# 3 Results

Results are presented in four separate sections:

- Tomago Wetland
- Fullerton Cove
- Kooragang Wetland (Ash Island)
- Hexham Swamp and Shortland Wetlands – these two sites are combined as they both border Ironbark Creek

## 3.1 *Tomago – Summary of site inspections*

The study area covers about 1200 ha, extending south of Tomago Road to the perimeter drain and raised embankment. The main road follows the edge of an elevated sandy ridge about 2-3 metres above sea level, the land slopes downward to the south very gradually with higher areas at 1m AHD at the western end. In the centre the wetland elevation drops to 0m AHD with patches below this. The digital elevation model for Tomago is provided in Appendix 3 (page 81).

Five of the soil inspections were located below 1m AHD (four were below 0.5m), see table T1. Even so, field testing indicated that the sulfidic (PASS) layer was not reached at 3 sites (i.e. 2, 4 and 5).

At these three sites the maximum depth of inspection was 1.2m, indicating that the sulfidic layer, if present, occurred beyond that depth. Previous testing by Glamore in 2007 that penetrated to 0.7m also failed to reach the main sulfidic layer (laboratory testing shows only minor amounts of sulfidic material at shallower depths, as shown in table 3).

At three sites where field tests revealed the presence of substantial sulfide levels, laboratory testing confirmed that the top of the sulfidic layer was well below sea level (between -0.7 and -0.9m AHD).

At this low elevation the layer is likely to be waterlogged most of the time, reducing oxidation and acid production. Only a trace of jarosite was seen in two profiles (T3 and T4), while none was found in the other four sites. Shells were seen within the sulfidic layer at only one site (T6), and were also observed in spoil heaps adjacent to the main north-south drain.

The sulfidic layer was found to be a silty clay, occasionally more sandy and containing partly decomposed vegetation. Surface soils were often loamy, while thick sandy layers were absent from the study area.

**Table 3:** Acid Production Profile Features / ASS Indicators: Tomago

| Site no. | Core Depth | Elevation | Top of PASS | | Notable Profile Features | Top of AASS | |
|---|---|---|---|---|---|---|---|
| | (m) | m (AHD) | Depth from surface (m) | Elevation m (AHD) | Depth from surface (m) | Depth from surface (m) | Elevation (m AHD) |
| **T1** | **1.55** | **0.70** | **1.4** | **- 0.7** | **Waterlogged grey clay below 0.4m** | **absent** | |
| T2 | 1.2 | 1.65 | absent | | | absent | |
| **T3** | **1.4** | **0.3** | **1.0** | **- 0.7** | **Trace of jarosite above sulfidic layer** | **0.7** | **-0.4** |
| T4 | 1.2 | 0.3 | absent | | Trace of jarosite below 0.5m | absent | |
| T5 | 0.9 | 0.4 | absent | | | absent | |
| **T6** | **1.85** | **0.2** | **1.1** | **-0.9** | **Tubular Fe concs below 1.1m, shells below 1.4m** | **absent** | |

Note: **Bold** indicates ASS indicators

**Table 4:** Soil and Water chemical properties important for Acid Production: Tomago

| Site No. | Elevation (m AHD) | Soil Parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Max TAA (moles H+/t) | % of Profile top 1m with TAA >100 moles H+/t # | %Profile top 1m with TAA 50-100 moles H+/t # | Minimum profile soil pH | % of profile top 1m with a pH ≤ 4 | Ground-water pH (surface ponds) | Max % exchange Al value in profile | Max. sulfide % value in profile | Thickness of Jarosite layer (cm) |
| **High Risk Areas** | | | | | | | | | | |
| T1 | 0.7 | 100 | 0 | 100 | 3.8 | 45 | 5.8 | 16.2 | 0.568 | absent |
| **Medium Risk Areas** | | | | | | | | | | |
| T3 | 0.3 | 73 | 0 | 15 | 4.2 | 0 | 4.4 | 1.8 | 0.581 | 30 |
| T4 | 0.3 | 110 | 15 | 15 | 4.0 | 0 | 4.3 | 5.1 | 0.012* | absent |
| T5 | 0.4 | 60 | 0 | 20 | 3.7 | 20 | (4.0) | 4.3 | 0.027* | absent |
| T6 | 0.2 | 35 | 0 | 0 | 4.3 | 0 | (6.3) | 0.7 | 0.808 | absent |
| **Low Risk Areas** | | | | | | | | | | |
| T2 | 1.65 | 9.2 | 0 | 0 | 6.1 | 0 | 7.4 | <1 | 0.008 | absent |

*data indicates that PASS layer lies below the depth of inspection (i.e. short core).
# Centimetres of soil in the top 1 metre of the profile that is accounted for by a soil material that had a test result for TAA that was greater than the stated value (moles of H+/ tonne of soil).

### 3.1.1 Soil Properties and the risk to water quality

Differences in soils and elevation mean that the risk of acid discharges varies across the site. The main area of high risk appears to be the more elevated strip along the northern boundary, close to the sandy rise and the Tomago Road (see table 4). The level of stored acidity in the top metre of the soil profile is highest here probably due to slightly better surface drainage. About 45% of the top metre of the T1 profile had a pH of 4 or less when sampled, and TAA levels were over 50 moles $H^+$/tonne at all four sampling depths (see table 5, and graphs in Appendix 4).

Acidity levels are lower further south. At the less elevated sites (T3 - T6) there is more waterlogging and less opportunity for oxidation and acid production. Soil pH is generally over 4, and TAA levels in the subsoil mostly below 50 moles $H^+$/tonne. The risk of acid discharge in this area is rated medium, however, mainly because the highest TAA level within the profile is in the topsoil (sites T3 and T4, see table 5). This appears to be related to the frequency of waterlogging.

There are small areas of low risk in Tomago Wetland where the sulfide layer is either absent or lies at great depth, where it is permanently waterlogged. For example, the profile of the T2 site, in the western part of the study area, is not acidic, the groundwater pH was 7.4 and the maximum TAA in the profile was less than 10 moles $H^+$/tonne. It is possible that similar features are more common on nearby areas of similar elevation (i.e. over 1-1.5m AHD).

