Coastal acid sulfate soil processes in Barker Inlet, South Australia

Doctor of Philosophy

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School of Earth and Environmental Sciences

Brett P. Thomas

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C h a p t e r S e v e n

7. Mapping

Hazard mapping of acid sulfate soil is important because it provides a method for land managers to predict the impact that land-use changes and land development may have on soils, the environment and built infrastructure. The hazard maps can assist in the planning and implementation of long-term management strategies for coastal land use in relation to both environmental and developmental purposes (Dear *et al.* 2002; Stone *et al.* 1998; Tulau 1999).

The inherent hazards posed by acid sulfate soil materials are related to:

(i)   the thickness and "potency" of layers containing sulfuric, hypersulfidic, hyposulfidic and monosulfidic materials,

(ii)   soil texture; as coarser soil material generally provides less buffering capacity (due to lower clay contents) and increased porosity, which allows for rapid oxidation of pyrite and transport of oxidation products,

(iii) depth from surface to acid sulfate soil materials; as near surface soil materials are easily disturbed, and

(iv)   proximity of acid sulfate soil materials to surface water bodies and other environmental receptors (Ahern *et al.* 1998).

In this chapter, soil-landscape maps are produced for the St Kilda and Gillman study sites. The map units are correlated to acid sulfate soil characteristics that were described in Chapters 5 and 6.

As well, a range of geophysical mapping techniques have been used to:

(i)   better refine acid sulfate soil map unit boundaries,

(ii)   understand associations between map units and physio-chemical soil conditions (e.g. soil texture, EC, and mineralogy), and

(iii) provide new tools for more rapid acid sulfate soil mapping.

7.1. Soil-landscape maps

The soil-landscape maps that were drafted for focus areas in the Gillman and St Kilda study sites were used to extrapolate to the whole of the Gillman and St Kilda study areas by incorporating the following data sets: topography, geomorphology, vegetation, drainage, dynamics of water status (e.g. seasonal ponding and tidal influences), anthropogenic influences (e.g. constructed soil mounds and wetlands) and additional field verification across map unit boundaries. At Gillman, a geophysical survey was also conducted over Focus area A using EM38 and magnetic susceptibility and the results were used to refine map unit boundaries (refer to Section 7.7).

The map unit polygon boundaries were delineated on georectified, 1:7500 scale aerial photography using ArcGIS 9.1. This meant that map units have quantifiable areas. The soil-landscape map for the St Kilda study site is displayed in Figure 7-1. The soil-landscape map for the Gillman study site is displayed in Figure 7-2.

