disturbance in this catchment, which consists only of three deep stormwater drains that have been excavated through ASS areas around East Mackay. This conclusion is also supported by the absence of iron staining anywhere in the catchment, and by the structural integrity of all the concrete bridge pylons and stormwater pipes in the Pioneer River. Slight decreases in salinity occur after heavy rainfall and runoff during the wet season. The dissolved oxygen levels of 5.4 to 8.0 mg/L measured at these two sites over the monitoring period are also within acceptable levels for estuarine waters. (Dissolved oxygen and temperature data are tabulated in the Appendix.)

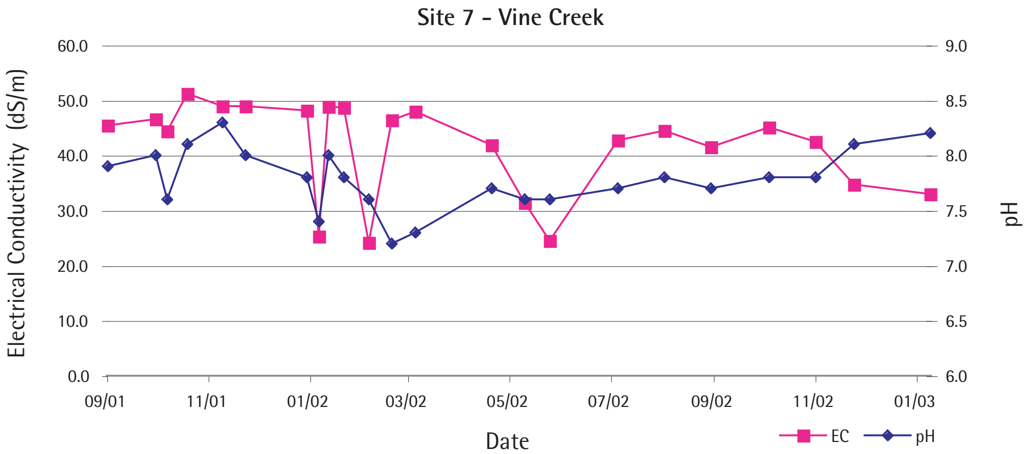


Figure 14: pH and EC of estuarine waters of Vine Creek at North Mackay

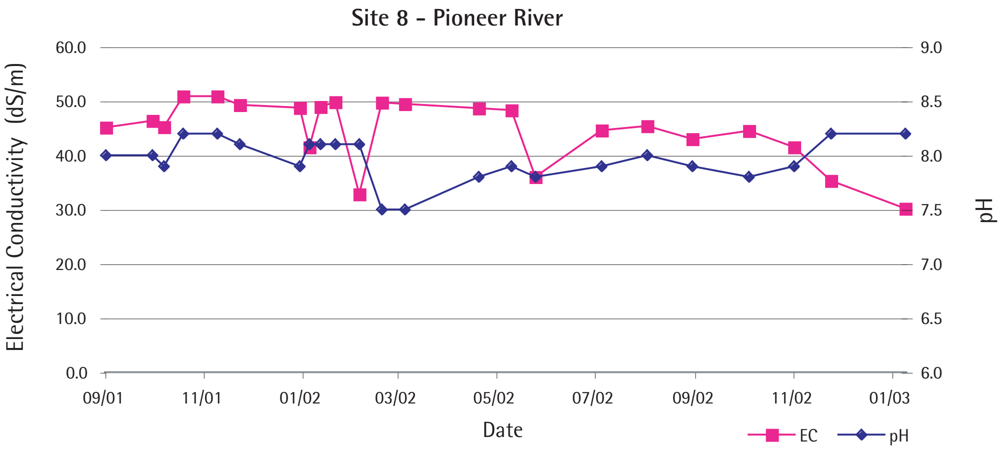


Figure 15: pH and EC of estuarine waters of Pioneer River at the boat ramp

5.4 Bakers Creek catchment area

Catchment geomorphology

Bakers Creek is one of the major drainage lines of the Pioneer River floodplain. It extends some 15 km inland, and mainly drains the low hills formed on the sedimentary and acid volcanic rocks of the Carmilla Beds. As a result, topsoils in the area are very fine, sandy, and silty.

The Bakers Creek estuary is considered a WDE, although it also has some properties of a TDE system. It has a well developed sand barrier extending southward from Mackay, which has allowed a mud-filled central basin to form directly behind it. However, because of the high tidal range on this part of the Queensland coast, the creek has a 500 m wide, open mouth that allows a full tidal exchange, particularly in the lower estuarine reaches. The flood-tide delta is also well developed, and extensive sand flats that are exposed at low tide have been deposited in the lower reaches of the creek channel and seaward from the creek mouth for over a kilometre. Bakers Creek is fully exposed to the dominant south-easterly winds, and coastal sand dunes have formed along the coastline to the north and south of the creek mouth (Figure 16).

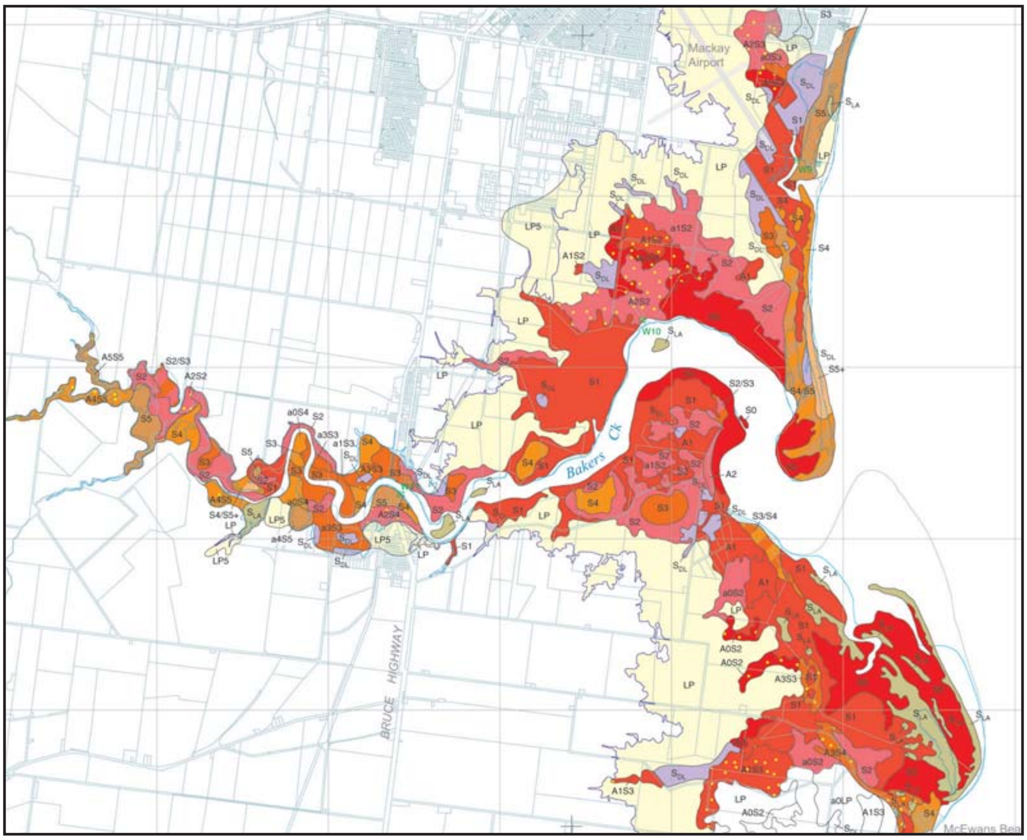


Figure 16: Bakers Creek catchment area

From behind the sand barrier to close to the Bruce Highway dense mangrove forests, marine couch flats, and melaleuca flats represent the central basin area of this catchment. Only small areas of saltpans and marine couch flats fringe the mangrove forests. A small melaleuca wetland just to the south of the Mackay airport also occurs at the head of the central basin. This part of the basin is generally fairly shallow, and only 1.0 to 3.5 m of estuarine sediments have been deposited on top of the gley, Pleistocene heavy clay basement. It is also only 0.5 to 1.2 km wide throughout.

A separate central basin area between Bakers Creek and McEwens Beach discharges directly to the sea, rather than into the creek. It consists mainly of dense mangrove forests protected by a series of parallel sand dunes that have built up from sandy sediments discharged from Bakers and Sandy creeks. During the Holocene epoch, this extended the coastline about 2 km seaward. Saltpans, marine couch and melaleuca flats also occur behind the mangrove forests. This basin is also relatively shallow with usually only 2 to 4 m of estuarine sediments overlying the gley, heavy clay basement.

As the gorge-like valley of Bakers Creek narrows at the Bruce highway, channel benches either side of the creek line represent the bay-head delta area in the floor of this narrow valley. These benches, composed of recent estuarine and alluvial sediments, were deposited here during the Holocene, indicating that current flows are less than those that initially carved out the valley. Bakers and Sandy creeks are considered to represent former channels of the Pioneer River before it migrated to its present course (Gourlay & Hacker 1986; Holz & Shields, 1985), which would explain why these two drainage lines are larger than required for current flows.

There is a drop of only 0.5—1.0 m from the older Pioneer River alluvial plain onto the channel benches at the highway, which increases to 4 to 5 m further inland as the elevation of the plain increases. Estuarine sediments have been deposited on the Bakers Creek valley floor for some 5 km inland from the highway.

Acid sulfate soils

In the Bakers Creek catchment area, 1992 ha of ASS were defined from 135 boreholes, including 369 ha of AASS and 1918 ha of PASS. (Seventy-four hectares of AASS are not underlain by PASS.) Of this area of PASS, 1205 ha (61%) occur within the tidal zone, which shows that most of the ASS in the Mackay district occur within this landform. The main areas of ASS outside the tidal zone are under the channel benches (280 ha), and coastal sand dunes (283 ha). Table 6 shows the areas of AASS and PASS for each depth category, and the areas of disturbed and limited assessment land within the catchment area.

Table 6: Area (ha) and proportion (%) of AASS and PASS for each depth category, disturbed and limited assessment lands in the Bakers Creek catchment area

ASS	0–0.5 m	0.5–1.0 m	1–2 m	2–3 m	3–4 m	4–5 m	5m+	S_{DL}	S_{LA}	Total
AASS	65	127	101	41	26	9	-	-	-	369
%	18	35	27	11	7	2				100
PASS	261	498	431	203	156	137	19	110	103	1 918
%	14	26	22	11	8	7	1	6	5	100

LP: 1 008 ha

The 369 ha of AASS occur across a range of landforms. The largest areas (293 ha or 80% of the total) are in the upper 2 m of the soil profile (**A0**, **A1** and **A2** units), mainly on the salt pans and marine couch flats of the tidal zone, and on the melaleuca backplains and wetlands. Lesser areas (76 ha or 20%) occur at depths of 2 to 5 m (**A3**, **A4** and **A5** units) underlying the coastal sand dunes and the channel benches. Bakers Creek is the only catchment in the study area where AASS are found deeper than 3 m.

Most of the PASS (1190 ha or 62%) also occur within 2 m of the soil surface (**S0**, **S1** and **S2** units), mainly in the tidal zone and the melaleuca backplains and wetlands. There are significant areas (203, 156 and 137 ha) at depths of 2 to 5 m (**S3**, **S4** and **S5** units). Most of these are beneath the coastal sand dunes and channel benches but, unusually, some occur under the less frequently inundated mangrove forests in the upper estuarine reaches. Only a small area (19 ha) occur deeper than 5m (**S5+** units) under the channel benches in the upper reaches of the creek.

AAS disturbances (**S_{DL}** units) are mainly the result of excavations for farm dams, sand and gravel extraction pits, an aquatic centre and a fish farm, while there are significant areas of ASS under a landfill site and the Mackay airport runway extension. Islands within the Bakers Creek channel and inaccessible coastal sand dunes in the separate basin to the south of the creek constitute a large area (103 ha) of limited assessment lands (**S_{LA}**).

In the Bakers Creek catchment, as in all catchments in the study area, there is a large area of land (1008 ha) below 5 m AHD that is not underlain by ASS on the older, slightly more elevated Pioneer floodplain. However, significant areas of land on the channel benches above 5 m AHD, are underlain by ASS.

Analyses of the AASS show that most are nearly fully oxidised, with between <0.01 and 0.41% S, with a mean of only 0.04% (in this catchment only four AASS exceed the action level of 0.1% for a clay soil). There is also one sandy AASS with 0.17% S, which exceeds the 0.03% action level for sand texture. The actual acidity levels (retained acidity was not measured) of these soils vary from <10 to 58 mol H^+/t, with a mean of 29 mol H^+/t. However, two of the sandy AASS, which have actual acidities of 25 and 26 mol H^+/t, exceed the sand texture action level of 18 mol H^+/t. Levels in all the clay AASS are below the action level of 62 mol H^+/t.