**Table 5**: The TAA distribution within soil profiles from the Tomago wetland area (Indicators of Acid Storage).

| Site No. | Depth below the soil surface (cm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 - 20 | 20 - 40 | 40 - 60 | 60 - 80 | 80 - 100 | 100 - 120 | 120 - 140 | 140 - 160 | > 160 |
| T1 | **100** | 67 | 54 | - | 59 | - | - | 38s | - |
| T3 | **73** | 46 | - | 28 | - | 18s | 21s | - | - |
| T4 | **110** | 65 | - | 25 | - | 43 | - | - | - |
| T5 | 40 | - | - | 41 | **60** | - | - | - | - |
| T6 | 16 | - | 26 | **35** | - | - | 9.9s | - | <5s |
| T2 | **9.2** | - | <5 | <5 | - | <5 | - | - | - |

**Bold** numbers e.g. **110** = maximum TAA value (moles H+ / tonne) in profile.
(<5) = pH>7 and sample not tested for TAA. s = sulfidic materials present.

### 3.1.2 Surface sulfide concentrations and stored acidity

Oxidation / reduction processes can generate acid in surface soils, due to intermittent water logging (Lawrie and Eldridge, 2006), provided the topsoil is rich in sulfate. During the field inspections in Tomago, large areas were completely waterlogged with standing water across the study area after a fortnight of rain.

The pasture plants intolerant of prolonged waterlogging are left dead on the surface prone to rotting. The decomposing plant matter turns black and anaerobic conditions prevail at the soil surface under the standing water. These reducing conditions transform sulfate in the soil to sulfide minerals like pyrite or iron monosulfides.

This is the process most likely to create the slightly elevated sulfide concentrations found by Glamore (2007) in the top 10cm of the profiles he tested. When the soil subsequently dries out, some of these sulfide minerals will oxidise and generate acid.

The more frequent the water logging, the higher this small surface accumulation of sulfide (see graphs in Appendix 4 of sulfide data for the T6 profile).

It is significant that at site T6 pools of water on the surface contained black rotting vegetation on top of the soil surface, below a layer of orange-stained dead vegetation just under the water surface (which is more aerated than below). When tested in the laboratory water from this shallow pond (10cm deep) was non-acidic (pH 6.3) and severely depleted of sulfate (chloride / sulfate ratio 18.75).

Reducing conditions consume acid (lowering TAA) and convert the water soluble sulfates to insoluble sulfides. The black iron sulfide minerals forming near the bottom, on top of the soil surface, are oxidised to orange iron oxide and hydroxide minerals when there is enough air or oxygen present, i.e. near the water surface. Warm weather decreases the level of dissolved oxygen in the water and speeds up the microbial activity, breaking down the vegetation, a process which consumes oxygen.

When the oxygen supply in the water runs out, microbes obtain the necessary oxygen from sulfate ions dissolved in the water. Some of the sulfide minerals formed are left behind in waterlogged pockets in the soil, after the ponded water has dried out. As the sulfides gradually oxidise, they generate acid, boosting the level of stored acidity in the topsoil.

In Glamore's (2007) study four of the six topsoils tested from Tomago recorded a higher TAA level than in any sample from their subsoil (Glamore's sites 1 – 4, see table 6). In the other profiles, TAA levels peaked in the subsoil, close to where the sulfidic zone as been oxidised.

**Table 6**: Stored acidity and soil depth: Tomago

| Site Number | Depth (cm) | TAA (mole $H^+$/+) | KCL Sulfate-S (mg/kg) | Peroxide Oxidisable-S (%) | pH (in KCL) |
|---|---|---|---|---|---|
| 1 | 10 | 58 | 300 | 0.11 | 4.5 |
|  | 30 | 96 | 900 | 0.13 | 4.1 |
|  | 50 | 83 | 700 | 0.07 | 4.1 |
|  | 70 | 85 | 500 | 0.07 | 4.1 |
| 2 | 10 | 78 | 600 | 0.04 | 4.2 |
|  | 30 | 103 | 900 | 0.09 | 4.0 |
|  | 50 | 108 | 1200 | 0.10 | 4.1 |
|  | 70 | 71 | 700 | 0.09 | 4.1 |
| 3 | 10 | 41 | 1600 | 0.10 | 4.7 |
|  | 30 | 51 | 1900 | 0.04 | 4.8 |
|  | 50 | 31 | 1800 | 0.06 | 4.9 |
|  | 70 | 29 | 800 | <0.02 | 4.9 |
| 4 | 10 | 78 | 700 | 0.13 | 4.4 |
|  | 30 | 66 | 1000 | 0.11 | 4.4 |
|  | 50 | 78 | 800 | 0.14 | 4.2 |
|  | 70 | 91 | 700 | 0.07 | 4.1 |
| 5 | 10 | 83 | 800 | 0.23 | 4.5 |
|  | 30 | 88 | 800 | 0.15 | 4.3 |
|  | 50 | 63 | 1000 | 0.04 | 4.1 |
|  | 70 | 64 | 1200 | 0.05 | 4.2 |
| 6 | 10 | 96 | 1400 | 0.10 | 4.3 |
|  | 30 | 66 | 1400 | 0.03 | 4.2 |
|  | 50 | 73 | 1700 | 0.04 | 4.1 |
|  | 70 | 73 | 1500 | 0.09 | 4.2 |

Source: Glamore (2007)

### 3.1.3 Soil salinity and stored acidity

The salinity of the soil profiles at T3, T5 and T6 is higher than at site T4, which is more saline than the higher sites T1 and T2 (also see graphs in Appendix 4). This appears to be related to elevation i.e. the lower sites were once subject to tidal activity, intermittently at least, and have retained much of the salt.

If there was a greater frequency of tidal flooding at sites T3, T5 and T6 than at site T4, this may have helped to neutralise acidity produced at these three profiles compared to less frequent flooding at site 4. This process would also affect the duration and frequency of waterlogging, and subsequent period available for oxidation of the deep sulfidic layer.

### 3.1.4 Effect of soils on ground and surface water quality

The influence of acid sulfate soil properties on water quality varies across the study area. Water tables were high at the time of sampling, and a large part of the study area was under shallow water following rainfall the previous week. The effect is to dilute any acidity or salinity that may be present, masking to some extent any extreme values. Results of ground and surface water sampling are presented in table 7.