This information was then used to produce an acid sulfate soil map of the whole Barker Inlet (Figure 12-2) using the legend of the Atlas of Australian acid sulfate soils (Fitzpatrick *et al.* 2008a).
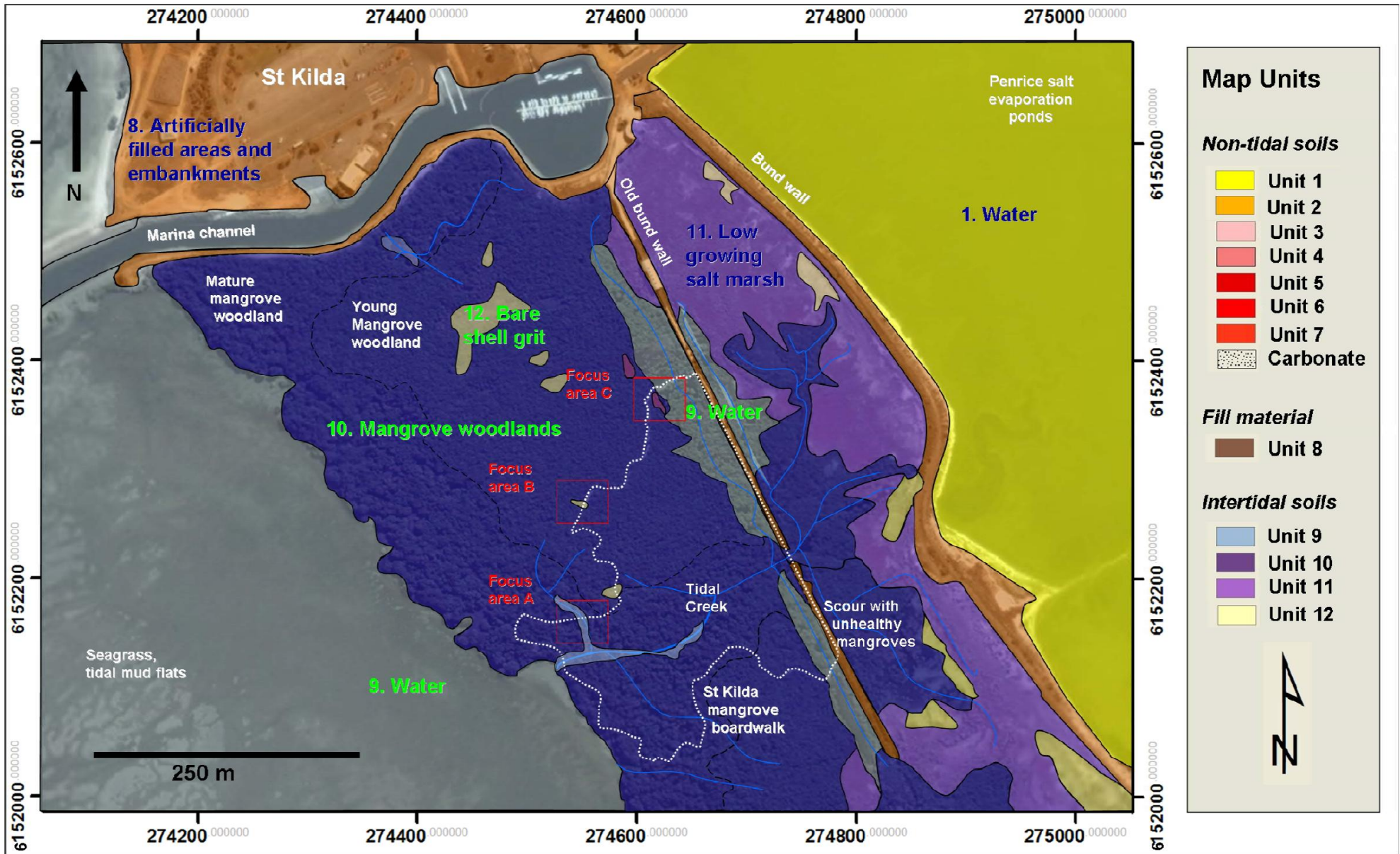
Figure 7-1 Soil-landscape map for the St Kilda study site. Refer to Table 7-6 for a detailed map legend and descriptions of Map units.
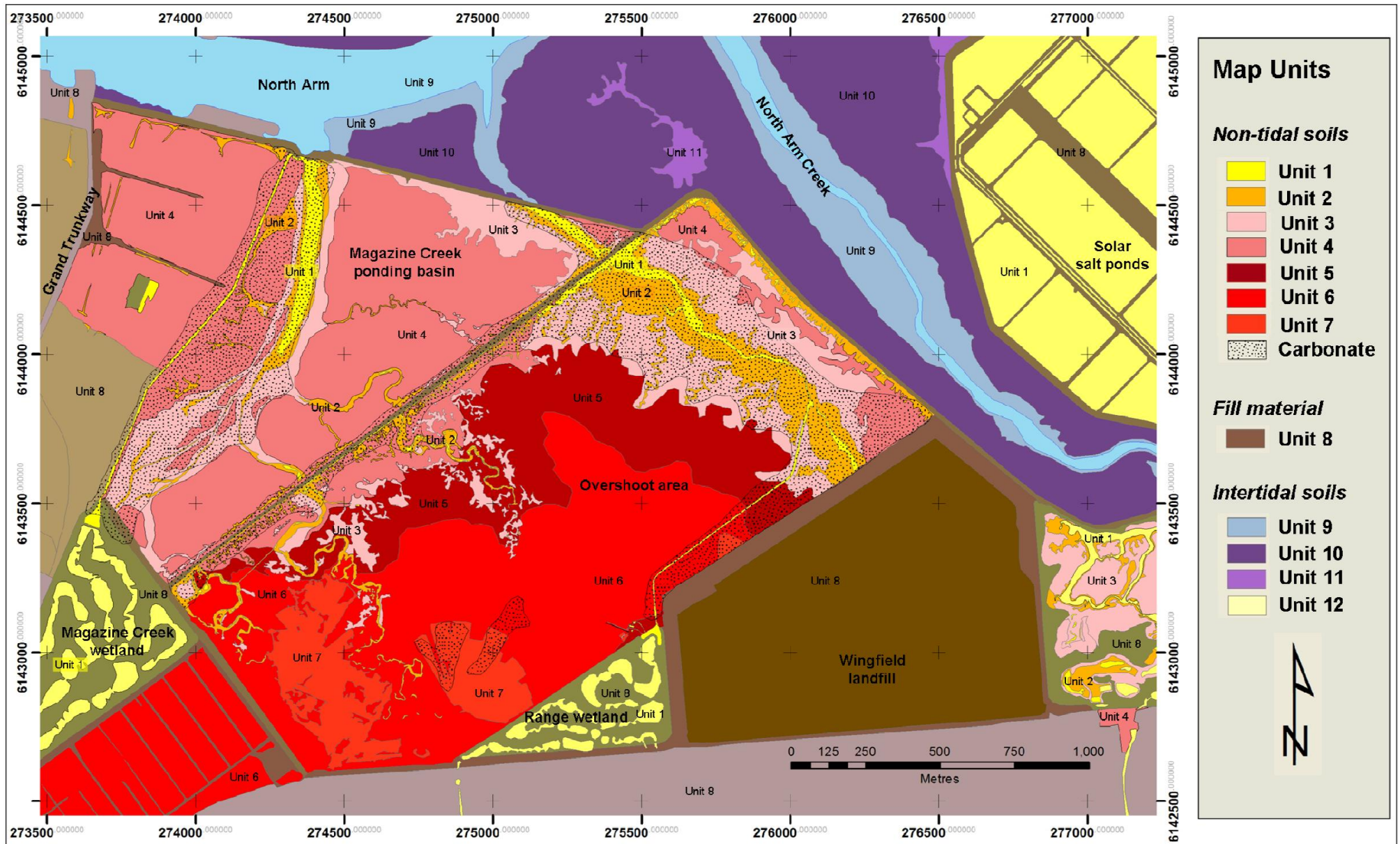
Figure 7-2 Soil-landscape map for the Gillman study site. Refer to Table 7-6 for a detailed map legend and descriptions of Map units. The Dean Rifle Range was located at coordinates E 73500, N 6142500 (at the bottom left corner of the map).

7.2. Acid sulfate soil hazards

The nature, type and distribution of acid sulfate soil materials within landscapes (coastal or inland) pose potential hazards to surrounding ecosystems, infrastructure and amenities. The various acid sulfate soil types mapped have the potential to present a number of hazards, specifically through:

i) **Acidification** (of soil, groundwater and surface waters),

ii) **Metal mobilisation** (from soil material to groundwater and surface water), and

iii) **Deoxygenation** of surface waters.

The hydrogeochemical processes that are responsible for these hazards are inherently linked in that both acidification and deoxygenation are likely to cause the mobilisation of metals. These hazards may present a **'current'** risk to environmental receptors - where the hazard has been measured or observed, **or** may present a **'potential'** hazard to environmental receptors - where laboratory analyses of soil properties indicates that a hazard is likely to eventuate if environmental conditions are changed (refer to Table 7-1).

Table 7-1 General relationships between acid sulfate soil material and hazard types. Condition of the hazard is also depicted.

Acid sulfate soil material	Hazard type and condition		
	Acidification	Metal Mobilisation	Deoxygenation
Sulfuric	current	current	negligible
Hypersulfidic	potential	potential	negligible
Hyposulfidic	potential (low)	potential	negligible
Monosulfidic	potential	potential	potential
Non acid sulfate soil materials	negligible	negligible	negligible

In this study acidification hazards are quantified according to the amount of lime required to neutralise the components of net acidity, following acid base accounting (ABA) analyses in accordance with methods outlined by Ahern *et al.* (2004). This method enables the range of acid sulfate soil materials to be ranked according to treatment categories (refer to Table 7-2). Texture-based action criteria for acid sulfate soil management planning has been developed by Ahern *et al.* (1998) and require that if a development project is to disturb < 1000 t of acid sulfate soil material with a net

acidity of 18.7 mol H^+/t for coarse texture soil (sand to loamy sand), 37.4 mol H^+/t for medium texture soil (sandy loam to light clay and 64.8 mol H^+/t for fine textured soils (medium heavy clay to silty clay). For disturbances greater > 1000 t the action criteria is set at 18.7 mol H^+/t for all texture classes. For disturbances, greater than 1000 m^3, the highest net acidity detected at the site should be used to calculate the amount of neutralising material required. When the volume of soil to be disturbed is less than 1000 m^3, the mean net acidity plus the standard deviation may be used to calculate the amount of neutralising material required, provided a sufficient number of laboratory analyses have been performed to satisfactorily characterise the soil profile and acid sulfate soil materials at the site (Ahern *et al.* 1998). Net acidity provides a measure of the degree of the acidification hazard. To better understand the hazards posed by acidification, the components of net acidity (existing acidity, potential sulfidic acidity and ANC) should be considered in order to provide a temporal element to the acidification hazard. In this study the treatment categories defined by Ahern *et al.* (1998) have been used but with the addition of one lower category (N) and two higher categories (XXH and XXXH) (Table 7-2).