The % S content of the PASS varies throughout the catchment, but most markedly between textures. In the clays or mangrove muds, the mean is 0.62% with a range of 0.02–1.70%, while in the sands it varies from 0.02 to 1.2%, with an average of 0.2%. As Figure 17 shows, in nearly all of the sandy PASS sediments, the level is less than 0.5%, while in most of the clay PASS it is higher than 0.25%. At 0.62%, the mean % S content of the clay is significantly lower than it is in the three catchments mentioned previously, where the means are 1.1%, 0.89% and 0.84% respectively.

All of the seven clay samples with <0.1% S were from the surface soil or from the very top 0.2 m of a PASS horizon in the mangrove areas, though sandy layers with very low levels were found anywhere within a PASS horizon. There were only four samples in the loam texture group (sandy loam to clay loam), most with <0.1% S, giving a mean of 0.14%. There were also significantly more sandy than clayey PASS sediments in the Bakers Creek catchment, with more than half of the clay PASS sediments occurring in the mangrove areas.

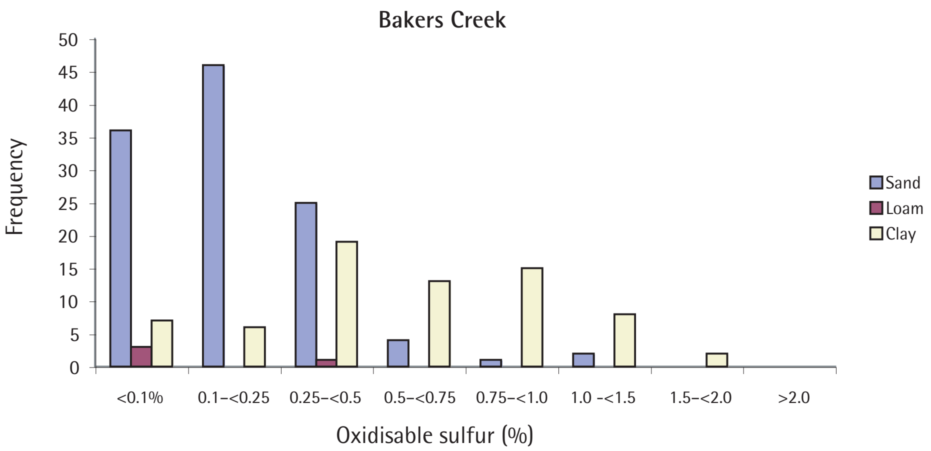


Figure 17: Frequency of samples within the oxidisable sulfur ranges for the sand, loam and clay texture groups, for the profiles of the Bakers Creek catchment area

Detailed descriptions of landforms

Central basin—intertidal flats

The mangrove areas or intertidal flats of the central basin are either **S0** or **S1**, with the PASS occurring within the upper metre of the soil profile, and these are the shallowest areas of PASS in the catchment area. The **S0** areas occur in the wetter parts of the intertidal flats around the creeks, which are the domain of the *Rhizophora* spp. (red and tall, stilted) mangrove. However, within this catchment, yellow mangrove forests (*Ceriops tegal*) also occasionally occur in these **S0** areas. The PASS are either at, or just below, the surface (0.1—0.3 m) in the **S0** map units; whereas in the **S1** areas, they occur at depths of 0.6 to 0.8 m. Yellow mangrove forests dominate the **S1** areas, with associates of grey (*Avicennia marina*), red (*Rhizophora stylosa*) and rib-fruited mangrove (*Bruguiera exaristata*).

The soils of the intertidal flats are Sulfidic, Intertidal Hydrosols. In the **S0** areas, they consist of a black to very dark grey-brown (10YR2/1, 2/2, 3/2) light clay, surface soil overlying very dark grey to dark grey-brown (2.5Y3/0; 10YR2/2, 3/2) light clay PASS sediments to depths of 1.3 to 1.6 m. Either sandy PASS layers or the gley, heavy clay basement occur below these depths. The soils of the **S1** areas are similar, except that a dark grey or grey (10YR4/1, 5/1; 5Y5/1) mottled B2 horizon has developed in the upper 0.5—0.8 m of the profile in response to the drier conditions. The B2 horizon overlies the light clay PASS materials, which in turn overlie sandy PASS layers, or occasionally the gley clay basement at depths of 1.3 to 2.3 m. Levels of oxidisable sulfur in the mangrove muds, excluding the surface soils, are 0.2—1.5%, while in the sands they are much lower (0.1–0.3%).

The mangrove forests continue into the bay-head delta section of the estuary, adjoining the channel benches and fringing the creeks as far inland as the HAT level. As they are slightly more elevated (2.5–3.0 m AHD), and the tidal influence is less, they are inundated less frequently than those in the central basin. The species composition is therefore completely different, and the forest is dominated by milky mangrove (*Excoecaria agallocha*), with associates of black mangrove (*Lumnitzera spp.*), and sometimes a non-mangrove species, the salt-tolerant cotton tree (*Hibiscus tiliaceus*), in the driest parts of these intertidal flats. River mangrove (*Aegiceras corniculatum*) often occurs in the mid-stratum, while holly mangrove (*Acanthus ilicifolius*) is common in the ground layer (Photograph 23).

The PASS are also significantly deeper under these forests, which are nearly all mapped as **S2**, **S3** and **S4**. They consist mainly of fine to coarse sandy sediments occurring between depths of 1.2 and 3.2 m, overlain by layers of non-pyritic light clays, loams and sands. These soils are mainly Sulfidic or Argillaceous, Intertidal Hydrosols. The % S content of the sandy PASS varies from 0.1 to 0.72%.

Central basin—supratidal and extratidal flats and melaleuca flats

The rest of the central basin consists of saltpans, marine couch flats and melaleuca flats, all **S2** map units with the PASS occurring between 1.1 and 1.8 m. The PASS underlying all these areas are almost exclusively very dark or dark grey, pyritic sands, with only one clay layer recorded. The % S content of the pyritic sands ranges from 0.10 to 0.44%, while that of the clay PASS layer is much higher at 1.7%.

In most of this area, clayey AASS, with very strongly acid (pH 3.3–4.0) soil layers, often containing jarosite, overlie the PASS at depths between 0.25 and 1.5 m. These are the **A0S2**, **A1S2** and **A2S2** units. These soils are Sulfuric or Sulfidic, Supratidal, Extratidal or Redoxic Hydrosols with dark grey, grey, or grey-brown (10YR 4/1, 4/2, 5/1, 6/1; 2.5Y 6/2), light clay B2 horizons, with many (20–50%), coarse (15–30 mm), red, brown, yellow (jarosite) or orange mottles.

In several areas on the margins of the central basin, thin layers of mangrove muds only 1 to 2 m thick have been deposited over the gley, heavy clay basement. These whole layers have oxidised to form either an AASS, or a strongly acid soil with a pH of 4.1 to 5.0, with jarosite present in at least part of them in all cases. These are the **A0**, **A1** map units that occur on the periphery of both the north and south central basin areas.

In most cases, all these AASS layers are almost fully oxidised, with <0.01 to 0.17% S. However, in a jarositic horizon in one profile (site 306) the level is significantly higher at 0.41%. Actual acidity levels vary from <10 to 42 mol H^+/t, which are all below the action level for a clay soil, and only one sandy AASS with an actual acidity of 25 mol H^+/t (previously mentioned) exceeds the action level for that texture. A large area of land on the melaleuca flats has a pH of only 4.8 in the upper metre (the **a1S2** map unit), but it lacks jarosite. This acidity is probably due to organic acids produced by the melaleuca trees, rather than by AASS.

Another feature of the central basin of Bakers Creek is its relative shallowness, as even in the mangrove areas, the heavy clay basement occurs at 1.25 to 2.20 m in places. On the other landforms, it underlies the estuarine sediments between 2.0 and 4.9 m (not including the previously reported marginal areas).

Sand barrier and coastal sand dunes

On both the north and south sides of Bakers Creek, the seaward side of the central basin is protected by coastal sand dunes, which are all underlain by ASS. The dunes on the north side, which form the estuary barrier, are larger and higher than those to the south, and are mapped as **S4/S5**, and **S5+** on the steeper frontal dunes. The sandy PASS under them occur between 3.2 and 5.7 m, whereas those under the south-side dunes are between 1.8 and 3.1 m, and are mapped as **S2/S3** and **S3/S4**. The depth range indicates the elevation difference between the dune and swale. In an area of shallow basement, only a thin layer of AASS (0.5 m) underlies one dune, which is mapped as **A2**.

The PASS underlying the sand dunes consist mainly of fine to coarse sandy sediments. Oxidisable sulphur levels range from 0.04 to 0.52%, with 75% of the layers having less than 0.2%. The soils of the dunes, which are young and lack profile development, are classified as Basic, Arenic Rudosols. Apart from a dark topsoil 0.2 m thick, they consist of 1 to 3 m of light grey or pale brown (10YR7/2, 7/3 d), fine, aeolian sands. In turn, these usually overlie yellow-brown (10YR5/4, 6/4), coarse, gravelly, fluvial sands often containing few to common (2–20%) shell fragments. The fluvial sands overlie the PASS sediments.

Bay-head delta—channel benches

The depth to underlying ASS is highly variable in the channel benches, which have quite undulating topography due to numerous terraces, flood-out channels and levees (Photograph 24), so a depth range (**S2/S3**) is used on the map units to indicate this. As the depth to PASS varies from 1.25 m to more than 5 m depending on the thickness of overlying alluvium, the map units vary from **S2** to **S5+**. AASS layers also overlie the PASS in some of these areas, and the depth to them varies from 1.75 to 4.50 m, resulting in **A2S2** to **A5S5+** map units.

Photograph 23: Milky mangrove forest on drier intertidal flats in the Bakers Creek catchment area

Photograph 24: Undulating topography of a channel bench on Bakers Creek

The PASS vary from sands to mangrove muds, with only 20% more sand than clay layers. The % S content of the sands ranges from 0.04 to 0.57%, with that of one layer very high at 1%. That of the clay material is mainly from 0.3 to 1.3%. It is not unusual for these PASS layers to be only 0.05 to 0.20 m thick. The AASS layers are extremely acid (pH 2.8–3.9), but often do not contain any jarosite. With <0.01% S (except in one layer where the concentration is 0.22%) they are almost fully oxidised. Actual acidity levels vary from <10 to 42 mol H^+/t, with only one sandy AASS with an actual acidity of 26 mol H+/t exceeding the action level for sand texture.

The soils of the channel benches are highly variable both between, and within the benches. They are either fine sandy, loamy or clayey soils, and are often stratified with alternating layers within a profile. However, as Bakers Creek rises in the hills formed on the fine-grained sedimentary rocks of the Carmilla Beds, between 2.2 and 4.8 m of uniform fine sands overlie the ASS on many of the channel benches. The soils therefore vary from Hydrosols on the lower-lying channel benches, to Tenosols, Rudosols, Sodosols and occasionally Dermosols, on the more elevated and less wet landforms.

Bakers Creek to McEwens Beach Basin

The final area included in the Bakers Creek catchment area (really a separate catchment discharging directly to the sea) consists of the extensive tidal flats and sand dune systems between the mouth of the creek and McEwens Beach further to the south. It is unique in the entire study area as it demonstrates contemporary coastline development. It consists of three parallel systems of sand dunes, 200–500 m apart, with the interdunal spaces occupied by dense, mangrove forests. The first discontinuous line of dunes, which borders the original coastline, is underlain by ASS. Deposition of sand from both Bakers and Sandy creeks has provided sediment enabling two more lines of dunes to develop seaward, from a point just north of McEwens Beach. A study of the 1947 aerial photographs shows that the present frontal dune has extended northwards by 1 km during the last 50 years, allowing another 13 ha of mangroves to colonise former sand flats behind it.

The interdunal spaces have been infilled by mangroves. The protection afforded by the sand dunes has reduced the water velocity so that up to 2 m of mangrove muds have been laid down over the former sand flats. The mangrove areas are either **S0** or **S1**, depending on the frequency of tidal inundation, with the wetter **S0** areas surrounding the creek channels. PASS occur between depths of 0.2 and 0.9 m, and the % S content of both the sand and clay sediments ranges from 0.2 to 1.2%. The fringing saltpans and marine couch flats vary from **S1** to **S2**, sometimes with an overlying AASS layer (**A0S2**). The PASS occur at depths of 0.8 to 1.7 m, with 0.5 to 1.3% S in the clays, and only 0.03 to 0.11% in the sands.