The least acidic watertable (pH 7.4) was found where no sulfidic layer was observed (at site T2). This was a low salinity site, but site T1 was less salty and more acidic, almost certainly due to the greater level of stored acidity in the soil. The pH of ground and surface water across the main part of the study area (i.e. below 1m AHD) was generally low (between 4.0 and 4.3), except in surface water at site T6 (pH 6.3). The drain water near sites T3, T4 and T5 was much less acidic than the groundwater (by about 2 pH units) and was dominated more by chloride. Salinity in the drains was also generally less. This discrepancy is in part due to the dilution with surface runoff, but also the heavy textured clay profiles found across the low floodplain have low permeability, restricting access of groundwater to the drains.

The $K_{sat}$ tests have showed a range of soil permeability in the upper profile from moderate to high at sites T3 and T4. Other sites were too slow to measure or water table too low (see graphs in Appendix 5). This indicates that migration of acid into drains may be of some concern. Previous studies, however, have shown that in the absence of large crab holes, estuarine clays in the south west corner of the Tomago site had a permeability of only 0.01m/day (Hughes *et al*, 1998).

The surface water at T6 is depleted in sulfate due to sulfide formation. This situation is reversed in the ground water at the other sites where acidity and sulfate levels are higher.

**Table 7**: Drain and **ground water*** quality: Tomago

| **Site No.** | Drain water and **Groundwater Properties** (Ponded water) | | | | | | |
|---|---|---|---|---|---|---|---|
| | pH | E C (mS/cm) | chloride (mg / L) | sulfate (mg / L) | Cl / $SO_4$ ratio | Ground water depth (cm) | Sampling date |
| T1 | **5.8** | **0.21** | **16** | **8.9** | **1.8** | **45** | 30/04/08 |
| T3 | **4.4**<br>5.9 | **16.0**<br>0.74 | **3900**<br>140 | **1200**<br>51 | **3.25**<br>2.7 | **55** | 30/04/08 |
| T4 | **4.3**<br>6.8 | **6.3**<br>1.1 | **1400**<br>220 | **310**<br>37 | **4.5**<br>5.9 | **15** | 30/04/08 |
| T5 | (4.0)<br>6.8 | (1.2)<br>0.67 | (150)<br>110 | (140)<br>23 | (1.1)<br>4.8 | | 2/05/08 |
| T6 | (6.3) | (3.3) | (600) | (32) | (18.8) | | 2/05/08 |
| T2 | **7.4** | **1.2** | **83** | **18** | **4.6** | **45** | 30/04/08 |
| Tidal Water (approx.) | 7 - 8 | 55 | 19,000 | 2,700 | 7.0 | | |

*** bold** numbers e.g. **4200** = ground water quality at site

Figure 37: Soil core sampling at Tomago site T6 (photo: J Fredrickson)

## *3.2 Fullerton Cove – Summary of Site Inspections*

Acid sulfate soils were found in the low-lying western part of the study area, within about a kilometre of the raised levee bank. Further away, approaching Fullerton Cove Road on the east, the sub-soil changes to a very dense, dark clay, so impermeable that a water table can form on top of it. This clay, only 15cm below the surface, is very sticky when wet and non-acidic. Most probably it represents a vestige of an older landscape, now buried under a veneer of younger alluvial sediments. It was encountered at two of the five profiles inspected (at sites F4 and F5) both at an elevation of 0.5 to 0.6m AHD (see digital elevation model for Fullerton Cove in Appendix 3, page 87).

The three profiles with distinct ASS features (F1, F2 and F3, see table 8) were located further away from the higher ground. The closest one, site F3, had a sulfidic layer at a relatively high elevation. At the other two sites (F1 and F2), further from the higher ground, the sulfidic layer was less elevated, at –0.5 m AHD and -0.9m AHD. Both these profiles were jarositic in a band 10 – 15 cm wide directly above the sulfidic layer. The layer itself contained pockets of decayed but still recognisable plant material, as well as shells in a band 35cm below the top of it.

### 3.2.1 Soil properties and the risk to water quality

The risk to water quality arising from the presence of ASS is highest in the low lying western part of the study area, and decreases eastward as the elevation rises. This rise is only around 20cm, but is significant in terms of soil properties. The amount of acid stored within the soil, as indicated by soil pH and TAA values (see tables 9 and 10), is very large and the groundwater is highly acidic in the western part of the site (near F1 and F2 sites). F1 site also has high aluminium readings in the subsoil.

The risk decreases to medium at site F3, where the soil pH is no lower than 6.0 nor the TAA above 14 moles H+/tonne at any depth in the soil. The reason for this remarkable decrease is possibly a much longer period of subsoil waterlogging, brought about by much reduced evapo-transpiration by the vegetation (few, if any, roots were observed below 25cm), and low-moderate permeability in the subsoil (see $K_{sat}$ graphed results in Appendix 5).

On the higher ground TAA was barely detectable at site F5 (the maximum was 5.5 moles $H^+$/tonne), no sulfidic layer was present and the risk of acid discharge is virtually nil.

**Table 8:** Acid Production Profile Features / ASS Indicators: Fullerton Cove

| Site no. | Core Depth | Elevation | Top of PASS | | Notable Profile Features | Top of AASS | |
|---|---|---|---|---|---|---|---|
| | (m) | m (AHD) | Depth from surface (m) | Elevation m (AHD) | Depth from surface (m) | Depth from surface (m) | Elevation (m AHD) |
| F1 | 1.45 | -0.05 | 0.55 | -0.60 | Shells below 0.80m, jarositic 0.35-0.60m. | 0.35 | -0.4 |
| F2 | 1.70 | 0.24 | 1.15 | -0.91 | Shells below 1.4m, jarositic 1.1-1.2m | 1.1 | -0.86 |
| F3 | 1.3 | 0.33 | 0.45 | -0.12 | Shells below 0.70m | absent | |
| F4 | 0.70 | 0.53 | absent | | Dense mottled dark clay subsoil | absent | |
| F5 | 0.80 | 0.55 | absent | | Dense mottled dark clay subsoil | absent | |