Table 7-2 Acidification hazard characterisation (after Ahern *et al.* 1998)

NOTE:
This table is included on page 155 of the print copy of the thesis held in the University of Adelaide Library.

The AVS content of monosulfidic materials provides an indication of the deoxygenation hazard. The contamination characteristics of the acid sulfate soil materials, and of the surrounding environment, provides an indication of the metal mobilisation hazard. The spatial variability of these components is discussed for the Gillman and St Kilda study sites in the following sections.

7.3.   Spatial distribution of acid sulfate soil materials in tidal areas

To evaluate acid sulfate soil hazards in tidal landscapes it is important to understand the factors controlling the concentrations and spatial variability of potential acidity and neutralising materials (i.e. components of acid base accounting) and monosulfides (Table 7-1). Mapping the spatial distribution of acid sulfate soil materials with respect to surface-landscape features at the St Kilda study site (Figure 7-1) and the Gillman study site (Figure 7-2) therefore enabled these assessments to be made.

There are four map units representing intertidal soils at St Kilda and Gillman. The map units reflect surface elevation, strength of tidal flushing and geomorphology and are therefore distributed from the lowest position in the landscape to the most elevated position.

Map unit 9 (water) covers the lowest areas at St Kilda and Gillman and represents subtidal mud flats, lagoons, drains and tidal creek depressions with a permanent cover of water. Map unit 9 represents subaqueous soils (e.g. Erich *et al.* 2010) where the water is not greater than 2.5 m deep (Fitzpatrick *et al.* 2006). These areas are dominated by hyposulfidic material and often contain monosulfides at the soil/water interface. Hypersulfidic material also occurred within these areas but are limited in extent and net acidity content due to the high carbonate content. Monosulfidic material was most abundant in tidal creeks that were subject to minimal tidal flushing.

Map unit 10 (mangrove woodlands) occurs at slightly more elevated position in the landscape and generally contain higher contents of organic matter than the subaqueous soils, due to the thick vegetation cover. This map unit constitutes a large portion of the St Kilda and Gillman study sites and contains both hypersulfidic and hyposulfidic materials (Figure 7-3). Monosulfidic materials have a minor occurrence and are of low concentration. At St Kilda, the organic rich soils of map unit 10 are thickest (up to 2 m) on the seaward (western) side of the mangrove forest and along tidal creek depressions, where large, mature mangrove trees dominate (Figure 7-1).

Map unit 11 (low growing salt marsh plants) occurs in relatively elevated areas of the intertidal zone at St Kilda and Gillman. It generally occurs on the landward side of the mangrove woodlands at St Kilda (Figure 7-1). At the Gillman study site map unit 11 represents the most elevated portion of intertidal land which is surrounded by mangrove woodland (Figure 7-2). Map unit 11 contains both hypersulfidic and hyposulfidic materials. Soil profiles from within this map unit at the St Kilda study site generally contain a thin (up to 50 cm thick) organic matter rich layer of hypersulfidic materials that overlay carbonate rich, shell based hyposulfidic materials. At Gillman the organic matter rich layers may be up to 1.5 m thick and contain a mixture of hyposulfidic and hypersulfidic materials. Carbonate rich, shell based layers (hyposulfidic materials) also occur at depth at Gillman.

Map unit 12 (bare chenier ridge) is a shell based chenier ridgeline that forms the most prominent geomorphic landform at St Kilda (Figure 7-1). The chenier is composed of a thick shell-grit layer containing hyposulfidic material that underlay most of the St Kilda study site. Hyposulfidic material dominates soil profiles within 50 m of map unit 12 due to incorporation of reworked shell fragments. Map unit 12 did not have a surface expression at the Gillman study site.

7.3.1. Acid-base characteristics of tidal soils at St Kilda study site

Due to frequent tidal inundation, no soil profiles from map units 9, 10, 11 or 12 contained existing acidity. Potential sulfidic acidity (PSA) was measured in all soil samples collected from intertidal areas. Near surface soil layers from profile BSK 3 (map unit 12) contained the lowest PSA of 13 mol H^+/t (Table 7-3). Map unit 12 was also characterised by low mean PSA value of 39 mol H^+/t. The highest PSA of 773 mol H^+/t was measured in subaqueous soil profile BSK 8 (from map unit 9) (Table 7-3). Soil profiles from map units 10 and 11 at St Kilda had similar PSA contents, with mean values measuring 228 mol H^+/t (n=9) and 246 mol H^+/t (n=3), respectively. At the St Kilda study site, map unit 9 had the highest mean PSA value of 346 mol H^+/t (n=6). The highest PSA contents at St Kilda correspond to subaqueous soils in low energy environments containing highly decomposed organic matter (sapric material).

At St Kilda the mean PSA values for the all map units measured above the action criteria for medium textured soils (i.e. 37.4 mol H^+/t). However, the net acidity values for most soil samples were low or negative. Samples with negative net acidity values contained considerable ANC and were consistent with results from soil incubation experiments (i.e. $pH_{Incubation}$), classifying them as hyposulfidic material (Figure 7-3). The high ANC content of some soils at St Kilda is due to the dominant geomorphologic feature being a prominent, north trending chenier (shell-grit) ridge line. The ridge line has a mid point at profile BSK 3 (map unit 12in Focus area B and forms a protective barrier to wave action for soils developing on the landward side (i.e. in Focus area C). The net acidity of hypersulfidic material ranged from 42 mol H^+/t in profile BSK 8 (map unit 9) to 660 mol H^+/t in profile BSK 6 (map unit 11). Hypersulfidic material was common in this lower energy, back barrier environment and was the dominant acid sulfate soil material in profiles BSK 6 and 7 (Figure 7-3). This may be due to less reworked carbonate being incorporated into the soil layers during sedimentation, resulting in lower acid neutralising capacities. The limited tidal exchange in Focus area C may help to concentrate S and Fe and contribute to higher iron sulfide contents in the soils. Longer periods of exposure between tides may allow partial oxidation of pyrite and subsequent removal of carbonate from the upper portion of elevated profiles.