The discontinuous line of subdued and rounded landward sand dunes, only 2 to 3 m high, overlie ASS between depths of 2.1 and 2.6 m and are mapped as either **A3S3** or **A3S4**, with AASS layers usually overlying PASS sediments. The ASS under the dunes, which are in layers only 0.5–0.7 m thick, overlie the gley, heavy clay basement at depths of 2.9 to 3.2 m. The % S content of the AASS is very low (0.02–0.03%), with actual acidity ranging from 39 to 46 mol H^+/t, while the % S content of the PASS ranges from 0.16 to 0.73%. As restricted vehicle access prevented examination of the two outer series of dunes, they are mapped as **S_{LA}** as it is assumed that they are also underlain by ASS.

The main drainage line of this basin is fringed by melaleuca flats with well developed ASS profiles, usually with thick (0.9–1.2 m) AASS layers, with many (20–50%) jarosite mottles, overlying silty, light clay PASS sediments. These flats are mainly **A1S3**, with AASS occurring at depths of 0.7 to 1.5 m. The PASS extend to depths of 4 to 5 m where they overlie the gley, Pleistocene clay basement. The AASS are almost fully oxidised with only 0.01 to 0.04% S, and actual acidity levels of 10 to 58 mol H^+/t, which are below the action level for clay soil. The % S content of the PASS is from 0.5 to 2.1%. A small valley flat at the head of this drainage line has a similar profile to that described above and is also an **A1S3** area. Most of this valley flat is covered by a large ring tank (**S_{DL}**).

Water quality monitoring

The estuarine water quality of the Bakers Creek catchment was measured in Shellgrit Creek (W9), at the end of the Farrellys Lane stormwater drain (W10), which has been excavated through ASS over its final 600 m, and in Bakers Creek at the Bruce Highway (W11). Shellgrit Creek was monitored near its mouth as it also receives water from two stormwater drains excavated through ASS areas of South Mackay. As the ASS from the deep stormwater drains had been formed into a bank or left as spoil beside these drains (Photograph 25), they were believed to have the potential to discharge acid leachate. There are only four other ASS disturbances, either small farm dams or aquaculture ponds, over the remainder of the Bakers Creek catchment area.

Figures 18, 19 and 20 show estuarine water pH and electrical conductivity trends over the monitoring period from the three sites (dissolved oxygen and temperature data are tabulated in the appendix). At 6.8 to 8.5, the pH of Shellgrit Creek and the Farrellys Lane drain is normal, indicating that if acid leachate is still being generated here, it is not affecting water quality. (As the drains were excavated over 20 years ago, the PASS left on the banks has probably fully oxidised.) Iron staining from oxidation of the PASS was observed on the sides and floor of one drain (Photograph 26), but it does not appear that sulfuric acid produced from this oxidation is sufficient to affect the pH of the water in the drain, and in Bakers Creek.

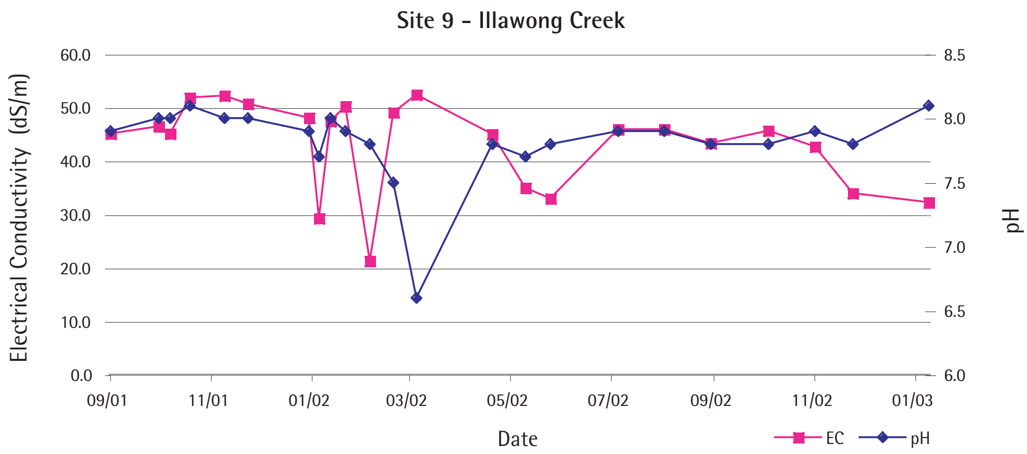


Figure 18: pH and EC of estuarine waters of Shellgrit Creek

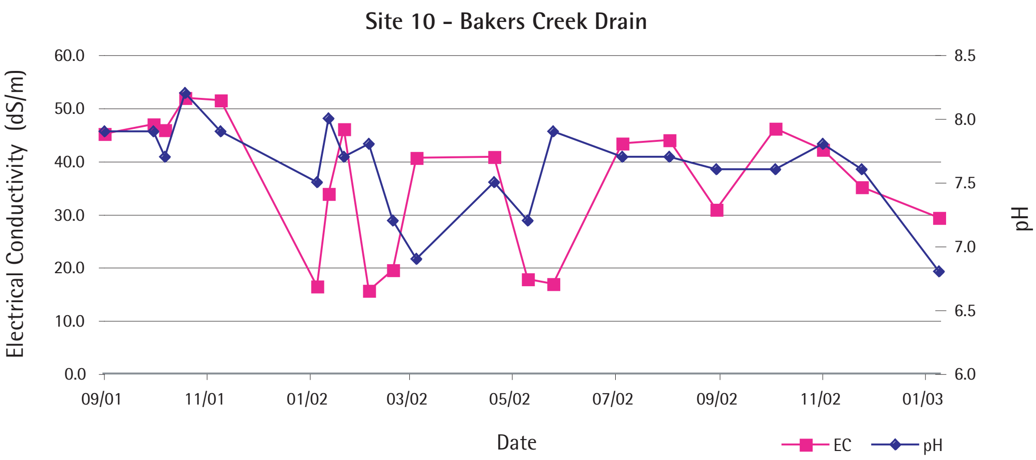


Figure 19: pH and EC of estuarine waters in the Bakers Creek drain

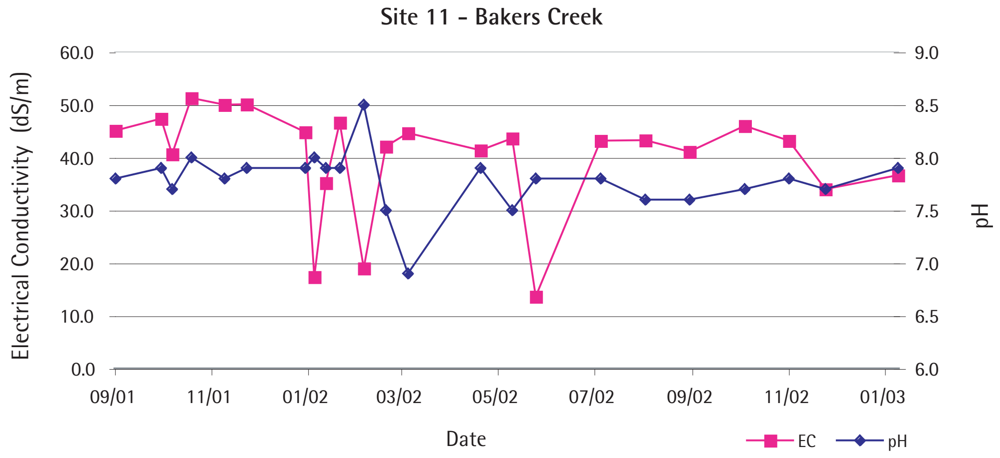


Figure 20: pH and EC of estuarine waters of Bakers Creek at the Bruce Highway

The pH of Bakers Creek is between 7.0 and 8.5, which is within the acceptable range for estuarine waters. The electrical conductivity of the waters at sites W9, W10 and W11 is between 30 and 52 dS/m over the dry season, only decreasing to lower levels (15–20 dS/m) during periods of rainfall and runoff in the wet season. The dissolved oxygen levels, which were all between 3.7 and 11.9 over the monitoring period are another indication that there have been no adverse effects from ASS disturbances.

Photograph 25: South Mackay stormwater drain with ASS spoil formed into a bank on the left side of the drain

Photograph 26: Localised iron staining on the floor of a stormwater drain excavated through ASS in South Mackay

5.5 Sandy Creek catchment area

Catchment geomorphology

Sandy Creek, which drains the southern region of the Pioneer alluvial plain is also one of the major drainage lines of the floodplain. It rises in the foothills of the coastal ranges formed from the sedimentary and acid volcanic rocks of the Carmilla Beds, and extends beyond Eton, some 30 km inland. Its mouth is comparable in size to that of the Pioneer River, as it is believed to have been a former channel of this river (Gourlay & Hacker 1986; Holz & Shields, 1985).

The estuary morphology of Sandy Creek is different from that of the Pioneer River and Bakers Creek as it lacks a protective sand barrier. Sandy and Alligator creeks join at their mouths and share a common inlet, known as Sandringham Bay, which is about 5 km long and 2 km wide (Figure 21). The mouths of the creeks are 500 m wide, thereby allowing full tidal exchange. The coastal hills of Hay Point on the eastern side of the Sandringham Bay inlet also protect these creeks from wave action caused by the prevailing south-easterly winds. As tidal-current energy exceeds that of wave energy at the creek mouth, extensive sand flats that are exposed at low tide have developed in Sandringham Bay. As it has a wide open mouth, strong tidal exchange throughout, and an extensive tidal delta, Sandy Creek is therefore a TDE (Dalrymple et al. 1992).

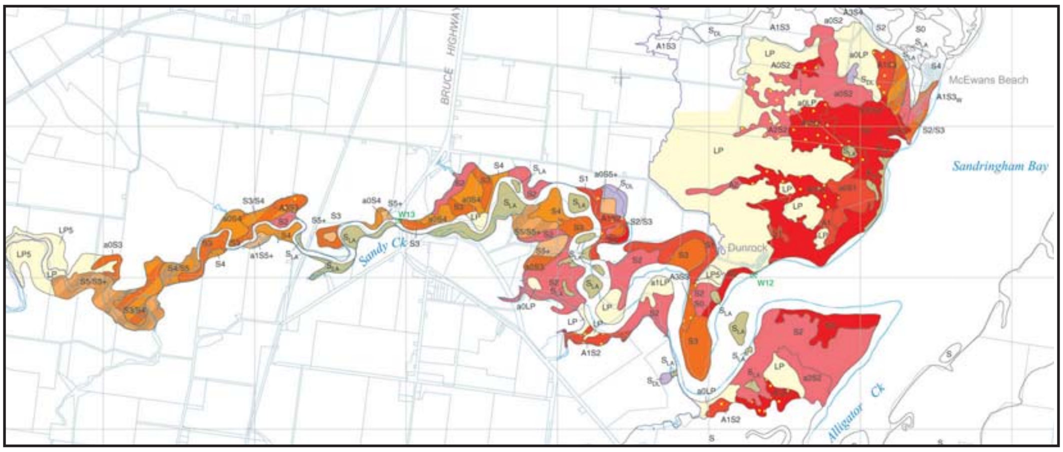


Figure 21: Sandy Creek catchment area

It is probable that the central basin is represented only by mangrove forests and saltpans at the mouth of Sandy Creek. As the river valley has infilled during the current still stand, well developed channel benches have formed. They are widest where they begin in the lower estuary mouth, and they continue along the full length of the creek. Standing between 2 and 10 m below the level of the older Pioneer floodplain, they represent the bay-head delta development of this estuary from fluvial deposition. Sandy Creek follows a very meandering course around these channel benches, islands and former elongate sandbars.

As it is protected by coastal hills to the east, the creek completely lacks coastal sand dune development, and is one of only two estuaries in the study area like this. The only sand dunes in this catchment area are at McEwens Beach, north of the mouth of Sandy Creek, where less protection and sufficient wind energy to deposit sand inland have resulted in a series of low dunes. The two small tidal inlets between McEwens Beach and Dunrock are also included in this catchment area, although they are fed by short, ephemeral, shallow drainage depressions that drain the Pioneer alluvial plain, and are really separate small catchments.

Acid sulfate soils

In the Sandy Creek catchment, there are 1085 ha of ASS, which were defined from 87 boreholes. This includes 181 ha of AASS and 1074 ha of PASS (11 ha of AASS are not underlain by PASS). Of the ASS, 696 ha (64%), occur within the tidal zone, showing that most of the ASS in the Mackay district occur within this landform. The only other significant area of PASS (322 ha or 30%) underlies the channel benches of Sandy Creek, some of which are above 5 m AHD. Table 7 shows the areas of AASS and PASS for each depth category, and the areas of disturbed and limited assessment land within the Sandy Creek catchment area.