**Table 9:** Soil and Water chemical properties important for Acid Production: Fullerton Cove

| Site No. | Elevation (m) | Soil Parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Max TAA (moles H+/t) | % of Profile top 1m with TAA >100 moles H+/t # | %Profile top 1m with TAA 50-100 moles H+/t # | Minimum profile soil pH | % of profile top 1m with a pH≤4 | Ground-water pH (surface ponds) | Max % exch Al value in profile | Max. Sulfide % value in profile | Thickness of Jarosite layer (cm) |
| **High Risk Areas** | | | | | | | | | | |
| F1 | -0.05 | 180 | 100 | 0 | 3.5 | 90 | 3.6 | 26.8 | 2.603 | 25 |
| F2 | 0.24 | 100 | 0 | 60 | 4.1 | 0 | 3.8 | 3.6 | 0.871 | 10 |
| **Medium Risk Areas** | | | | | | | | | | |
| F3 | 0.33 | 14 | 0 | 0 | 6.0 | 0 | 6.5 | <1 | 1.007 | absent |
| **Low Risk Areas** | | | | | | | | | | |
| F4 | 0.53 | NT | - | - | - | - | 7.2 | NT | NT | absent |
| F5 | 0.55 | 5.5 | 0 | 0 | 6.4 | 0 | NT | <1 | 0.03 | absent |

# Centimetres of soil in the top 1 metre of the profile that is accounted for by a soil material that had a test result for TAA that was greater than the stated value (moles of H+/ tonne of soil).

**Table 10**: The TAA distribution within soil profiles from the Fullerton Cove area (Indicators of Acid Storage).

| **Site No.** | **Depth below the soil surface (cm)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **0 - 20** | **20 - 40** | **40 - 60** | **60 - 80** | **80 - 100** | **100 - 120** | **120 - 140** | **140 - 160** | **> 160** |
| F1 | 130 | 150 | **180** | 100s | - | - | <5s | - | - |
| F2 | 35 | 46 | - | **100** | - | 87 | 55s | - | <5s |
| F3 | **14** | 13 | 7s | - | - | <5s | - | - | - |
| F4 | NT | | | | | | | | |
| F5 | **5.5** | <5 | <5 | 5.4 | - | - | - | - | - |

**Bold** numbers e.g. **110** = maximum TAA value (moles H+ / tonne) in profile.
(<5) = pH>7 and sample not tested for TAA. S = sulfidic materials present.

### 3.2.2 Surface sulfide concentrations and stored acidity

Stored acidity in the surface soil is a significant feature of only one profile (F1). This is the most acidic soil inspected in the Fullerton Cove study area, and also the lowest lying. It has a slightly uneven surface, with water ponding in the hollows at the time of inspection. These conditions favour reduction of sulfates to sulfides, and accordingly laboratory data revealed that the topsoil has a slightly elevated content of reduced inorganic sulfur (0.093%) compared to the immediate subsurface (15-25cm depth contains 0.031%). Surface runoff from this part of the study area will be acidic, as well as leachate from the subsoil.

### 3.2.3 Soil salinity and stored acidity

There is a marked contrast in the level of stored acidity in the Fullerton Cove soil profiles, where salinity differences may be a significant influence on the risk of acid discharge. Surface salinity in the F1 and F2 soils is lower than at F3 where salinity and sulfate levels are very high (see graphs in Appendix 4). The EM38 test results support this finding, with the F5 transect (which covered sites F3, F4 and F5) finding highly elevated salinities particularly around F3 and F4, then decreasing substantially at towards site F5 (see EM38 graphed results in Appendix 6).

Remnants of saltmarsh vegetation survive here with patches of couch on low mounds about 15 cm high. A history of tidal flooding prior to construction of the raised levee may have left this area very salty, preventing much drying and oxidation (by plant roots extracting moisture). Alternatively any acid that may have been produced may have been neutralised by salty water. The groundwater is dominated by chloride (chloride / sulfate ratio 11.7 - well above the seawater benchmark of 7.2). This suggests that some sulfates have been converted to sulfides, a process which consumes acid.

Significantly the amount of stored acid reaches a peak in the subsoil in the high risk section of the study area (at F1 and F2 sites). This part of the subsoil is directly above the sulfidic layer. Acid leaching out of this zone needs to be neutralised prior to discharge and the production of new acid needs to be kept as low as possible.

The impact of acid sulfate soil on water quality appears to be higher around Fullerton Cove than in any other of the study sites on the Lower Hunter floodplain. Only part of the Fullerton Cove area needs to be targeted by remediation strategies. Salt water neutralisation via floodgate modification requires serious consideration in this area. Further site investigations may be appropriate, in consultation with landholders, to develop a more detailed remediation program, particularly since parts of the area are below sea level.

Unlike other parts of the lower Hunter, there appear to be no previous soil investigations in the Fullerton Cove area, apart from a single profile near Williamtown (EES, 2000). Although sampled to 1.7m depth there was no sulfidic layer, the minimum soil pH found was 4.1 and one subsoil sample was very high in exchangeable aluminium (52% of CEC).

Profiles with no sulfidic layer occur in the Fullerton Cove area, apparently on terrain associated with older (Pleistocene) subsoil clays in lower elevations. On the higher ground (over about 2m AHD) around the study area, soils are very sandy and any sulfidic layer that may be present would lie very deep in the profile, beyond the reach of plant roots or below the water table, and therefore poses at most only a low risk to water quality.

### 3.2.4 Effect of soils on ground and surface water quality

Prior to the construction of the raised levee most of the Fullerton Cove study area would have been prone to various degrees of tidal flooding. This no longer occurs, but the soils and groundwater are still very salty. The highest salinity is not close to the perimeter drain and raised levee on the western edge of the study area, but further east, near sites F3 and F4 (see also EM38 results in Appendix 6). The high salinity may have neutralised some acidity here, and the water table is depleted of sulfate (relative to tidal water, see table 11). Less salt has been leached out of the F3 soil than at F1 and F2, probably because of lower permeability.

The F3 subsoil is likely to be more waterlogged, and may still be accumulating sulfides, since it contains pockets of decayed vegetation that greatly assist the reduction of sulfates.

Any new drains in the F3 area, where the depth of the AASS layer is only 0.5m, would need to be very shallow to prevent oxidation. The current low drainage density and low soil permeability seems to have prevented much drying and subsequent discharge of acid to ground or surface water.