On the coastal side of the chenier ridgeline, a thickening wedge of organic rich soils has formed under mangrove vegetation (map unit 10). These soils were more exposed to tidal forces and wave action and predominantly contained hyposulfidic material, with only a few subsoil layers in profile BSK 4 containing hypersulfidic material (Figure 7-3). Relatively low concentrations of monosulfidic material were measured in subaqueous soil profiles BSK 5 (on the seaward fringe of the mangrove woodland) and BSK 8 (located on the landward side of the chenier ridge). AVS contents were higher (maximum of 0.18%) in profile BSK 8 than in BSK 5 (maximum value of 0.02%), which may be attributed to more stable physico-chemical conditions of the lower energy environment at profile BSK 8.
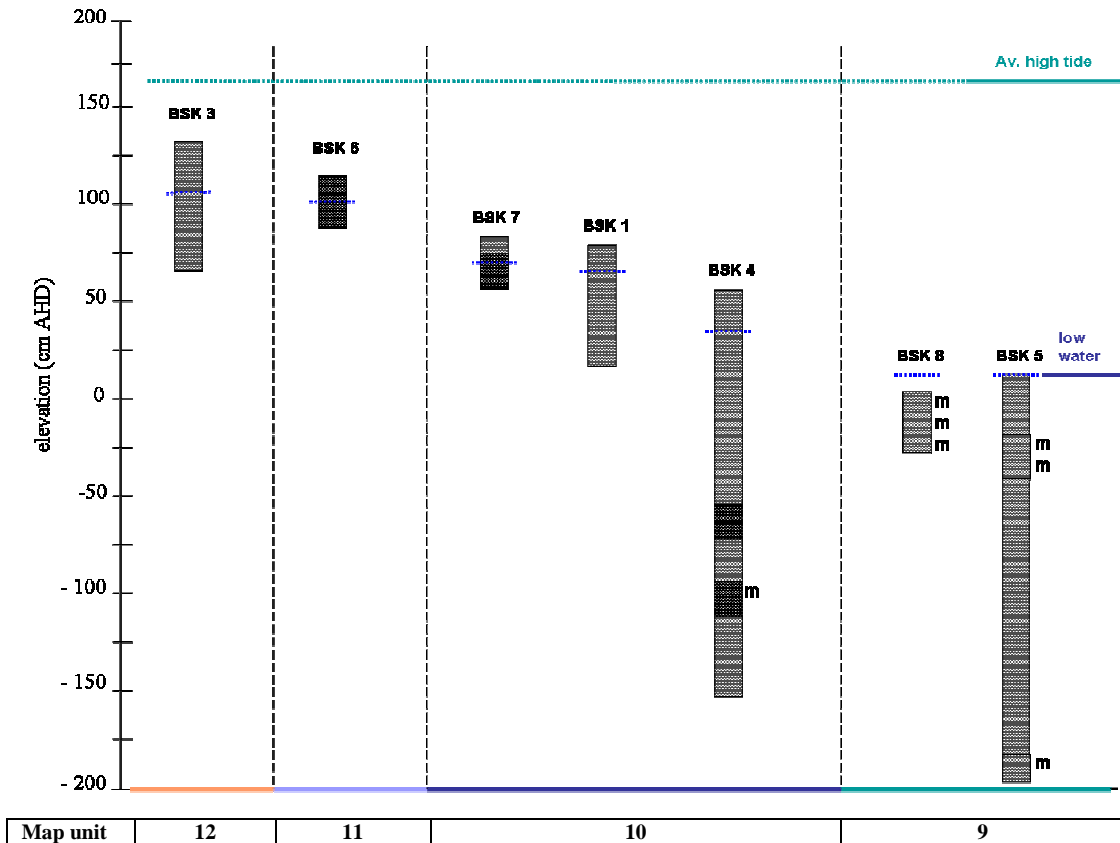
Figure 7-3 Descriptive soil-regolith model of the St Kilda study site, which transects a range of map units from the most elevated (map unit 12) to the least elevated (map unit 9). The model shows the variation in; surface elevation and depth to (and thickness of) acid sulfate soil materials. Hyposulfidic material is represented by the light grey columns, hypersulfidic material is represented by the black columns and monosulfidic material (with AVS contents ≥0.02%) is represented by the 'm' adjacent to the columns. Tidally controlled water table fluctuations are shown by the blue coloured dotted lines on each profile.

7.3.2. Acid-base characteristics of tidal areas at Gillman study site

Three tidally influenced soil profiles (BG 20, BG 21 and BG 24) sampled mainly adjacent to the bund wall at the Gillman study site were described in Chapter 6. Frequent tidal inundation has ensured that negligible existing acidity has been produced in these soil profiles and area. The potential sulfidic acidity measured in these profiles was similar to the profiles from respective map units at the St Kilda study site. The mean PSA of samples (n=2) from profile BG 24 (map unit 9) was 380 mol H^+/t. The mean PSA of profile BG 21 (map unit 10) was 165 mol H^+/t (n=3), and profile BG 20 (map unit 11) was 191 mol H^+/t (n=3).

The net acidity values of intertidal soil samples from Gillman ranged from -1129 mol H^+/t in profile BG 24, which was the lowest value measured for map unit 9, to 420 mol H^+/t in profile BG 21 (Table 7-3). The mean net acidity values of intertidal soil profiles at Gillman were slightly lower than in soil profiles from the equivalent map units at the St Kilda study area. The mean net acidity of profile BG 20 (map unit 11) was 58, BG 24 (map unit 9) was -1175, and BG 21 (map unit 10) was 92. Although a few soil samples contained reasonably high net acidity, they classified as hyposulfidic material (Figure 7-4). This may be an artefact of the incubation technique employed. Although care was taken to maintain an optimum moisture content, some samples may have been slightly too moist, maintaining the soils in a reduced condition, due to the high organic matter content of the samples. The incubated samples also contained large shell fragments that were removed (sieved) from the samples that were analysed for ABA. In addition, large organic (mangrove and seagrass) fragments (> 2mm) that were left in the incubated samples may have contained acid buffering capacity in the form of carbonate epiphytes on organic litter. These were observed as 'scale' on some organic fragments. Carbonate epiphytes are producers of carbonate sediment in shallow cool-water marine environments (Brown 2005).