Nearly all the AASS occur within the salt pans and marine couch flats of the tidal zone, with only small areas underlying the channel benches and coastal sand dunes. Half of it (89 ha) occurs within 0.5 m of the soil surface (**A0** units), with most of the other half lying between 0.5 and 2.0 m deep (**A1** and **A2** units). It is deepest on the channel benches where there are 13 ha between 2 and 3 m (**A3** units).

PASS are found in all depth categories in the Sandy Creek catchment, with the largest area (422 ha) occurring between 1 and 2 m (S2 units) on the salt pans and marine couch flats of the tidal zone, melaleuca backplains and channel benches in the lower estuarine reaches. Also significant are the S0 units where the PASS occur in the surface 0.5 m of sediments in the wetter areas of the mangrove forests (161 ha), and the S3 units of many of the landforms where they are between 2 and 3 m deep (159 ha). Smaller areas underlie some of the sand dunes and channel benches at depths of less than 3 m (S4, S5 and S5+ units).

Excavations for farm dams have disturbed only a small area (12 ha) of land underlain by ASS (**S_{DL}**), while the inaccessible channel benches and mangrove-forested islands in the Sandy Creek channel are considered limited assessment lands (**S_{LA}**). As in all catchments, Sandy Creek has a significant area (479 ha) of land below 5 m not underlain by ASS. This is mainly on the older, more elevated Pioneer floodplain that adjoins the areas of Holocene ASS deposition around the mouth of Sandy Creek.

Table 7: Area (ha) and proportion (%) of AASS and PASS for each depth category, disturbed and limited assessment lands in the Sandy Creek catchment area

ASS	0–0.5 m	0.5–1.0 m	1–2 m	2–3 m	3–4 m	4–5 m	5m+	S_{DL}	S_{LA}	Total
AASS	89	44	35	13	-	-	-	-	-	181
%	49	24	19	8						100
PASS	161	69	422	159	86	35	48	12	82	1 074
%	15	6	39	15	8	3	5	1	8	100

LP: 479 ha

Analyses of the AASS show that nearly all of these sediments are almost fully oxidised, with % S levels mainly less than 0.1% (mean of 0.11%), except in two clay soils where they are 0.23 and 1.07%. There are only two sandy AASS, and the % S and actual acidity of both are below action levels. Actual acidity levels for all soils vary from <10 to 96 mol H^+/t, with a mean of only 27 mol H^+/t. Only two of these soils exceed the action level of 62 mol H^+/t for a clay soil. Retained acidity was measured in only six of the 24 AASS samples from Sandy Creek, and in these it varies from 0.5 to 63.0 mol H^+/t, resulting in existing acidity levels (actual + retained) of 0.5 to 131.0 mol H^+/t.

The % S of the PASS varies throughout the catchment, but most markedly between textures. In the clays or mangrove muds, the mean concentration is 0.69%, with a range of 0.03 to 2.7%, while in the sands it is 0.27%, with a range of 0.02 to 1.30%. At mainly 0.5–2.0%, its concentration in the muds of the tidal zone is considerably higher than it is in the muds of the channel benches, where it is mainly <0.5%, indicating stiller water-deposition conditions in the tidal areas than on the channel benches. The same trend also occurs in the sandy PASS sediments, but at lower levels. As Figure 22 shows, in the pyritic sands, % S content is usually less than 0.5%, while in the clay PASS sediments, it is usually between 0.25 and 1.50%. There are only six PASS samples in the loam texture group, and their % S levels are consistently between 0.1 and 0.4%, with a mean of 0.25%.

The mean % S content in Sandy Creek clay (0.69%) is similar to that in Bakers Creek (0.62%), which are both significantly lower than that in the other catchments (0.84–1.10 %) in the study area. This is most likely due to the stronger tidal exchange within these estuaries where still backwater areas are limited. All the clay PASS sediments with less than 0.1% S are from the surface soils in the mangrove forests, or from the top of a buried PASS layer, though very low % S levels can be found anywhere within a sandy PASS horizon.

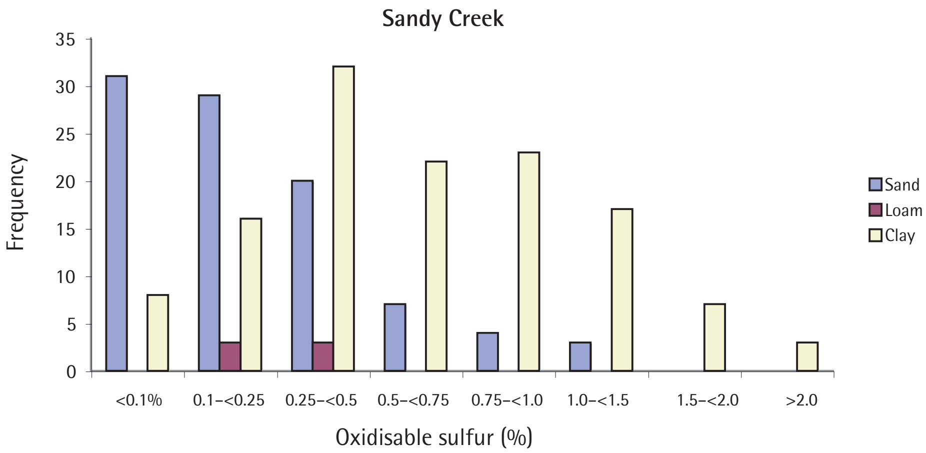


Figure 22: Frequency of samples within the oxidisable sulfur ranges for the sand, loam and clay texture groups for the profiles of the Sandy creek catchment area

Detailed descriptions of landforms

Central basin—intertidal flats

The mangrove forests or intertidal flats of the central basin vary from **S0** to **S2**. The main **S0** areas, which are the shallowest areas of PASS in the catchment, occur in the two tidal inlets to the north of Dunrock, and in the wetter areas adjacent to the creek channel in the lower estuarine reaches. These are characterised by dense forests of the red mangrove (*Rhizophora stylosa*), which have interwoven aerial roots. The PASS occur either at, or just below the surface, between 0.1 and 0.4 m, whereas in the **S1** and **S2** areas they are between 0.8 and 1.7 m deep.

The remainder of the mangrove forests are mainly **S2**, with only small areas of **S1** on drier, slightly more elevated intertidal flats just upstream of the creek mouth. In the mid and upper reaches of Sandy Creek, the mangrove areas are limited to narrow forests lining the creek channel and becoming insignificant upstream of the Bruce Highway. The vegetation associations of these tidal flats are less consistent than those in other catchments. They are mainly co-dominated by milky mangrove (*Excoecaria agallocha*) and yellow mangrove (*Ceriops tegal*), with black mangroves (*Lumnitzera spp*) and orange mangroves (*Bruguiera spp*) sometimes as minor associates, while river mangrove (*Aegiceras corniculatum*) often occur in the understorey. The mangrove forests on the islands in the creek channel are mapped as $\mathbf{S}_{LA}$ due to restricted access.

The soils of the intertidal flats are classified as Sulfidic or Argillaceous, Intertidal Hydrosols which, in the **S0** map units, consist only of a black to very dark grey-brown (10YR 2/1, 3/1, 3/2), silty light clay surface soil with many fine, orange mottles, that overlie very dark grey to grey (2.5Y 3/0, 4/0; 5Y 5/1), silty light clay C horizons of PASS. Fine, sandy, pyritic sediments often underlie these mud layers at depths of 2.3 to 2.9 m. The soils of the **S1** and **S2** intertidal flats have well developed, non-pyritic dark grey or grey (10YR 4/1, 5/1; 5Y 5/1) B horizons with many (20—50%), fine (<5 mm), orange or brown mottles that have formed in the drier conditions. The B horizons grade into clay PASS C horizons at depths of 0.75 to 1.4 m, which in turn consistently overlie sandy PASS layers between 1.3 and 2.1 m. The % S content of the mangrove muds (excluding the surface soils) is usually between 0.5 and 2.0%, while that of the pyritic sands is mainly less than 0.5%.

Central basin—supratidal flats, extratidal flats and melaleuca swamps and flats

There are quite extensive areas of saltpans, marine couch flats and melaleuca flats inland of the mangrove forests in the tidal inlets to the north of Dunrock, and on the south side of the creek mouth. Nearly all AASS areas in this catchment occur on these landforms. The saltpans (or supratidal flats) are either **S1** to **S2** with clay PASS at depths of 0.5 to 1.5 m. AASS or subsoils with very strongly acid pH (4.1—5.0) are nearly always present in the upper profile of these soils (**A0** to **A2**, and **a0** to **a2** units). On two shallow areas of the central basin, the AASS directly overlie the gley, heavy clay basement.

The PASS sediments of the saltpans consist of interbedded layers of silty light clays and sands underlain by the gley, heavy clay basement between depths of 2.4 and 5.4 m. The % S content of the clay PASS ranges from 0.6 to 1.8%, while that of the sands is more variable at 0.02 to 0.90%. The AASS layers are almost fully oxidised, with % S of only <0.01 to 0.09% and actual acidity levels of <10 to 20 mol H^+/t. Both parameters are well below the action levels for clay sediments. The soils are classified as Sulfuric or Sulfidic, Supratidal Hydrosols. They have dark grey or grey (10YR 4/1, 5/1), light to medium clay, B horizons, usually with very few to common (<2—20%) jarosite mottles and many (20—50%) brown and orange mottles, overlying very dark grey to grey (10YR 3/1; 2.5Y 3/0, 4/0) light clay PASS C horizons.

The marine couch or extratidal flats in the tidal areas to the north and south of Dunrock have either AASS, or ASS with strongly acid layers. However, there are no AASS layers in the extratidal flats adjoining the channel benches, which are underlain only by PASS or sandy fluvial sediments. Classification of the marine couch flats, therefore, varies from **A1S2** and **a2S2** to **S2**, **S3** or **LP**. The PASS, which occur between depths of 1.0 and 2.1 m, consist of dark grey (2.5Y 2/0, 3/0, 4/0), silty light clays that are underlain by dark grey or grey (2.5Y 4/0, 5/0) pyritic sands. The PASS are underlain by dark brown, fluvial sands or the gley, Pleistocene, heavy clay basement, the depth to which varies from 0.65 to 3.0 m on the tidal inlet north of Dunrock, and from 4.1 to >6.0 m in other areas.

These soils are mainly Sulfidic or Sulfuric, Extratidal Hydrosols and, like those in the saltpans, have well developed, dark grey or grey (10YR 4/1, 5/1; 5Y 5/1), light to medium clay subsoils with many (20—50%), orange, brown and occasionally few (<2—10%) yellow jarositic mottles. The % S content of the AASS is mainly from <0.01 to 0.04%, with one soil having a level of 0.23%. Existing acidity levels vary from 3 to 131 mol H+/t, with only one soil exceeding the action levels for % S and acidity. The % S content of the clay PASS sediments is mainly between 0.3 and 1.2%, while that of the sandy PASS is from 0.1 to 0.4%.

There are only limited areas of melaleuca flats and wetlands at McEwens Beach in the Sandy Creek catchment area, and they are either **A0S2** or **A1S3w**. The clay PASS occur between depths of 1.2 and 2.1 m and are always overlain by an AASS. The soil profiles are similar to those in the extratidal flats with dark grey to brownish-grey (10YR 4/1, 5/1, 6/2), light clay subsoils with many (20—50%) orange, brown, and yellow jarosite mottles overlying dark grey (2.5Y 3/0, 4/0), light or light medium clay PASS. The tidal inlet at McEwens Beach is relatively shallow and the predominantly clay PASS are underlain by the gley, heavy clay basement at depths of 2.5 to 5.4 m. These soils are Sulfuric, Redoxic Hydrosols. The % S levels (<0.01—0.09%) and actual acidity (<10—45 mol H+/t) (retained acidity was not measured) in the AASS are below the action levels for both the clay and sandy sediments. Oxidisable sulfur in the clay PASS ranges from 0.6 to 1.0%, while in the pyritic sands levels are from 0.1 to 1.1%.

Coastal sand dunes

The small area of coastal sand dunes at McEwens Beach consists of a series of three short parallel dunes that extend only some 500 m inland. These sand dunes are also underlain by PASS, and are mapped as **S3** and **S4** on the dunes and urban area of McEwens Beach, and as **S2** in the swales. The previously mentioned melaleuca wetland (**A1S3**$_w$) occurs in a swale directly behind the McEwens Beach township. The PASS are at depths of 2.7 to 3.9 m under the dunes, and from 1.1 to 1.3 m in the swales. They consist of alternating thin (0.2–0.6 m) layers of dark grey (2.5Y 3/0, 4/0) pyritic sands and muds. The % S content of the clay PASS varies from 0.28 to 0.75%, while that of the pyritic sands is similar (0.18 to 0.89%).