**Table 11**: Drain and **ground water*** quality (Fullerton Cove area)

| **Site No.** | Drain water and **Groundwater** Properties (Ponded water) | | | | | | |
|---|---|---|---|---|---|---|---|
| | pH | E C (mS/cm) | chloride (mg / L) | sulfate (mg / L) | Cl / $SO_4$ ratio | Ground water depth (cm) | Sampling date |
| F1 | **3.6** | **11.0** | **4000** | **460** | **8.7** | **15** | 10/04/08 |
| F2 | **3.8** | **12.0** | **3400** | **880** | **4.3** | **35** | **10/04/08** |
| | | | | | | | |
| F3 | **6.6** | **34.0** | **14000** | **1200** | **11.7** | **10** | 10/04/08 |
| | | | | | | | |
| F4 | **7.2** | **24.0** | **8900** | **680** | **13.1** | **10** | 10/04/08 |
| F5 | 7.2<br>7.5 | 1.3<br>0.49 | 290<br>80 | 28<br>21 | 1.0<br>3.8 | -<br>- | **10/04/08** |
| Tidal Water (approx.) | 7 - 8 | 55 | 19,000 | 2,700 | 7.0 | | |

*** bold** numbers e.g. **4200** = ground water quality at site

## *3.3 Kooragang Wetland (Ash Island) – Summary of Site Inspections*

Profiles were inspected and sampled west and north of the rail line where the landscape is low and swampy, with slightly higher ground near Scott's Point. An irregular network of braided channels traverses the island, converging towards the east, heading into Kooragang Nature Reserve. Here the vegetation is mostly mangrove swamp and saltmarsh with some swamp oaks. Pasture land gradually becomes dominant to the west on the more elevated areas. To the south are large surface water bodies, some of which are tidal. Soil coring covered a range of elevations, the most elevated site being located near the north, close to the river bank (K8). The lowest was in the south (K1), where the original topsoil was close to 0m AHD and buried by 0.75m of fill. The digital elevation model for Kooragang Wetland is provided in Appendix 3, page 88).

Several previous soil tests (Cooper, 2000; PKK, 2001; Parsons Brinckerhof, 2003) had found sulfidic material at only one location (near Phoenix Flats close to profile K5). Here the top of the sulfidic layer was rather deep in the profile at an elevation of -0.8m AHD. Other previous tests failed to core deeply enough to penetrate this layer.

This was also the case at two sites examined in the current study (K6 and K7). At these two sites, the profiles had chemical and morphological features consistent with the presence of sulfidic material at depth, i.e. elevated total actual acidity (TAA) levels, high sulfate concentrations, low soil pH and jarositic mottles at one site (K7), see table 12. Sulfidic material was found at six other sites, but at a range of elevations between -0.05m and -1.4m AHD (see table 13). This suggests a range of depositional environments where sulfides have accumulated.

### 3.3.1 Soil properties and the risk to water quality

Oxidation of sulfides is often weak or negligible when the profile remains waterlogged. TAA levels stay low, and the soil pH around 6 or 7. This is the case at two sites (K1 and K3), both of which had unusual features. There was a stony hard pan layer (at depth of 0.6m AHD) with a reduced inorganic sulfur level of 0.85% at K3, but other ASS characteristics were absent.

At K1 site, adjacent to the tidal Swan Pond in the south, the soil was buried under a coal wash layer 75cm thick. The black silty clay beneath this is at the same elevation as the floor of the adjoining pond (-0.05m AHD) and has a high reduced inorganic sulfur level (2.247%).

The layer beyond the pond floor is much less sulfidic, but deep in the profile, below a depth of 2.1m (-1.4m AHD), the sulfide level rises again. Despite having two sulfidic layers, the K1 profile exhibited total actual acidity below the limit of detection at all four sampling depths in this profile. This demonstrates that the waterlogged conditions prevailing in the soil have prevented any oxidation of sulfides.

Deep drains are absent from the Kooragang study area, and many of the natural drainage depressions have silted up, or are blocked by vegetation. This is why the profiles have only a medium risk of producing acid. The TAA levels are low-moderate due to generally poor drainage conditions across the Kooragang study area.

**Table 12:** Acid Production Profile Features / ASS Indicators: Kooragang

| Site no. | Core Depth | Elevation | Top of PASS | | Notable Profile Features | Top of ASS | |
|---|---|---|---|---|---|---|---|
| | (m) | m(AHD) | Depth from surface (m) | Elevation m(AHD) | Depth from surface (m) | Depth from surface (m) | Elevation (m AHD) |
| K1 | 2.3 | 0.70 | 0.75<br>2.1 | -0.05<br>-1.4 | Coalwash fill 0.75m thick as top layer, | absent | |
| K2 | 1.6 | 1.08 | 1.5 | -0.44 | Waterlogged dark grey clay | absent | |
| K3 | 0.6 | 0.76 | 0.6* | NA | A stony hard pan was found below 60cm. *Potentially the top of the sulfidic layer. Further testing required | absent | 0.16 |
| K4 | 1.7 | 1.00 | 1.6 | -0.6 | Tubular concs. | absent | |
| K5 | 1.5 | 1.04 | 1.3 | -0.26 | Dark clayey sand below 1.1m, | absent | |
| K6 | 1.6 | 1.06 | absent | | Dark grey clay below 60cm | absent | |
| K7 | 1.7 | 1.12 | absent >1.7m | | Jarosite below 1.28 | 1.28 | -0.16 |
| K8 | 1.8 | 1.24 | 1.55 | -0.31 | Jarosite below 1.15 | 1.15 | 0.09 |