An extensive subsoil layer of shell-grit occurs at Gillman and comes very close to the surface in the northern portion of the study site. The carbonate rich layer contains substantial acid buffering capacity to the hyposulfidic soils that contain shel-grit. The shell grit was intercepted in all soil layers of profile BG 24, which had a mean ANC of -2333 mol H^+/t for the profile. The shell-grit layer has been demarcated (as map unit

'carbonate') on the Gillman soil-landscape map where it occurs within 30 cm of the surface (Figure 7-2).

The monosulfide content of intertidal profiles at Gillman had a similar distribution pattern to the St Kilda landscape, with the highest concentrations being measured (0.32% AVS) in tidal creek soils (map unit 9). Minor occurrences of monosulfide (maximum value of 0.02% AVS) were measured in profiles from map units 10 and 11.

Table 7-3 summarises the acids sulfate soil characteristics of intertidal soil profiles from St Kilda and Gillman, for each of the map units displayed in Figure 7-1 and Figure 7-2.

Table 7-3 Summary data for soil pH testing and acid sulfate soil characteristics of intertidal soil profiles from the St Kilda and Gillman study sites.

Map unit no.	Intertidal - Gillman and St Kilda												Unit	LOR
	Sulfidic materials (hypersulfidic and hyposulfidic)													
	9			10			11			12				
Parameter	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max		
pHw	6.5	7.2	7.8	5.1	6.8	7.8	6.2	7.0	7.9	7.3	7.6	7.8	pH	0.1
TAA	0	0	0	0	0	0	0	0	0	0	0	0	mol H$^+$/t	1
Retained acidity	0	0	0	0	0	0	0	0	0	0	0	0	mol H$^+$/t	1
AVS	0.00	0.05	0.32	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	%	0.01
PSA	105	352	773	20	250	660	42	219	349	13	39	69	mol H$^+$/t	1
ANC	256	1419	2368	0	995	2498	0	100	270	2478	2482	2488	mol H$^+$/t	1
Net acidity	-1229	-594	42	-1618	-413	660	-24	152	349	-1639	-1616	-1583	mol H$^+$/t	1
[1]Liming rate	-62	-30	3	-81	-21	50	-1	11	26	-82	-81	-79	kg/t soil	1
[2]no.	9	9	9	12	12	12	6	6	6	3	3	3		

[1] The theoretical lime required (kg of CaCO$_3$ per tonne of soil material) to neutralise **Net Acidity** (Ahern *et al.* 2004). A safety factor of 1.5 **has** been applied to the liming rates listed here (to the positive net acidity values only). Texture based action criteria for net acidity: 18.7 mole H$^+$/t (sands), 37.4 mole H$^+$/t (loams), 64.8 mol H$^+$/t (clays) if disturbances < 1000 tonne of soil (Ahern *et al.* 1998). Map units are assigned to treatment categories in Table 7-6.
[2] Number of samples.
LOR = limit of reporting.

7.4. Spatial distribution of acid sulfate soil materials in non-tidal areas at Gillman

The spatial variation of sulfide formation, deposition and oxidation are complex in dynamic and disturbed environments. Although the factors controlling pyrite oxidation are well documented, relating this to landscapes is not straight forward. In order to manage these landscapes effectively, it is important to understand the location and quantity of acidity and potential acidity within the landscape so that management options can be tailored to the desired outcomes.

The majority of the Gillman area contains sulfuric material that is underlain by hypersulfidic and/or hyposulfidic materials. The most prominent geomorphic landform at Gillman forms a 2-3 m AHD ridge and covers an area of about 3.5 km^2. This area is dominated by sandy soils and has been assigned to map units 5, 6 and 7 on the Gillman soil-landscape map (Figure 7-2). Sulfuric material in these sandy areas ranges from 20 cm to > 2 m thick (Figure 7-4) and the pH of soil solution is generally less than 3. Map units 5, 6 and 7 account for the majority of existing acidity at the Gillman study site. Most of this existing acidity is still contained within the soil profile due to the low hydraulic gradient of the area.

Lower in the landscape sandy soils give way to sandy peat soils (map unit 4) and salt scalded sandy clay soils (map unit 3). Sulfuric material is less extensive in these areas, primarily due to a higher water table (Figure 7-4).

Seasonally flooded areas (map unit 2) generally contain sulfidic material in the form of hypersulfidic, hyposulfidic and monosulfidic materials (Figure 7-4). Map unit 2 is mostly associated with former tidal creek depressions and drains (Figure 7-2). Where former tidal creeks have eroded into the sandy soils of map units 5, 6 and 7, map unit 2 contains hypersulfidic material that is prone to seasonal oxidation and formation of sulfuric material (e.g. profile BG 4). Hyposulfidic materials dominate map unit 2 in the northern and western portions of the Gillman study site due to the influence of the extensive shell grit layer. The 'carbonate' map unit on the soil-landscape map (Figure 7-2) indicates where the shell grit layer occurs within 30 cm of the surface.