The soils of the sand dunes are either Arenic Rudosols or Orthic Tenosols as they consist of 1.2 to 2.0 m of fine aeolian sands with a dark topsoil grading into either a brown or yellow-brown (10YR 4/3, 5/5, 6/4) B horizon or pale brown (10YR 7/3) C horizon. The aeolian sands overlie yellow-brown to white (10YR 5/8, 6/4, 7/3, 8/1), coarse, fluvial, gravelly sands which in turn overlie the PASS sediments. The swales consist of shallower layers of aeolian and fluvial sands overlying the PASS, or of alternating layers of estuarine clays and sands where the swales are still subject to tidal influence. These low-lying swales are wet, and the soils are Sulfidic or Sulfuric, Redoxic Hydrosols.

Bay-head delta—channel benches

There are channel benches over the full length of the Sandy Creek valley floor, varying in elevation from 3 m to >12 m AHD. They were not mapped above a surface elevation of 8 m AHD, as the sampling equipment was not long enough to reach any underlying ASS at these higher elevations. The topography of the channel benches is highly variable and undulating in some areas due to numerous terraces, relict channels, billabongs and levees. Where these landforms could not be mapped separately, two depths are indicated on the map (e.g. **S3/S4**) to indicate varying depth to an ASS within the mapping unit.

The depth to PASS varies from 1.2 to 6.5 m, and the map units therefore increase from **S2** on the low-lying benches in the lower reaches of the estuary, to **S5+** in the upper estuarine areas. The PASS are mainly underlain by thick layers of gravelly, fluvial coarse sands between 3.0 and 4.4 m, and the Pleistocene, gley, heavy clay basement is only occasionally reached at depths of 4.60 to 5.85 m. AASS are present under only three of the channel benches, and occur only in thin (0.3 m) layers at depths of 0.9 to 2.3 m. These areas are mapped as **A1S2** and **A3S3**.

The PASS sediments are mainly pyritic sands and mangrove muds with occasional loams. The oxidisable sulfur content of the sands is mainly less than 0.5%, while that of the muds is usually between 0.25 and 1.00 %. In the loams, it is consistently low at 0.15 to 0.30%. In the AASS layers, it is usually <0.1%, except in one thin layer where the level is very high at 1.7%. This was interpreted as a PASS layer that has only recently begun to oxidise, as it has less than 2% of jarositic mottles. Its actual acidity of 96 mol H^+/t is also the highest recorded in the study area. Levels in the other AASS range from <10 to 23 mol H^+/t (retained acidity was measured in only one profile, and it is negligible at 0.5 mol H^+/t).

The overlying alluvial sediments vary from dark (10YR 2/1, 2/2, 3/2) clays to brown (10YR 3/4, 4/3, 4/4) loams and pale brown (10YR 5/3, 6/3, 6/4) sands, which are often highly stratified within the one profile. However, because of the rock types of the Carmilla Beds, these soils generally tend to be more sandy. Sandy profiles occur throughout the estuary, while clay sediments are present mainly in the mid to upper estuarine reaches. These soils are classified mainly as Hydrosols on the lower-lying channel benches, and as Kandosols, Tenosols and Rudosols on the more elevated and well-drained channel benches.

Water quality monitoring

The estuarine water quality of Sandy Creek was measured at its mouth at the Dunrock boat ramp (W12), and at the Bruce Highway (W13) in the mid-estuarine area. Alligator Creek was also monitored at the Bruce Highway (W14) and was included in this catchment area. The only disturbance of ASS identified is at the intake channel and sections of the ponds of a now defunct prawn farm at McEwens Beach (Photograph 27). AASS are present on the channel banks, and iron staining is evident in sections of the channel (Photograph 28); however, this disturbance is outside Sandy Creek in the tidal inlet area south of McEwens Beach. The intake channel was monitored separately for a short period only, with the water quality showing no effects from this disturbance (see data in the Appendix).

Photograph 27: AASS that has formed on the bank of a prawn farm intake channel excavated across mangrove flats at McEwans Beach

Photograph 28: Iron staining on the gley, Pleistocene clay basement from oxidation of the overlying PASS in the McEwans Beach prawn farm intake channel

Figures 23, 24 and 25 show the estuarine water pH and electrical conductivity at the Sandy and Alligator Creek sites (W12, 13 and 14) over the period of monitoring (dissolved oxygen and temperature data are tabulated in the Appendix). The pH varies from 7.2 to 8.1 at these two sites, which is within the acceptable range for estuarine water. At the inlet channel of McEwens Beach prawn farm, it varied from 7.7 to 8.1 over five measurements. As with the dissolved oxygen levels of 5.1 to 10.2 mg/L (see Appendix), these data do not indicate any off-site impacts from ASS disturbance in the Sandy Creek catchment area. The electrical conductivity of the waters at these sites varies from 40 to 55 dS/m (normal estuarine water salinities) during the dry season, to 0.5 to 10 dS/m during the wet season following rainfall and runoff.

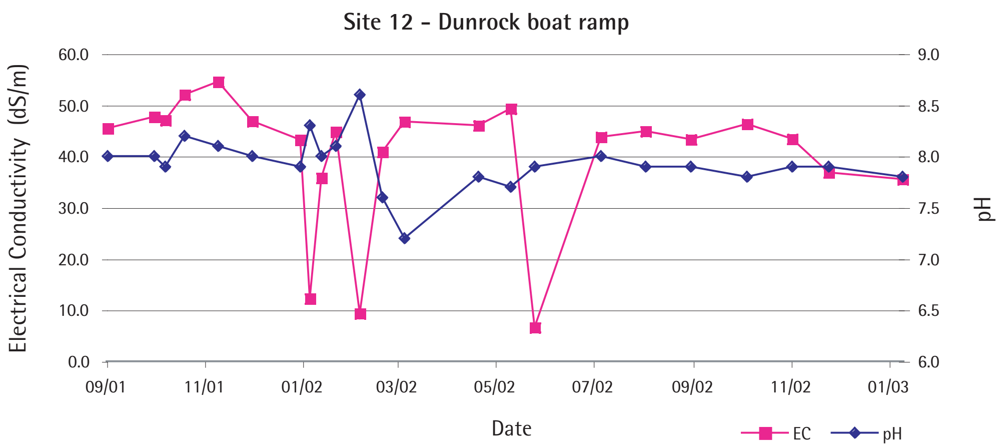


Figure 23: pH and EC of estuarine waters of Sandy Creek at Dunrock boat ramp

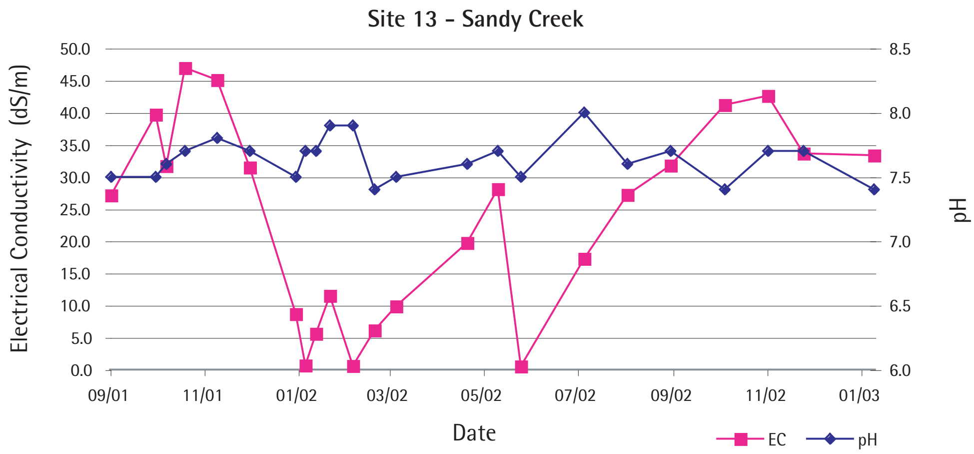


Figure 24: pH and EC of estuarine waters of Sandy Creek at the Bruce Highway

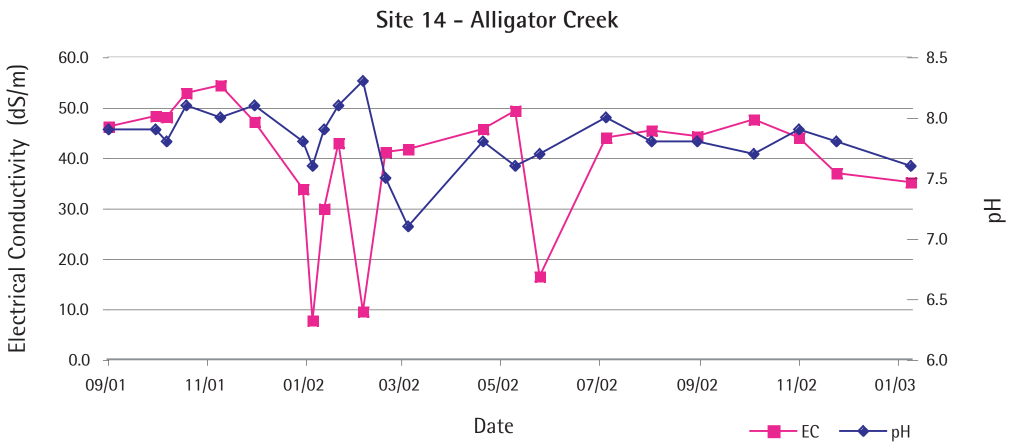


Figure 25: pH and EC of estuarine waters of Alligator Creek at the Bruce highway

5.6 Seaforth–Ball Bay catchment area

The Seaforth area consists of the coastal settlements of Seaforth, Ball and Halliday bays and their associated estuaries (Figure 26). Tidal inlets of the Victor and Constant creeks to the west and east of the Seaforth–Ball Bay area, which have also been included in the study, have been mapped only by interpreting aerial photographs.

Catchment geomorphology

The Seaforth–Ball Bay area consists of three north-east facing, crescent-shaped bays protected by mountainous headlands on their eastern flanks. This area, as well as the rest of the coastline in this region, has short, coastal drainage systems confined by the surrounding hills and ranges. The basins of these estuaries are long and narrow and extend only a few kilometres inland.

Seaforth and Ball Bay have a series of parallel sand ridges laid down along a narrow coastal strip only 300 to 500 m wide. The south-eastern sections of these coastal dunes form a sand spit, or barrier, that protects the estuaries on their seaward sides. The northern sections of the dunes directly abut the colluvial footslopes of the surrounding hills. These two estuaries are therefore barrier type or wave-dominated estuaries, with dense, mangrove-filled, central basins. The meandering creek lines of the central basin enter the bay via the constricted channels at the eastern end of the sand spit. As the creeks entering these estuaries drain narrow, tight valleys, bay-head delta or floodplain development has been restricted to only a short section of Seaforth Creek. The Ball Bay estuary is almost identical to the Eimeo estuary, as it is fully enclosed by low hills, and lacks significant watercourses.

Halliday Bay is different from the others as it is a short bay, only 500 m wide, between two steep, rocky headlands, and does not have a creek directly entering it. Instead, the creek drains westward back into the Seaforth estuary with deposition of sand along the beach front cutting off its seaward access. Halliday Bay was assessed only as disturbed land (S_{DL}), as field sampling was not possible in the resort area.

Behind the coastal Holocene sand dunes of Seaforth and Ball Bay are long, narrow melaleuca swamps with an older, more rounded and subdued sand dune on the landward side, with a well-developed soil profile that has a dark reddish-brown subsoil. This is interpreted as a Pleistocene sand dune, similar in age to the sand sheets at Andergrove and Blacks Beach at Mackay, which represents a former, pre-Holocene coastline. The soil profile of this sand dune has developed to a significantly greater extent than that of the younger sand dunes to the east. It directly overlies the colluvial footslopes of the surrounding hills and defines the limit of Holocene ASS deposition underlying the coastal dunes in these two bays.