**Table 13:** Soil and Water chemical properties important for Acid Production: Kooragang

| Site No. | Elevation (m) | Soil Parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Max TAA (moles H+/t) | % of Profile top 1m with TAA >100 moles H+/t # | %Profile top 1m with TAA 50-100 moles H+/t # | Minimum profile soil pH | % of profile top 1m with a pH≤4 | Ground-water pH (surface ponds) | Max % exch Al value in profile | Max. Sulfide % value in profile | Thickness of Jarosite layer (cm) |
| **High Risk Areas** | | | | | | | | | | |
| | | | | | | | | | | |
| **Medium Risk Areas** | | | | | | | | | | |
| K1 | 0.7 | <5 | 0 | 0 | 7.5 | 0 | 7.2 | <1 | 2.247 | absent |
| K2 | 1.08 | 110 | 20 | 80 | 4.2 | 0 | NT | 8.2 | 0.93 | absent |
| K3 | 0.76 | <5 | 0 | 0 | 7.0 | 0 | 7.2 | <1 | 0.85 | absent |
| K4 | 1.00 | 72 | 0 | 20 | 4.6 | 0 | 5.9 | 1.0 | 2.372 | absent |
| K5 | 1.04 | 110 | 15 | 25 | 4.0 | 0 | 5.3 | 1.2 | 0.441 | absent |
| K6 | 1.06 | 95 | 0 | 20 | 4.5 | 0 | 5.1 | 11.0 | 0.043 | absent |
| K7 | 1.12 | 110 | 25 | 15 | 4.1 | 0 | 5.7 | 17.4 | 0.04 | 12 |
| K8 | 1.24 | 49 | 0 | 0 | 4.1 | 0 | 3.9 | 22.4 | 0.818 | 10 |
| **Low Risk Areas** | | | | | | | | | | |
| | | | | | | | | | | |

# Centimetres of soil in the top 1 metre of the profile that is accounted for by a soil material that had a test result for TAA that was greater than the stated value (moles of H+/ tonne of soil).

### 3.3.2 Surface sulfide concentrations and stored acidity

Total actual acidity (TAA) peaked at 110 moles H+/tonne at three sites (K2, K5 and K7), showing that some drying and oxidation has been occurring in parts of the study area. All these peaks are in the upper profile, well above the sulfidic layer deep in the subsoil (see table 14). Levels of reduced inorganic sulfur in the upper profiles show a slight surface accumulation, similar to that seen at the K1 topsoil (originally the pond floor), but on a much smaller scale. This suggests that these soils are waterlogged at the surface long enough for sulfates to be reduced to sulfides, but when they dry out oxidising conditions return and raise the acidity in the topsoil. This process can affect surface water quality potentially much more than acidity produced deep in the subsoil. None of the Kooragang profiles tested had a peak in acidity just above their sulfidic layer, suggesting that this layer is too deep and the conditions too wet for it to dry out and produce much acid.

**Table 14:** The TAA distribution within soil profiles from the Kooragang area (Indicators of Acid Storage).

| **Site No.** | **Depth below the soil surface (cm)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **0 - 20** | **20 - 40** | **40 - 60** | **60 - 80** | **80 - 100** | **100 - 120** | **120 - 140** | **140 - 160** | **> 160** |
| K1 | - | - | - | <5s | <5 | - | - | <5 | <5s |
| K2 | - | **110** | 75 | - | - | 49 | 18 | 18s | - |
| K3 | <5 | <5 | <5 | - | - | - | - | - | - |
| K4 | <5 | **72** | 21 | - | 20 | - | - | - | 25s |
| K5 | 23 | **110** | 63 | 9.7 | - | - | 8.7s | - | - |
| K6 | 28 | **95** | 33 | 19 | - | - | - | 8.6 | - |
| K7 | 15 | - | **110** | 84 | 28 | - | 25 | - | 9.7 |
| K8 | 25 | - | **49** | - | 22 | 39 | - | - | 26s |

Bold numbers e.g. **110** = maximum TAA value (moles H+ / tonne) in profile.
(<5) = pH>7 and sample not tested for TAA. S = sulfidic materials present.

### 3.3.3 Salinity and stored acidity

The water table at Kooragang can be very saline, approaching sea water in some cases (see table 15). While sea water can neutralise soil acidity to some extent, the data reveal that the water table is depleted of sulfate, suggesting that reducing conditions are dominant. Sulfide formation consumes acid, and this process may be responsible for lowering the acidity of Kooragang profiles (certainly K1, and possibly K3, K4 and K8).

### 3.3.4 Effect of soils on ground and surface water quality

The Kooragang ground water, and also the samples of pond water, are remarkable in having a generally high ratio of chloride to sulfate. Only one water sample (at K7) was found with a ratio of below 7, a result indicating sulfate enrichment. Significantly this sample was also the least saline. In a low salinity environment, sulfates produced by oxidation of sulfides in the soil more readily influence the salt concentration than in soils with high background salt concentrations. The deep subsoil at K7 is salty, rich in sulfate and a very low content of reduced inorganic sulfur (i.e. non-sulfidic). Perhaps it was once slightly sulfidic, but is now oxidised (enough to produce jarosite) and the acid produced has nearly all been neutralised.

All other sites had more saline water tables. The K1 profile shows no signs of being oxidised, with ground water having a pH of 7.2 and a chloride/sulfate ratio of 22.9. This water table is severely depleted of sulfate compared to sea water (see table 15), indicating that sulfates are being removed, and probably being reduced as sulfides.

**Table 15:** Drain and **ground water*** quality: Kooragang area

| **Site No.** | Drain water and **Groundwater** Properties (Ponded water) | | | | | | |
|---|---|---|---|---|---|---|---|
| | pH | E C (mS/cm) | chloride (mg / L) | sulfate (mg / L) | Cl / $SO_4$ ratio | Ground water depth (cm) | Sampling date |
| K1 | **7.2** | **32.0** | **11000** | **480** | **22.9** | **45** | 7/04/08 |
| K1 pond | (9.1) | (14.0) | (7800) | (500) | (15.6) | - | 7/04/08 |
| K3 | **7.2**<br>(7.3) | **45.0**<br>(12.0) | **20000**<br>(7400) | **1500**<br>(290) | **13.3**<br>(25.5) | **50** | 8/04/08 |
| K4 | **5.9** | **30.0** | **15000** | **800** | **18.75** | **75** | 8/04/08 |
| K5 | **5.3** | **18.0** | **6900** | **770** | **9.0** | **30** | 8/04/08 |
| K6 | **5.1** | **6.7** | **2700** | **380** | **7.1** | **10** | 8/04/08 |
| K7 | **5.7** | **3.7** | **1700** | **640** | **2.7** | **85** | **9/04/08** |
| K8 | **3.9** | **5.0** | **3200** | **150** | **21.3** | **70** | **9/04/08** |
| Tidal Water (approx.) | 7 - 8 | 55 | 19,000 | 2,700 | 7.0 | | |

*** bold** numbers e.g. **4200** = ground water quality at site

Figure 38: Retrieving a soil core from Kooragang K8 site (Photo: J Fredrickson)

## *3.4 Hexham Swamp and Shortland Wetlands – Summary of Site Inspections*

Hilly terrain surrounds Hexham Swamp on three sides, feeding large volumes of surface runoff into the swamp. Impeded by the natural levee along the river, water banks up for weeks or months after prolonged wet weather, before draining away slowly though Fishery and Ironbark Creeks to the south and some smaller channels further north.