Thick (up to 50 cm) accumulations of black monosulfidic material occur in the low lying, semi-permanently waterlogged and subaqueous soils (designated by map unit 1) (Figure 7-2). Soils in map unit 1 generally contain significant acid neutralising material and classify as hyposulfidic (Figure 7-4). During dry periods monosulfides occur in subsoil layers of profiles in map unit 2, and form in surface soil layers when these areas are flooded for extensive periods.
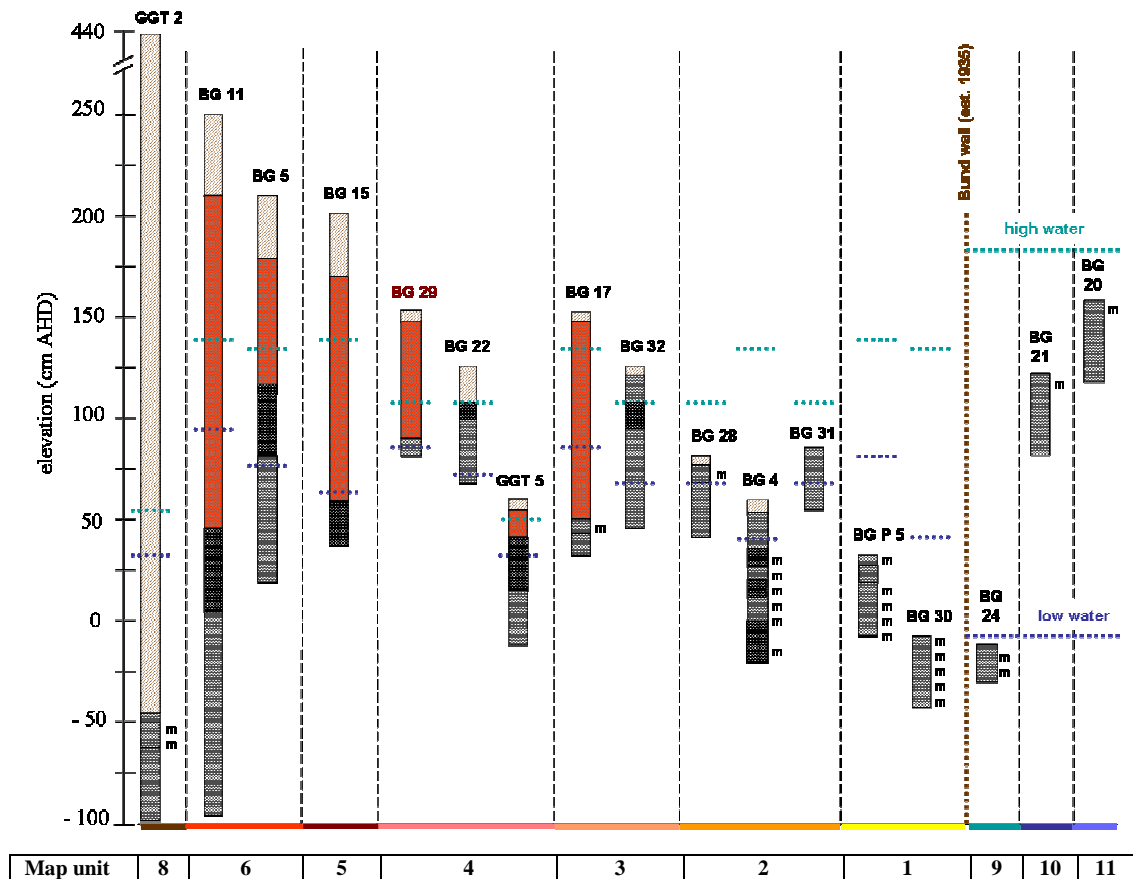

Figure 7-4 Descriptive soil-regolith model of the Gillman study site, which traverse a range of map units. The model shows the variation in surface elevation, depth to sulfuric material (red column) and sulfidic materials (light grey column represents hyposulfidic and black represents hypersulfidic materials). Monosulfidic material (with AVS contents ≥0.02%) are represented by 'm' adjacent to the column. Beige sections of columns represent non acid sulfate soil materials. Acid sulfate soil characteristics are for soils sampled during summer 2003. Water table fluctuations observed between 2002 and 2005 are shown by blue shaded dotted lines on each profile.

Groundwater heights and fluctuations within the Gillman study site were variable, and not easily correlated with micro-elevation (Figure 7-4). This is largely due to the progressive expansion of artificial drainage structures which has divided the area into multiple, separate ponding basins.

Existing acidity

In this section the severity of the *current* acidity hazard has been quantified to highlight 'hot spots', which can be addressed in management plans. To examine the spatial distribution of existing acidity across the Gillman study site soil profiles were grouped according to their map unit. An existing acidity value for each profile was calculated by summing the depth-weighted horizon values. An overall value was calculated for each map unit by averaging the profile values. This method for estimating profile acidity characteristics is similar to that used by Smith *et al.* (2003). The soil-landscape map of the Gillman site (Figure 7-2) can therefore be used to show the distribution of existing acidity within the area. In this study, however, the existing acidity values calculated for each soil profile only include soil samples that classified as sulfuric material. Non-acid sulfate soil materials and sulfidic materials were not included in the calculations so not providing a 'diluted' estimate of the current acidity hazard. Acid sulfate soil characteristics are summarised for sulfuric materials in Table 7-4. It should be noted that the oxidation (and formation) of sulfides is a continuous process in acidic sulfate soil landscapes and the measured values listed here are valid for the time of sampling. However, the general statements on spatial variability and processes will remain valid for many years, or decades, depending on major changes to the environment through future development of sites.

Profile values show a fairly consistent acid sulfate soil stratigraphy within each map unit, but there is considerable variation among the different map units (Figure 7-4). Existing acidity (TAA + retained acidity) was only detected in soil profiles located within map units 3, 4, 5, 6 and 7 (Table 7-4). Within sulfuric materials existing acidity ranged from 6 to 1637 mol H^+/t. Values generally increased with depth and peaked at a depth approximating the top of the capillary fringe (and the top of the high seasonal water table) where evapoconcentration of acidity is greatest (Figure 7-4). Below this depth existing acidity values decreased to a minimum at depth below the low water table. Elevated profiles, from map units 5 and 6, had negligible existing acidity while profiles from map units 3 and 4 contained existing acidity near or at the surface. Mining of topsoils from areas mapped as unit 7 has exposed sulfuric materials. The topsoils were used to construct the backstop mound at the Dean Rifle Range.

The top 30 to 50 cm of profiles in map unit 6 generally contained little or no existing acidity, with values less than the action criteria (18.7 mol H^+/t) for coarse textured soils. Within the acidic portion of the profiles in map units 6 and 7 retained acidity (mean 58 mol H^+/t) was generally higher than TAA (mean 21 mol H^+/t), indicating that the majority of existing acidity is contained in less soluble mineral forms. Profiles in map unit 5 contained the highest concentrations of existing acidity (mean 569 mol H^+/t), with the majority occurring as retained acidity (Table 7-4). Soils from map unit 4 generally had higher TAA (mean 95 mol H^+/t) concentrations than retained acidity (mean 11 mol H^+/t) (Table 7-4). This difference is likely due to soil textural contrasts, with low clay, peaty soils forming sulfuric material in map unit 4, which help to buffer acidity and maintain soil pH >3.5, where jarosite formation in minimal. Where map unit 3 abuts map units 5, 6 or 7 (i.e. located on or close to the sandy shoreface facies) sulfuric material was far more extensive than in lower positioned areas on map unit 3 at the northern end of the Gillman site. Shell grit layers occur close to the surface in these areas (indicated by the coverage of the 'Carbonate' map unit) and the occurrence of sulfuric material is rare (Figure 7-2).