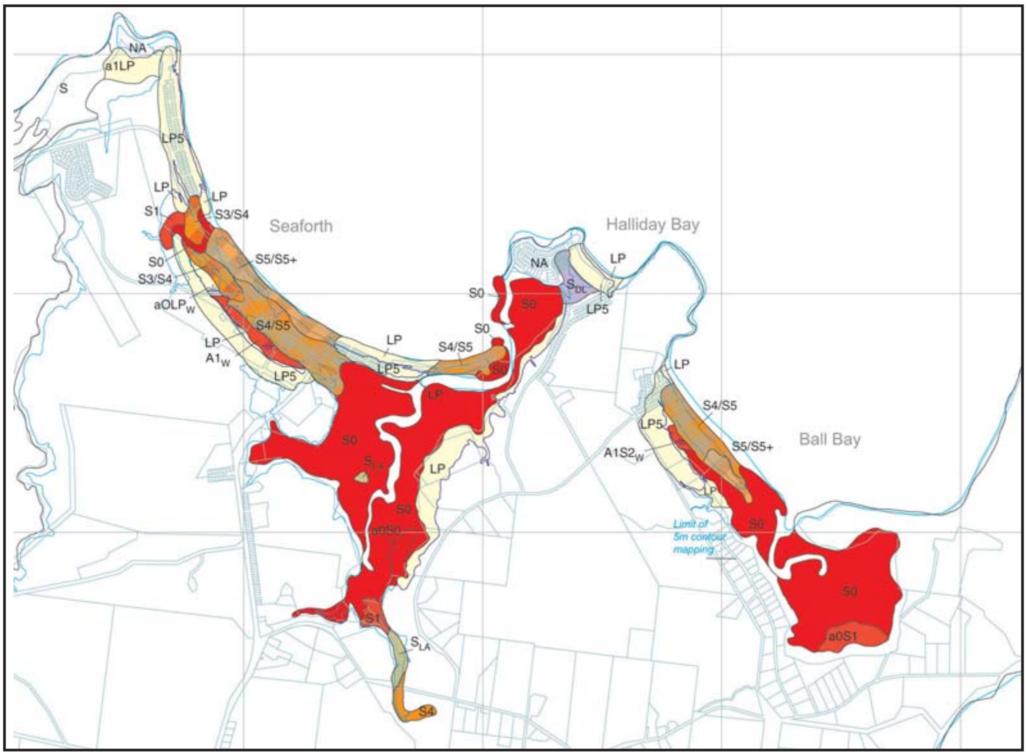


Figure 26: Seaforth to Ball Bay catchment area

Acid sulfate soils

Four hundred and eight hectares of ASS were identified in the Seaforth–Ball Bay area from 38 boreholes, including 9 ha of AASS and 401 ha of PASS (7 ha of AASS are not underlain by PASS). AASS are found only in the melaleuca swamps, directly overlying either the PASS or the Pleistocene basement. Of the area of PASS, 258 ha (71%) occur within the tidal zone, thus showing that most of the ASS in the Mackay district occur within this landform. The remaining PASS underlie the coastal sand dunes (98 ha), valley flats (13 ha) and melaleuca swamps (9 ha). Table 8 shows the areas of AASS and PASS for each depth category, and the areas of disturbed and limited assessment land in the Seaforth catchment area.

Table 8: Area (ha) and proportion (%) of AASS and PASS for each depth category, disturbed and limited assessment lands in the Seaforth to Ball Bay catchment area

ASS	0–0.5 m	0.5–1.0 m	1–2 m	2–3 m	3–4 m	4–5 m	5m+	S_{DL}	S_{LA}	Total
AASS	-	9	-	-	-	-	-	-	-	9
%		100								100
PASS	275	17	2	6	37	39	12	8	5	401
%	69	4	0.5	1.5	9	10	3	2	1	100

LP: 66 ha

The main area of PASS (275 ha), which is also the shallowest, occurs in the surface half metre of the sediments (**S0** units) in the estuaries at Seaforth and Ball Bay, and represents 69% of all PASS in the catchment area. The other main areas, at depths of 3 to 5 m (**S4** and **S5** units), underlie the coastal sand dunes. There are only 8 ha of disturbed lands and 5 ha of limited assessment lands in the area, and three areas (66 ha), and of **LP** land, which were determined by field assessment. The LP land occurs on the footslopes of the hills and rises surrounding the basins.

The AASS occur only under the melaleuca swamps at the rear of the Holocene sand dunes. However, not all the strong acidity in these wetland areas is from oxidised estuarine sediments—in some places it is caused by organic acids produced by the melaleuca trees in the swampy environment. Where AASS are present, they are almost fully oxidised, with % S contents of <0.01 to 0.10% (mean of 0.04%). Only one of the soils sampled (a surface soil) reaches the action level of 0.1% for a clay soil. Existing acidity levels (actual and retained) are also below the threshold of 62 mol H^+/t, varying from <10 to 21 mol H^+/t, with a mean of 17 mol H^+/t.

The % S content of the PASS in the tidal zone is very high, regardless of texture, averaging 1.4% in the sands (from only two samples) and 1.3% in the mangrove muds. This indicates very still water-deposition conditions in these estuaries, conducive to the formation of pyrite. Levels in the PASS under the sand dunes, however, are much lower, averaging 0.25% in the sands (most PASS here are sandy sediments), and 0.43% in the muds. Therefore in the Seaforth area there is very little variation in the % S contents of different soil textures in these two landforms, compared with those in similar landforms in other catchments examined during this study. Overall, the average level of oxidisable sulfur of the clay PASS is 1.1%, with a maximum of 4.0%, while that of the sands is 0.35%, with a maximum of 1.50%. These are the highest means in all the catchments assessed. Figure 27 shows the number of samples within the % S ranges for the clay, loam and sand texture groups. In the clays, levels are 1.0% or more in over half the samples analysed, while most sands have concentrations of less than 0.5%. The % S content of the one sample in the loam texture category is 0.16%.

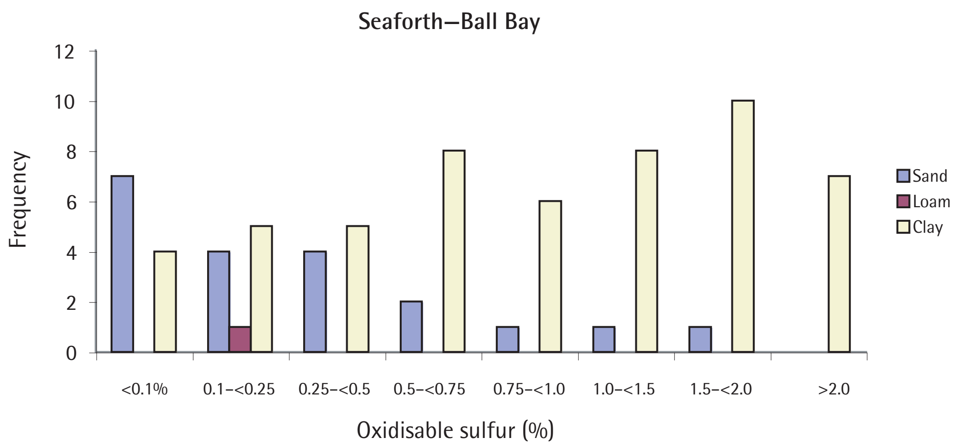


Figure 27: Frequency of samples within the oxidisable sulfur ranges for the sand, loam and clay texture groups for the profiles of the Seaforth–Ball Bay catchment area

Detailed descriptions of landforms

Central basin—intertidal and supratidal flats

The tidal flats of the two estuaries consist of thick forests of red mangrove (*Rhizophora stylosa*), with a narrow saltpan margin, only 100 to 200 m wide, mainly along the eastern perimeter. Both the mangrove forests and saltpans are nearly all mapped as **S0**, with the PASS at or just below the surface. There are only two small areas of **S1**, which are on a saltpan in the Ball Bay estuary and on another saltpan, and in a yellow mangrove (*Ceriops tegal*) forest area in the very small inlet in the middle of the Seaforth Bay. As outlined earlier, the PASS of the tidal zone nearly always consist of muds, with high levels of oxidisable sulfur, mainly between 0.3 and 2.5%.

The soils of the mangrove forests are Sulfidic, Intertidal Hydrosols with black or very dark brown (10YR2/1, 2/2), light or silty light clay surface soils overlying very dark grey to dark grey (10YR3/1, 3/2; 2.5Y4/0), silty light or light clay C horizons. The saltpan soils are Sulfidic, Supratidal, Hydrosols, similar to the previous soils, except that the topsoil is dark brown or dark grey-brown (10YR4/3, 4/4; 2.5Y4/2, 5/2), and as the saltpans are less inundated by tides, has B2 horizons to depths of 0.3 to 0.4 m. These subsoils are grey or grey-brown (2.5Y5/2; 10YR5/1; 5Y5/1) with many (20-50%), fine (<5 mm), grey, brown or red mottles. The textures are mainly light clay or silty or fine sandy light clays.

The B horizons are underlain by very dark or dark grey (10YR3/1; 2.5Y4/0), light clay, PASS layers overlying the gley, heavy clay basement between depths of 0.7 and 1.5 m. The estuarine sediments are relatively thin under the saltpans, and also under the mangroves along the margins of the tidal flats, becoming much thicker towards the centre of the basins. The pyrite has also penetrated into the upper layers of the basement heavy clays, which often have 1–2% S.

Sand barrier and coastal sand dunes

ASS were present only under the southern sections of the coastal sand dunes and sand spits of Seaforth and Ball Bay, because the land slopes upwards to the hilly headlands on the northern tips of these bays, and the original land surface was too high to be flooded by rising sea levels. These northern areas have been covered by aeolian sands only since sea levels stabilised. The southern sections were originally part of the central basin before they were buried by wind-blown sands.

The coastal dunes were mapped as **S3/S4** on the lowest dunes at the rear of the Seaforth dunefield, **S4/S5** over most of the dunefields, and **S5/S5+** on the higher frontal dunes. The map units were assigned two depth categories due to the difference in elevation between the dune crest and swale. The thickness of PASS underlying the sand dunes varies from 0.1 m to >2.5 m, and the PASS occurs between depths of 2.4 and 5.3 m below the surface of the swale or dune crest. As discussed earlier, the % S concentration of this PASS was 0.08–0.87%, with a mean of 0.43% in the muds, and 0.03–0.78%, with a mean of 0.25% in the pyritic sands.

The soils of the sand dunes were classified as Orthic Tenosols or Arenic Rudosols on the younger frontal dunes. The Tenosols consisted of dark brown or yellow-brown (10YR3/4, 4/4, 5/6), fine sandy subsoils, while the Rudosols were pale, fine sand (10YR6/4, 7/3, 7/4) C horizons underlying the dark surface soil. These dunes have between 1.5 and 3.4 m of fine aeolian sands that commonly overlie very shelly sand layers that resemble former beach deposits. These layers usually contain very many (50–90%), fine or medium (2–20 mm), shell fragments and the occasional larger (20–60 mm), round intact shell. They often overlie PASS, which also occasionally has few (2–10%), fine (2–6 mm), shell fragments. The PASS commonly overlie the gley, heavy clay basement which occurs between 5 and 6 m.

Bay-head delta—channel benches

A bay-head delta has developed only on Seaforth Creek, where floodplain deposits overlie former estuarine sediments. The other short drainage lines entering the Seaforth and Ball Bay estuaries do not appear to have sufficient catchment area to have generated the runoff required to cut down deeply into the valley floors to create a basin that could have been infilled by estuarine sediments.

PASS were found under the valley flat of Seaforth Creek, where it was possible to access only one site. This area is mapped as **S_{LA}** and **S4**. The PASS under the **S4** area occur at 3.5 m, and consist of dark grey (2.5Y2/0; 5Y4/2) muds and loams with 0.05 to 0.16% S. The overlying alluvium consists of dark, dark brown and mottled, and dark grey-brown (10YR2/2, 3/3, 3/4, 4/2), light or light medium clay sediments.

Melaleuca swamps

The only AASS found in the Seaforth mapped area occur in the melaleuca swamps at Seaforth and Ball Bay. The swamp at Seaforth has an AASS from the oxidation of PASS in a part of it only, and this section is mapped as **$A1_W$** as the AASS directly overlie the gley, heavy clay basement. Soils in the other section of this swamp are strongly acid (pH 4.4–5.2) due to the organic acids produced by the melaleuca trees, and are thus mapped as **$aOLP_W$**. The other swamp at Ball Bay, where the AASS is underlain by a PASS layer with 0.06 to 0.31% S, is mapped as **$A1S2_W$**. These AASS are almost fully oxidised, with 0.01 to 0.1% S, and actual acidities of <10 to 21 mol H^+/t. Retained acidity measured in the Ball Bay swamp varies from 2 to 6 mol H^+/t. The soils of these swamps are variable, consisting of uniform sandy or clay soils, or sandy-surfaced duplex soils overlying ASS, the gley, heavy clay basement, or bedrock. They are all extremely acidic and, where they occur, the estuarine sediments are between depths of 0.6 and 0.9 m. The soils are classified as Redoxic Hydrosols.

Water quality monitoring

The estuaries of the Seaforth area were not included in the water quality monitoring program of the project.