Cut-off from fresh additions of alluvial sediment coming down the river, parts of the swamp are still very low (below 0m AHD), see digital elevation model provided in Appendix 3, page 89 and 90. This means that waterlogged conditions can persist in the soil for months and that large areas are still saline, due to tidal action in the past. High tides no longer affect such areas, restricted by two sets of floodgates and natural drainage channels that have silted up.

Shortland Wetland lies to the south of Ironbark Creek, partly on rising ground, but mostly in small valleys and drainage lines with freshwater ponds that feed Hexham Swamp.

Profiles were inspected in April and early May, when areas of Hexham Swamp were under water. Sampling was largely restricted to areas accessible to the truck-mounted corer. There were no inspections north and west of the abandoned rail line because water there was too deep. Some profiles beneath shallow ponds were sampled (at S2, H2, H3 and H5).

There has been a history of testing for acid sulfate soils in Hexham Swamp and Shortland Wetlands (e.g. Carr, 1998 and Coffey, 2002). Sulfidic material was identified however at only a small proportion of sites, with results indicating that, “in general the soils around Ironbark Creek were neither actual nor potential acid sulfate soils” (WBM Oceanics, 2002).

This study detected sulfidic soil material at three sites (H1, H2 and S2), all located in the areas close to Ironbark and Fishery Creeks (see table 16). No sulfidic material was found at the other four sites; at S1 the soil was a typical lower slope profile material with no estuarine material, but at the other three sites it is possible that a sulfidic layer is present beyond the sampling depth. This may also be the case at some of the previous inspection sites. If so, the sulfidic layer is likely to be waterlogged and there is consequently a low risk of acid production.

### 3.4.1 Soil properties and the risk to water quality

The risk to water quality is greatest if the sulfidic layer is elevated and prone to more frequent drying. Coring penetrated below 0m AHD at all sites, and the top of the sulfidic layer ranged in elevation between -0.05m and -0.07m AHD. Due to the uneven distribution of the sulfidic layer across the study area, there is not sufficient evidence to rule out the presence of a PASS layer at lower elevations.

Shelly material was seen in the north of the site in excavated spoil (near the coal wash heap), even though previous studies did not detect any sulfidic layer. This irregular distribution pattern is probably related to topographic features of an older landscape, now buried by younger alluvial and estuarine sediments.

There is evidence that some profiles have been oxidised. Jarosite was observed at one site (H2) 60cm below the surface. This site also has high aluminium readings near the soil surface. Elevated TAA levels were observed in the reed bed swamp at Shortland Wetlands (S2) in a zone just above the sulfidic layer. These areas have the potential to generate acid and have been ranked high in table 17.

Low lying areas prone to waterlogging or tidal inundation have a much lower risk of generating acidity by oxidation of sulfides in the subsoil. On the other hand if they contain enough sulfate in the topsoil, some of this will be reduced to sulfide when the profile goes under water. A moderate risk of acidity is present at the H1 site, where vegetation has turned black and rotten by prolonged ponding. This favours reduction and sulfide formation, which can then oxidise once the soil dries out.

### 3.4.2 Surface sulfide concentrations and stored acidity

Stored acidity levels peak at the surface 10cm of four of the seven profiles tested in Hexham and Shortland. This zone is more likely to be the main source of acid leachate rather than the subsoil sulfidic layer, where evidence of oxidation is patchy. Ponding and waterlogging are frequent occurrences across much of Hexham, conditions which favour sulfide accumulation on the surface. At the H1 site, the groundwater had a greatly depleted sulfate level (i.e. high chloride: sulfate ratio, see table 19) suggesting that some sulfate was being reduced to sulfide. In the H1 soils profile, the chloride concentration is up to 18 times higher than the sulfate content (compared with sea water where chloride is seven times higher). When the H1 profile dries out the sulfides will oxidise, generating some of the acid that has corroded the nearby concrete bridge abutment (see figure 16). Acid discharging elsewhere in the catchment has also contributed.

### 3.4.3 Salinity and stored acidity

Soil salinity varies across the profiles tested. Several factors can be affecting the salt level, including tidal flooding in the past and movements of a brackish water table in the subsoil. The Ironbark Creek floodgates have prevented tidal action in recent years, and this has probably raised acidity levels by reducing the frequency of neutralisation and flushing of acid out of the swamp. Soil chemical properties indicate that the level of stored acidity is generally moderate, so that the improvement in drainage has not been as effective as in other locations, i.e. the soils are generally still too wet to produce much acid. Large areas however, have not been sampled, particularly in the western part of the swamp. The soils here may well be producing a large portion of the acid that has attacked the concrete in the Fishery Creek bridge.

### 3.4.4 Effect of soils on ground and surface water quality

The salinity and acidity of water across the Hexham and Shortland areas is influenced to varying degrees by soil properties, especially in dry weather. In wet weather, however, very large volumes of stormwater are delivered to the swamp from expanding areas of subdivision. This can overwhelm the influence of the soil profiles in the swamp on water quality. The higher areas may be less influenced, because the stormwater does not linger, unlike the lower parts of the swamp. Areas around the margin of the swamp may have a more elevated sulfidic layer (e.g. site S2), and here the soil profile will affect water quality to a greater extent than the soils closer to the centre of the swamp.

The most acidic groundwater was found at Shortland site S2, and it was enriched with sulfate, relative to sea water (see table 19). On the other hand, at sites where the PASS layer is less than half a metre lower, groundwater and surface water is not acidic.