The low levels of TAA in sulfuric material with high retained acidity may indicate that the sandy upland areas at Gillman have experienced a long period of oxidation and leaching that may pre-date bund wall construction and loss of tidal influences in 1935. Sea spray would have contributed some alkalinity to the soils since bunding. The dominance of retained acidity in these soils also has implications for selection of methods used to measure the acidity hazard. Many sulfuric samples from Gillman, mainly from map units 5 and 6, had pH_{KCl} values above 4.5 and contained high retained acidity contents, even in soils where jarosite mottles were not evident. Retained acidity would not have routinely been determined on these samples (Ahern *et al.* 2004). The retained acidity in soils with no visible jarosite mottles likely occurred as jarosite or other sulfate salts disseminated through the matrix (refer to Chapters 10 and 11). TAA constituted 90% of existing acidity in peaty soils from map unit 4 at Gillman. TAA constitutes only 25% of the existing acidity in sandy sulfuric materials from Gillman. Retained acidity is likely to be the major component of existing acidity in sandy coastal and inland acid sulfate soil landscapes where evaporation rates and sulfate salt efflorescence formation are high. Sulfuric material exists very close to the surface in salt

scalded areas (map unit 3). In dry periods, sulfuric acid and other ions such as Fe, Al, K, Na, Ca and Cl, and bicarbonate (where subsoils are alkaline) move vertically to the surface by capillary action and crystallise to form salt efflorescences (e.g. halite, jarosite, gypsum). These salts are largely dissolved during wet periods, transporting these products to lower positions in the landscape. Figure 7-5 displays profile acidity data on a schematic cross-section of Gillman landscape features, and indicates where acidity 'hotspots' occur.

Potential sulfidic acidity

Potential sulfidic acidity (PSA) values were associated to map units using the same methodology explained for existing acidity, enabling the soil-landscape map of the Gillman (Figure 7-2) to show the distribution of PSA within the study sites. In tidally influenced sites PSA occurs in hyposulfidic and hypersulfidic materials, with the latter indicating a potential acidity hazard. In former tidal areas at the Gillman study site PSA was excessive, with a maximum value of 4400 mol H+/t (7.05% S_{CR}), occurring at depth within hyposulfidic material in profile BG 4, a seasonally flooded creek depression (map unit 2). Very high monosulfides concentrations of up to 3.48% AVS occur in subsoils of profile BG 4. Subaqueous soils (map unit 1) also contain high AVS concentrations (Table 7-4).

Soils in elevated positions in the landscape had greater depths of the oxidation front. In map units 6 and 7 sulfuric material was present below 2 m of the surface. Concentrations of reduced inorganic sulfur (%S_{CR}) started to increase with depth from about 1 m of the surface in these map units. In soil profile BG 11, the highest concentrations of existing acidity coincided with the highest %S_{CR} content at 2.4 m depth, which is almost 1 m below the lowest groundwater level recorded during the study period. This suggests chemical oxidation of pyrite by Fe^{2+} is important, or that the water table has been lower in the past. A wide transition zone was also observed in soil profiles from map unit 5 where one soil layer in profile BG 15 had 6.88% S_{CR} and 1432 mol H^+/t existing acidity (Table 7-5 and Figure 7-6).

Acidity and oxidation products are mobile within these profiles, and the Gillman landscape. In profile BG 11, the movement of acidity seems predominantly to have been down to below the water table, while in profile BG 15 acidity may have also moved up through the profile to accumulate (or be stable) at a position approximating the high water table mark and capillary fringe. Figure 7-5 and Figure 7-6 show the relative positions of greatest potential acidity in profiles BG 11 and BG 15. Profile BG 17 also has very high existing acidity. The profile PSA data displayed on the schematic cross-section in Figure 7-6 indicated where potential acidity 'hotspots' occur in the Gillman landscape. The use of the Gillman area for stormwater ponding has caused former tidal creek depressions and drains to be sites of groundwater recharge during winter months and zones of groundwater discharge during summer. The proximity of profiles BG 4, BG 15 and BG 17 to these recharge sites may have lessened the amount of groundwater draw-down, and thus oxidation of pyrite, experienced by profiles in upland areas. Hyposulfidic, heavy clays of the Glanville Formation contain low concentrations of PSA (10 to 15 mol H^+/t) and occur below about 2.5-3 m depth under map units 5, 6 and 7. The majority of the northern and western portions of the Gillman site were covered by mangrove vegetation prior to land reclamation (map unit 4).

Net acidity

Significant variations in net acidity occur both vertically and laterally across the Gillman study site. The buried shell grit layer is responsible for very negative net acidity values (< -2000 mol H^+/t) at shallow depths (< 1 m) in the north and eastern portions of the non-tidal area (map units 1, 2, 3 and 4) (Figure 7-7). The majority of positive net acidity occurs in the sandy shore face facies (map units 5, 6 and 7) due to these soils containing high pyrite contents and negligible ANC (Table 7-4 and Table 7-5). Figure 7-7 displays profile acidity data on a schematic cross-section of the Gillman landscape and indicates where acidity 'hotspots' occur.

Table 7-4 Acid sulfate soil characteristics for sulfuric materials from the Gillman study site.

Map unit no.	Characteristics of sulfuric material in non-tidal area at Gillman																					Unit	LOR
	8			7 and 6			5			4			3			2			1				
Parameter	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max		
pHw				2.7	3.4	3.8	1.5	2.7	3.5	3.7	3.8	3.9	2.4	2.9	3.4							pH	0.1
TAA				6	21	68	15	168	468	27	95	164	0	38	140							mole H^+/t	1
Retained Ac.				0	58	122	18	401	1169	0	11	27	87	240	524							mole H^+/t	1
Existing Ac.				6	92	203	39	493	1432	27	106	182	87	278	556							mole H^+/t	1
AVS				0	0	0	0	0	0	0	0	0	0	0.01	0.03							%	0.01
PSA				0	38	127	5	938	4291	50	212	555	6	759	2751							mole H^+/t	1
ANC				0	0	0	0	0	0	0	0	0	0	0	0							mole H^+/t	1
Net Acidity				80	117	176	53	1507	5723	118	318	737	110	1037	2978							mole H^+/t	1
[1]Liming rate				4	6	9	3	75	286	6	16	37	6	52	149							kg/t soil	1
Sample size	0	0	0	9	9	9	6	6	6	4	4	4	6	6	6	0	0	0	0	0	0		

Table 7-5 Acid sulfate soil characteristics for sulfidic materials from the Gillman study site.