6. Discussion and conclusions

This project has defined the extent of ASS deposition in six catchments of the Mackay district. As one of the main project aims was to determine if disturbance of ASS was affecting water quality, estuarine water quality in these catchments was also monitored in order to correlate it with ASS disturbance.

Nearly all the AASS analysed are almost fully oxidised clay sediments, with the majority of the soils having less than the action level of 0.1% of oxidisable sulfur. Only an occasional profile has a % S content greater than this, with the mean for the catchments ranging from 0.04 to 0.14%, and the maximum from 0.1 to 1.7%. Similarly, most AASS have actual and retained acidity levels less than the action level of 62 mol H^+/t for a clay soil, with means of 12 to 41 mol H^+/t across the catchments, and maximums varying from 21 to 127 mol H^+/t. The few sandy or loamy AASS that occur, again only occasionally exceed treatment action levels for those textures. Only 15 AASS samples were analysed for retained acidity, which varies from 1 to 63 mol H^+/t. The AASS examined in the study area therefore pose only a low environmental risk in the case of accidental exposure, and are naturally leaking low concentrations of sulfuric acid into the environment.

The PASS in the six catchments are nearly always pyritic sands or muds, with only an occasional loamy sediment. The % S varies considerably between these two textures in all catchments. In the sands, the means vary from 0.16 to 0.35%, and the maximums from 0.72 to 2.7%; whereas the clayey PASS sediments have, on average, three to four times the % S, with means of 0.62 to 1.10%, and maximums of 1.7 to 5.2%. The muds, therefore, pose a significantly higher potential environmental risk.

The ASS maps show the extent of ASS and the depths to AASS and PASS in the six catchments, revealing that most (63%) ASS occur within the tidal zone (up to the HAT), and also at the shallowest depths, mainly 1 m or less (**A0/S0** and **A1/S1**). In the past, nearly all ASS disturbance occurred on these lands, from council stormwater drains, farm dams, sand and gravel extraction pits, aquaculture ponds and intake and discharge channels, and filling for urban or industrial lands or city infrastructure requirements.

Photograph 29: Irrigation dam in the McCreadys Creek catchment excavated into acid sulfate soils at 2.0 m: note the pile of AASS spoil in the background

Photograph 30: Filling on tidal lands underlain by PASS at 0.8 m for the Mackay city waste disposal facility in the Pioneer River catchment area (S1)

Outside the tidal zone, ASS also underlie floodplain deposits in the bay-head deltas and sand dunes around the estuary mouths and margins, but they are nearly always considerably deeper, usually between 2 and 6 m (**A3** or **S3** to **A5** or **S5+**). On only a few of the floodplain areas adjoining the tidal flats do they occur between 1 and 2 m (**A2** or **S2**). The implications of this are that the deeper the ASS, the lower the risk of disturbance as reflected by the colouring scheme on the maps. Disturbances of ASS on these lands are restricted to only two deep dams for irrigation water storages on the McCreadys and Bakers Creek floodplains and channel benches.

One of the main causes of ASS disturbance in other areas of Queensland and New South Wales is deep drainage on these poorly drained, low-lying coastal lands. Closely spaced networks of deep drains lower the watertable exposing the PASS to aerobic conditions, which can result in its oxidation over very large areas.

This has not occurred in the Mackay district, either because the slope of the land (usually around 0.3%) has meant that only shallow surface drains have been required, or because the overlying soils have been sandy and well drained so that drains have been unnecessary. In many of these areas, the ASS also occur at depths greater than 2 m, so that even if deep drains were in place they would not lower the watertable below the level of the ASS. Neither have there been large-scale excavations of ASS for developments such as canal estates, so their disturbance in the Mackay district has been relatively minor.

The data presented also indicate that waterways in the study area, during the monitoring period, were not affected by low pH acid leachate from disturbed ASS lands. At all 14 monitoring sites, the pH of the estuarine water was nearly always between 7.0 and 8.5, which is within the acceptable range for tidal waters (ANZECC & ARMCANZ 2000). Dissolved oxygen levels are also within the acceptable range for estuarine waters.

As these data confirm that there has been minimal, if any, disturbance of ASS in the six catchments mapped by this study, particularly in the so-called 'hot spots' of McCreadys and Bakers creeks, which are sites of recent fish kills, it is concluded that ASS disturbance has not been the cause of this. Neither has it contributed to mangrove dieback in the district over the monitoring period, or other measurable off-site impacts. However, this is not to say that disturbance of acid sulfate soils could not have an impact in the future. Indiscriminate large-scale excavations or deep drainage in ASS areas could result in the same levels of environmental degradation that have occurred in south-east Queensland and northern New South Wales.

Recently introduced Mackay City Council development conditions, and the Queensland Government State Planning Policy 2/02—*Planning and Managing Development Involving Acid Sulfate Soils*, and associated soil management guidelines (Dear et al. 2002), now prevent accidental excavations of ASS. All excavations below an elevation of 5 m AHD, and filling of low-lying lands below 5 m AHD now require an ASS assessment, thus ensuring that these soils will be avoided or effectively managed in future developments.

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Glossary

Acid sulfate soils (ASS): Soils or soil horizons which contain sulfides, or acid soil horizons affected by oxidation of sulfides. Acid sulfate soils is the common name given to naturally occurring sediments and soils containing iron sulfides (principally iron disulfide or their precursors). The exposure of the sulfide in these soils to oxygen by drainage or excavation leads to the generation of sulfuric acid. The term acid sulfate soils includes both actual and potential acid sulfate soils. (See below).

Action criteria: The oxidisable sulfur (% S) values of soil samples which exceed the Queensland acid sulfate soils guidelines (Ahern et al. 1998). Soils with % S above this level are therefore classed as ASS and may require remedial treatment such as application of neutralising agents if they are disturbed or drained. The action criteria used as the determinant of PASS are:

- 0.03% S or 18 mol H^+/t for sands
- 0.06% S or 36 mol H^+/t for loams to light clays
- 0.1% S or 62 mol H^+/t for light medium to heavy clays.

Note that when excavations exceed 1000 tonnes (or m^3), the action criterion of 0.03% S or 18 mol H^+/t applies regardless of texture.

Actual acid sulfate soils (AASS): Soils containing highly acidic soil horizons or layers resulting from the aeration of soil materials that are rich in iron sulfides, primarily pyrite. This oxidation produces hydrogen ions in excess of the capacity of the sediment to neutralise the acidity, resulting in soils with a pH of 4 or less, and often the formation of the iron mineral jarosite. These soils can usually be identified by the presence of yellow mottles and coatings of jarosite.

Anaerobic: Conditions where oxygen is excluded, usually by waterlogging.

Australian Height Datum (AHD): The datum used for determining elevations in Australia. Using a national network of benchmarks and tide gauges, a mean sea level has been set as zero elevation.

Borehole: The hole created when an auger or push tube is inserted into the soil body. The portion removed (the core) demonstrates the soil profile and is used for profile description and soil sampling.

Facies: The total properties of a sedimentary deposit, including mineral composition, texture, type of bedding and faunal content, reflecting the conditions and environment of formation.

Holocene: The period of time about 10 000 years before the present. It is an epoch of the Quaternary period (the last 1.8 million years).

Jarosite: An acidic, pale yellow iron sulfate mineral, $KFe_3(OH)_6(SO_4)_2$. The most conclusive indicator of AASS, jarosite is a byproduct of the acid sulfate soil oxidation process, and forms at a pH less than 3.7. It is commonly found along root channels and other soil surfaces exposed to air.

Pleistocene: An epoch of the Quaternary period (from 1.8 million years ago to about 10 000 years ago).

Potential acid sulfate soils (PASS): Soils which contain iron sulfides of sulfidic material which have not been exposed to air or have oxidised. The field pH of these soils in the undisturbed state can be 4.1 or more, and may be neutral or slightly alkaline. However, they pose a considerable environmental risk when disturbed, as they will become very acidic from the oxidation of the iron sulfides to sulfuric acid when exposed to air.

Pyrite: Pale bronze or brass yellow, isometric mineral (FeS_2). It is the most widespread and abundant of the sulfide minerals.

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

Still stand: A stable sea-level condition.

Watertable: The portion of the ground saturated with water; often used specifically to refer to the upper limit of the saturated ground.

Chemical acronyms and abbreviations

POCAS: Peroxide oxidation, combined acidity and sulfate method

POCASm: Peroxide oxidation, combined acidity and sulfate method (modified)

SPOCAS: Suspension peroxide oxidation, combined acidity and sulfate method

pH_F: Field pH

pH_{FOX}: Field oxidised pH of the soil sample by 30% hydrogen peroxide

pH_{KCl}: pH of a 1:5 solution of soil and 1 molar (M) potassium chloride (KCl)

S_{CR}: Chromium reducible sulfur method

TAA: Titratable actual acidity

TPA: Titratable peroxide acidity

TSA: Titratable sulfidic acidity

Appendix

Water quality data

Site W1: Reliance Creek					Site W2: Reliance Creek drain			
Date	pH	Electrical conductivity (mS/cm)	Temperature (ºC)	Dissolved oxygen (mg/L)	pH	Electrical conductivity (mS/cm)	Temperature (ºC)	Dissolved oxygen (mg/L)
18/09/01	8.0	46.2	23.4		7.7	1.0	22.0	
17/10/01	8.0	47.0	25.4		7.4	51.3	25.0	
24/10/01	7.7	48.9	25.9		8.1	4.9	30.7	
05/11/01	8.3	51.6	25.4		7.5	55.0	26.7	
26/11/01	8.1	53.5	27.8		7.9	29.3	33.2	
10/12/01	8.1	50.3	29.5		7.3	55.0	31.8	
16/01/02	7.7	46.8	30.3		7.4	29.2	30.6	
23/01/02	7.8	29.8	27.8		7.0	7.9	29.4	
29/01/02	8.0	48.1	30.3		7.2	44.4	30.5	
07/02/02	8.1	48.9	30.5		7.3	46.4	31.5	
22/02/02	8.0	37.6	27.8	5.7	7.3	7.8	29.3	6.7
08/03/02	7.1	49.4	25.9	6.7	6.5	37.0	27.5	4.7
22/03/02	7.4	53.0	27.2	5.1	8.4	4.5	27.5	11.1
07/05/02	7.5	47.6	22.4	6.5	6.8	20.6	23.2	4.7
27/05/02	7.2	49.4	23.3	7.3	6.7	33.5	26.8	4.6
11/06/02	7.2	39.1	19.4	6.9	6.9	11.3	24.8	7.3
22/07/02	7.3	48.0	18.4	7.8	6.9	23.0	22.6	8.3
19/08/02	7.8	47.6	20.0	7.4	7.1	29.8	22.8	5.5
16/09/02	7.7	46.8	20.8	7.3	7.4	25.9	21.9	6.6
21/10/02	7.8	46.9	25.7	7.0	7.0	50.3	28.8	4.2
18/11/02	7.7	45.1	23.1	6.9	7.3	47.1	25.1	6.0
11/12/02	8.0	42.8	31.6	7.3	7.6	51.1	31.7	6.0
26/01/03	8.1	35.0	28.8	7.5	8.0	35.5	29.5	8.0

Site W3: Eimeo Creek					Site W4: McCreadys Creek at golf course			
Date	pH	Electrical conductivity (mS/cm)	Temperature (ºC)	Dissolved oxygen (mg/L)	pH	Electrical conductivity (mS/cm)	Temperature (ºC)	Dissolved oxygen (mg/L)
18/09/2001	8.1	46.8	24.3		8.1	49.8	25.1	
17/10/2001	8.0	47.7	26.2		7.9	57.3	26.1	
24/10/2001	7.8	47.5	26.1		7.9	58.8	25.4	
5/11/2001	8.1	51.9	28.2		8.2	71.2	28.5	
26/11/2001	8.3	52.2	30.8		7.5	71.0	29.5	
10/12/2001	8.1	48.0	31.1		7.9	64.0	30.2	
16/01/2002	7.9	49.2	31.6		8.0	0.6	32.2	
23/01/2002	7.9	48.7	27.9		7.1	1.2	27.6	
29/01/2002	8.0	49.3	30.0		7.7	1.6	33.1	
7/02/2002	8.1	51.1	31.5		7.4	34.2	32.6	
22/02/2002	8.0	47.5	29.2	6.1	8.1	0.6	29.5	6.4
8/03/2002	7.4	50.6	28.1	7.4	6.5	12.3	28.2	5.6
22/03/2002	7.5	50.2	28.2	5.1	6.6	44.1	27.7	6.6
7/05/2002	7.6	50.5	23.4	6.7	7.8	1.9	23.5	5.9
27/05/2002	7.6	48.3	24.6	7.2	7.1	48.5	24.5	7.5
11/06/2002	7.6	47.0	22.9	6.8	6.7	0.8	23.1	4.4
22/07/2002	7.5	47.0	20.8	7.7	7.3	51.1	21.5	7.5
19/08/2002	7.9	47.5	21.5	7.4	8.0	57.4	21.8	8.8
16/09/2002	7.8	46.0	22.9	7.3	7.8	57.4	22.5	7.3
21/10/2002	7.8	46.3	27.4	6.8	7.9	67.5	28.4	7.6
18/11/2002	7.7	44.2	25.0	6.8	7.8	49.9	27.9	8.6
11/12/2002	8.0	39.3	31.6	7.9	8.0	50.0	34.2	10.9
26/01/2003	8.3	34.5	30.0	6.8	8.3	43.6	31.7	11.8