At the three Hexham sites where the sulfidic layer was not found (H3, H4 and H5), the ground and surface water was mildly acidic to neutral. Salinity was variable and possibly related to more recent rain prior to sampling. Soil salinity may have been elevated by previous tidal inundation, now prevented by the floodgates which exclude the majority of tidal flows from Ironbark and Fishery Creeks.

One remarkable effect on water quality is the effect by the soil on sulfate depletion. At the H1 site both groundwater and water in the nearby drain have depleted sulfate content (the chloride: sulfate ratio is three times higher than in sea water). This is likely to be a result of active iron sulfide formation, due to waterlogging and reducing conditions within the soil profile. This is the reverse of the process of oxidation of sulfides, seen in the high sulfate water at the nearby S2 site.

Figure 39: Soil core sampling at Hexham site H1 (photo J Fredrickson)

**Table 16**: Acid Production Profile Features / **ASS Indicators**: Hexham & Shortland

| Site no. | Core Depth | Elevation | Top of PASS | | Notable Profile Features | Top of ASS | |
|---|---|---|---|---|---|---|---|
| | (m) | m(AHD) | Depth from surface (m) | Elevation m(AHD) | Depth from surface (m) | Depth from surface (m) | Elevation (m AHD) |
| **H1** | **1.2** | **-0.10** | **0.60** | **-0.70** | **waterlogged grey clay below 0.45m** | **absent** | **absent** |
| **H2** | **1.35** | **0.62** | **0.85** | **-0.23** | **Jarositic 0.60-0.95m** | **0.60** | **0.02** |
| H3 | 1.05 | 0.26 | absent | | | absent | |
| H4 | 1.0 | 0.80 | absent | | | absent | |
| H5 | 0.75 | 0.52 | absent | | | absent | |
| | | | | | | | |
| **S2** | **1.5** | **1.00*** | **1.05** | **-0.05*** | **waterlogged grey clay with decayed veg'n 0.75-1.5m** | **absent** | **absent** |
| S1 | 1.7 | 2.44 | absent | | Dense mottled clay subsoil (Pleistocene?) | absent | |

* Estimate only given recent road works.

Note: **Bold** indicates ASS indicators

**Table 17**: Soil and Water chemical properties important for Acid Production (Hexham & Shortland)

| Site No. | Elevation (m) | Soil Parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Max TAA (moles H+/t) | % of Profile top 1m with TAA >100 moles H+/t # | %Profile top 1m with TAA 50-100 moles H+/t # | Minimum profile soil pH | % of profile top 1m with a pH≤4 | Ground-water pH (surface ponds) | Max % exch Al value in profile | Max. CRS % value in profile | Thickness of Jarosite layer (cm) |
| **High Risk Areas** | | | | | | | | | | |
| H2 | 0.62 | 120 | 35 | 65 | 3.7 | 90 | (6.6) | 26.5 | 0.984 | 35 |
| S2 | 1.00 | 84 | 0 | 40 | 4.2 | 0 | 4.7 | 12.8 | 2.437 | absent |
| **Medium Risk Areas** | | | | | | | | | | |
| H1 | -0.10 | 23 | 0 | 0 | 5.6 | 0 | 6.1 | <1 | 1.736 | absent |
| **Low Risk Areas** | | | | | | | | | | |
| H3 | 0.26 | 55 | 0 | 20 | 4.1 | 0 | (6.8) | 10.6 | 0.024 | absent |
| H4 | 0.80 | 74 | 0 | 40 | 4.4 | 0 | 7.5 | 6.4 | 0.007 | absent |
| H5 | 0.52 | 21 | 0 | 0 | 5.4 | 0 | 6.6 | <1 | 0.015 | absent |
| S1 | 2.44 | NT | NT | NT | NT | NT | absent | NT | NT | absent |

\# Centimetres of soil in the top 1 metre of the profile that is accounted for by a soil material that had a test result for TAA that was greater than the stated value (moles of H+/ tonne of soil).

**Table 18**: The TAA distribution within soil profiles from the Hexham and Shortland wetland areas (Indicators of Acid Storage)

| **Site No.** | **Depth below the soil surface (cm)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **0 - 20** | **20 - 40** | **40 - 60** | **60 - 80** | **80 - 100** | **100 - 120** | **120 - 140** | **140 - 160** | **> 160** |
| H2 | **120** | **-** | 71 | 63 | 63s | - | 11s | - | - |
| S2 | - | - | 28 | - | 57 | **84** | - | 9.9s | - |
| H1 | **23** | 21 | **23** | - | <5s | - | - | - | - |
| H3 | **55** | - | 11 | - | | | | | |
| H4 | 45 | **74** | 58 | - | 8 | | | | |
| H5 | **21** | 17 | 13 | - | - | - | - | - | - |

Bold numbers e.g. **170** = maximum TAA value (moles H+ / tonne) in profile.
(<5) = pH>7 and sample not tested for TAA. S = sulfidic materials present.

**Table 19:** Drain and **ground water*** quality (Hexham and Shortland Wetland Areas)

| Site No. | Drain water and **Groundwater Properties** (Ponded water) | | | | | | |
|---|---|---|---|---|---|---|---|
| | pH | E C (mS/cm) | chloride (mg / L) | sulfate (mg / L) | Cl / SO$_4$ ratio | Ground water depth (cm) | Sampling date |
| H2 | (6.6) | (1.1) | (190) | (17) | (11.2) | **-** | 1/5/08 |
| S2 | **4.7** | **4.1** | **1400** | **640** | **1.8** | **40** | **9/04/08** |
| H1 | **6.1**<br>6.7<br>6.1 | **10.0**<br>4.4<br>1.5 | **4200**<br>1700<br>430 | **160**<br>76<br>56 | **26.3**<br>22.3<br>7.7 | **30** | 11/04/08 |
| H3 | (6.8) | (1.2) | (330) | (36) | (9.2) | **-** | 1/05/08 |
| H4 | **5.0**<br>7.5 | **15.0**<br>2.4 | **4500**<br>610 | **1400**<br>84 | **3.2**<br>7.3 | **30** | **1/05/08** |
| H5 | (6.6) | (0.73) | (130) | (47) | (2.8) | | 1/05/08 |
| Tidal Water (approx.) | 7 - 8 | 55 | 19,000 | 2,700 | 7.0 | | |

*** bold** numbers e.g. **4200** = ground water quality at site