	Site W5: McCreadys Creek boat ramp				Site W6: Apsley Creek			
Date	pH	Electrical conductivity (mS/cm)	Temperature (ºC)	Dissolved oxygen (mg/L)	pH	Electrical conductivity (mS/cm)	Temperature (ºC)	Dissolved oxygen (mg/L)
18/09/2001	7.7	47.6	23.7		7.7	47.7	23.3	
17/10/2001	8.0	46.8	25.7		7.9	46.9	26.1	
24/10/2001	7.5	49.5	25.3		7.7	48.9	25.2	
5/11/2001	8.1	51.9	25.7		8.1	50.9	26.0	
26/11/2001	7.8	53.2	29.2		7.9	53.8	28.0	
10/12/2001	7.9	51.7	30.2		7.9	51.0	29.5	
16/01/2002	7.8	47.3	30.5		7.8	47.7	30.2	
23/01/2002	7.4	23.7	28.6		7.5	34.0	27.6	
29/01/2002	8.1	49.3	29.5		8.0	48.9	29.2	
7/02/2002	8.0	50.6	30.7		7.9	50.6	30.4	
22/02/2002	7.7	30.5	29.3	4.7	7.6	39.3	28.5	5.5
8/03/2002	7.2	49.1	27.1	6.2	6.9	49.8	26.7	6.4
22/03/2002	7.2	54.0	27.5	4.8	7.3	54.0	28.4	6.3
7/05/2002	7.4	35.8	23.2	5.5	7.5	40.7	22.8	6.0
27/05/2002	7.5	49.7	23.1	6.6	7.6	48.8	23.1	7.4
11/06/2002	7.4	30.7	19.8	5.5	7.5	36.8	19.6	6.4
22/07/2002	7.5	46.1	19.4	7	7.6	45.1	19.3	7.7
19/08/2002	7.7	46.1	20.8	6.7	7.9	44.9	21.7	7.6
16/09/2002	7.7	44.3	22.1	6.5	7.8	43.3	22.2	7.1
21/10/2002	7.7	45.1	26.3	6.6	7.7	45.1	26.3	7.0
18/11/2002	7.7	43.0	24.9	6.7	7.7	43.1	25.0	6.8
11/12/2002	8.0	35.5	31.4	7.5	8.2	35.5	30.0	7.2
26/01/2003	8.2	33.1	29.0	7.2	8.2	32.1	28.7	7.4

	Site W7: Vine Creek				Site W8: Pioneer River			
Date	pH	Electrical conductivity (mS/cm)	Temperature (ºC)	Dissolved oxygen (mg/L)	pH	Electrical conductivity (mS/cm)	Temperature (ºC)	Dissolved oxygen (mg/L)
18/09/01	7.9	45.4	24.2		8.0	45.1	22.7	
17/10/01	8.0	46.6	26.1		8.0	46.4	25.3	
24/10/01	7.6	44.4	24.7		7.9	45.2	24.0	
5/11/01	8.1	51.2	26.0		8.2	50.9	25.9	
26/11/01	8.3	48.9	28.5		8.2	50.9	27.8	
10/12/01	8.0	48.9	30.0		8.1	49.3	29.3	
16/01/02	7.8	48.1	30.5		7.9	48.8	30.3	
23/01/02	7.4	25.3	28.2		8.1	41.5	26.8	
29/01/02	8.0	48.8	29.5		8.1	48.9	29.3	
7/02/02	7.8	48.7	31.1		8.1	49.8	30.2	
22/02/02	7.6	24.2	28.3	5.4	8.1	32.8	28.4	7.2
8/03/02	7.2	46.4	27.1	6.7	7.5	49.7	27.1	6.8
22/03/02	7.3	48.0	27.2	5.5	7.5	49.5	27.2	5.6
7/05/02	7.7	41.9	22.9	6.3	7.8	48.7	23.2	6.8
27/05/02	7.6	31.4	23.0	6.8	7.9	48.3	23.4	7.5
11/06/02	7.6	24.5	20.3	6.1	7.8	36.0	20.5	6.7
22/07/02	7.7	42.7	19.8	7.5	7.9	44.6	19.1	8.0
19/08/02	7.8	44.5	21.5	7.2	8.0	45.4	20.2	7.9
16/09/02	7.7	41.5	22.3	7.0	7.9	43.0	21.7	7.5
21/10/02	7.8	45.1	26.4	6.7	7.8	44.5	26.2	7.0
18/11/02	7.8	42.5	24.7	6.9	7.9	41.5	24.7	7.0
11/12/02	8.1	34.7	29.3	7.1	8.2	35.3	29.3	7.1
26/01/03	8.2	33.0	28.9	7.3	8.2	30.2	28.2	6.9

	Site W9: Shellgrit Creek				Site W10: Bakers Creek drain			
Date	pH	Electrical conductivity (mS/cm)	Temperature (ºC)	Dissolved oxygen (mg/L)	pH	Electrical conductivity (mS/cm)	Temperature (ºC)	Dissolved oxygen (mg/L)
18/09/01	7.9	45.2	22.7		7.9	45.1	22.3	
17/10/01	8.0	46.5	26.4		7.9	46.9	26.1	
24/10/01	8.0	45.2	23.7		7.7	45.8	23.8	
5/11/01	8.1	51.9	25.4		8.2	51.9	24.4	
26/11/01	8.0	52.3	28.8		7.9	51.4	30.1	
10/12/01	8.0	50.7	29.9					
16/01/02	7.9	48.1	31.4					
22/01/02	7.7	29.3	27.5		7.5	16.4	31.2	
29/01/02	8.0	47.5	30.4		8.0	33.8	30.7	
7/02/02	7.9	50.3	30.6		7.7	46.0	31.6	
22/02/02	7.8	21.3	29.5	6.1	7.8	15.6	31.1	11.1
8/03/02	7.5	49.1	26.7	5.1	7.2	19.5	28.4	5.8
22/03/02	6.6	52.4	27.8	3.7	6.9	40.6	29.5	4.7
7/05/02	7.8	45.1	23.1	5.8	7.5	40.8	23.9	6.5
27/05/02	7.7	35.0	24.3	6.5	7.2	17.8	24.2	5.3
11/06/02	7.8	33.0	20.2	6.2	7.9	16.9	21.2	8.4
22/07/02	7.9	46.0	20.4	7.5	7.7	43.3	20.9	8.4
19/08/02	7.9	46.0	21.6	6.9	7.7	43.9	21.9	7.3
16/09/02	7.8	43.4	22.2	6.5	7.6	30.9	25.1	6.6
21/10/02	7.8	45.7	27.6	6.5	7.6	46.1	28.2	7.1
18/11/02	7.9	42.7	24.6	6.8	7.8	42.1	25.1	7.0
11/12/02	7.8	34.0	28.0	5.2	7.6	35.1	28.7	6.4
26/01/03	8.1	32.3	26.6	6.3	6.8	29.3	27.3	5.2

Site W11: Bakers Creek					Site W12: Dunrock boat ramp			
Date	pH	Electrical conductivity (mS/cm)	Temperature (ºC)	Dissolved oxygen (mg/L)	pH	Electrical conductivity (mS/cm)	Temperature (ºC)	Dissolved oxygen (mg/L)
18/09/01	7.8	45.1	23.7		8.0	45.5	24.0	
17/10/01	7.9	47.4	26.1		8.0	47.7	25.4	
24/10/01	7.7	40.6	25.2		7.9	47.1	23.7	
5/11/01	8.0	51.3	25.0		8.2	52.0	24.8	
26/11/01	7.8	50.0	29.6		8.1	54.6	28.6	
10/12/01	7.9	50.1	30.5		8.0	46.9	28.2	
16/01/02	7.9	44.8	30.0		7.9	43.2	29.5	
23/01/02	8.0	17.4	28.1		8.3	12.3	27.7	
29/01/02	7.9	35.2	29.9		8.0	35.8	29.9	
7/02/02	7.9	46.6	32.0		8.1	44.8	32.2	
22/02/02	8.5	19.0	32.0	11.9	8.6	9.4	29.1	10.2
8/03/02	7.5	42.1	28.1	7.9	7.6	40.9	27.6	6.8
22/03/02	6.9	44.6	27.5	6.9	7.2	46.8	26.8	5.1
7/05/02	7.9	41.4	23.9	6.1	7.8	46.0	23.3	6.6
27/05/02	7.5	43.6	24.2	6.2	7.7	49.3	23.2	8.1
11/06/02	7.8	13.6	21.8	7.1	7.9	6.7	20.4	6.1
22/07/02	7.8	43.2	20.4	6.8	8.0	43.8	19.2	7.7
19/08/02	7.6	43.3	22.2	6.0	7.9	44.9	21.5	7.3
16/09/02	7.6	41.1	23.6	6.0	7.9	43.3	22.6	7.2
21/10/02	7.7	46.0	27.6	6.2	7.8	46.3	26.8	6.5
18/11/02	7.8	43.2	25.0	6.4	7.9	43.4	24.3	6.9
11/12/02	7.7	34.0	29.3	6.1	7.9	36.8	28.3	7.4
26/01/03	7.9	36.6	27.7	7.7	7.8	35.5	27.9	7.6

	Site W13: Sandy Creek				Site W14: Alligator Creek			
Date	pH	Electrical conductivity (mS/cm)	Temperature (ºC)	Dissolved oxygen (mg/L)	pH	Electrical conductivity (mS/cm)	Temperature (ºC)	Dissolved oxygen (mg/L)
18/09/01	7.5	27.1	24.9		7.9	46.2	24.1	
17/10/01	7.5	39.7	26.6		7.9	48.3	25.7	
24/10/01	7.6	31.7	25.0		7.8	48.1	25.9	
5/11/01	7.7	46.9	25.9		8.1	52.9	25.0	
26/11/01	7.8	45.1	29.9		8.0	54.4	29.5	
10/12/01	7.7	31.5	29.1		8.1	47.1	29.7	
16/01/02	7.5	8.7	30.9		7.8	33.8	31.1	
23/01/02	7.7	0.7	27.8		7.6	7.7	28.2	
29/01/02	7.7	5.6	29.4		7.9	29.9	30.7	
7/02/02	7.9	11.5	31.9		8.1	43.0	32.1	
22/02/02	7.9	0.6	28.0	6.6	8.3	9.5	29.4	9.0
8/03/02	7.4	6.1	27.7	7.8	7.5	41.1	27.4	6.7
22/03/02	7.5	9.9	27.5	6.2	7.1	41.7	27.3	5.3
7/05/02	7.6	19.7	23.3	5.7	7.8	45.7	24.0	6.6
27/05/02	7.7	28.1	22.6	6.6	7.6	49.3	24.1	7.8
11/06/02	7.5	0.5	20.4	6.0	7.7	16.5	21.9	6.4
22/07/02	8.0	17.3	19.6	7.8	8.0	44.0	20.1	7.5
19/08/02	7.6	27.2	22.5	6.5	7.8	45.4	22.2	7.3
16/09/02	7.7	31.8	24.0	6.3	7.8	44.3	23.2	7.3
21/10/02	7.4	41.2	28.2	5.7	7.7	47.6	27.9	6.4
18/11/02	7.7	42.6	25.7	5.8	7.9	44.0	25.3	6.6
11/12/02	7.7	33.6	29.8	7.6	7.8	37.0	29.9	7.9
26/01/03	7.4	33.3	28.8	6.6	7.6	35.1	27.6	7.6

McEwans Beach prawn farm inlet channel

Date	pH	Electrical conductivity (mS/cm)	Temperature (ºC)	Dissolved oxygen (mg/L)
18/09/2001	8.1	45.5	23.5	
17/10/2001	7.9	49.3	26.5	
24/10/2001	7.8	48.1	22.3	
11/12/2002	7.7	38.2	32.0	8.1
26/01/2003	7.9	36.0	27.3	7.6