Map unit no.	Characteristics of sulfidic materials in non-tidal areas at Gillman																					Unit	LOR
	8			7 and 6			5			4			3			2			1				
Parameter	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max		
pHw	6.1	6.5	7.5	4.4	5.7	7.7	4.7	4.7	4.7	4.1	5.8	8.6	4.5	5.4	6.7	6.0	7.0	7.7	6.9	7.2	7.3	pH	0.1
TAA	0	1	3	0	16	110	34	34	34	0	9	86	0	6	16	0	0	0	0	0	0	mole H^+/t	1
Retained Ac.	0	0	0	0	12	93	110	110	110	0	0	0	0	0	0	0	0	0	0	0	0	mole H^+/t	1
Existing Ac.	0	1	3	0	41	203	144	144	144	0	9	86	0	6	16	0	0	0	0	0	0	mole H^+/t	1
AVS	0	0.02	0.08	0	0	0	0	0	0	0.00	0.00	0.01	0.00	0.00	0	0	0.80	3.48	0.08	0.50	1.14	%	0.01
PSA	16	369	808	6	128	654	518	518	518	4	36	138	13	36	144	44	1162	4400	115	403	705	mole H^+/t	1
ANC	0	643	2278	0	1	10	0	0	0	0	920	4749	0	813	4863	0	911	2256	140	1662	4675	mole H^+/t	1
Net Acidity	-1338	-60	810	8	154	175	662	662	662	-3123	-568	105	-3099	-500	37	-1335	554	3032	-2412	-705	456	mole H^+/t	1
[1]Liming rate	-67	-3	61	1	12	64	50	50	50	-156	-28	8	-155	-25	3	-67	42	228	-121	-35	34	kg/t soil	1
Sample size	5	5	5	8	8	8	1	1	1	10	10	10	6	6	6	15	15	15	6	6	6		

[1] The theoretical lime required (kg CaCO$_3$/kg material) to neutralise **Net Acidity** (Ahern *et al.* 2004). A safety factor of 1.5 has been applied to the liming rates listed here (to the positive net acidity values only). Texture based action criteria for net acidity: 18.7 mole H^+/t (sands), 37.4 mole H^+/t (loams), 64.8 mol H^+/t (clays) if disturbances < 1000 tonne of soil (Ahern *et al.* 1998). Map units are assigned to treatment categories in Table 7-6.

7.5. Hazards

This study used robust and tested acid sulfate soil assessment methodologies (e.g. peroxide testing, acid-base accounting (ABA), soil incubation/ageing and landscape characterisation to identify the acid sulfate soil hazard present at the St Kilda and Gillman study sites (Table 7-6). The acidification hazard is widespread throughout the Gillman study site and poses a direct and current hazard to groundwater and surface water quality. The main acidity hazard formed in upland areas associated with the sandy shore face facies (map unit 5, 6 and 7) due to negligible ANC in these soils. Map unit 5 represents also poses a very high potential acidity hazard. Map units 2 and 3 represent the greatest potential acidity hazard where they occur on the sandy shore face facies. Mangrove soils (map unit 10) present the greatest potential acidity hazard within tidal areas. High concentrations of monosulfidic material, indicated by map unit 1, present a high potential deoxygenation hazard to open water bodies year round. Monosulfidic material in map unit 2 presents a high deoxygenation hazard during sustained wet periods, particularly in channels where water velocities may be high.

The metal mobilisation hazard is greatest in areas that are currently acidic and where monosulfides are at risk of oxidising. It should be noted that some hyposulfidic material and some soils that did not classify as acid sulfate soils may still represent an environmental hazard to aquatic organisms by mobilisation of Al, and other metals which are released from clays at pH < 5.5. These soils are characterised by a field pH of below 5.5, or where soil pH dropped to below 5.5 after incubation.

The lime treatment categories assigned to each map unit range from 'N' (requires no treatment) to 'XXXH' (requires > 100 kg/t of pure lime) to neutralise the acidity hazard (Table 7-6). These categories were based on Ahern *et al.* (1998) and have been adopted to provide a ranking for each component of net acidity (existing acidity, PSA and net acidity) for the Gillman and St Kilda coastal landscapes.

Table 7-6 Map legend showing hazards associated with each map unit (Figure 7-1 and Figure 7-2). Acidity hazards are assigned to treatment categories (Table 7-1). Typical geomorphic relationships are described for each map unit.

Map Class Description	Map unit no.	Map unit description (cover type)	Depth to acid sulfate soil material	Acid sulfate soil materials	Hazards			*Treatment Category for acid sulfate soil materials			Typical Landform Types
					Acidity	Metal mobilisation	De-oxygenation	Existing acidity	PSA	Net acidity	
Non-tidal (disturbed)	1	Water	At the soil-water interface	Hypersulfidic, hyposulfidic materials and monosulfidic materials	Low to moderate	High	High	N	XXH	XH	**Subaqueous soils** (bottom sediment) of saline wetland lakes, lagoons, drains and non-tidal creeks.
	2	Benthic mat and bare salt scalded mud flats	At the surface	Hyposulfidic hypersulfidic and monosulfidic materials	High (summer)	High	High (winter)	N	XXXH	XXXH	**Seasonally subaqueous soils** of saline and fresh wetland lakes, lagoons, drains and creeks. Often covered by an extensive algae mat or water after periods of heavy rain and wet winters.
	3	Bare salt scalded mud flats	At the surface	Sulfuric, hyposulfidic hypersulfidic and minor monosulfidic materials	High	High	Low to moderate (winter)	XH	XXXH	XXXH	**Saline soils** fringing wetland lakes, lagoons, drains and creeks. Often covered by an extensive algae mat and salt crust. These soils indicate areas of groundwater discharge.
	4	Dense low heath - samphire shrublands	Below 10 cm of the surface	Sulfuric, hypersulfidic and hyposulfidic materials	High to moderate	High to moderate	Very low to negligible	VH	XH	XXH	**Coastal barrier and sandy foreshore,** estuarine swamps, estuarine swamps, back swamps, seagrass flats, intertidal samphire and mangrove flats, and supratidal samphire flats.
	5	Open low scrub and grasses	Below 20 cm of the surface	Sulfuric and hypersulfidic materials	Very high	Very high	Negligible	XXXH	XXXH	XXXH	**Coastal barrier and sandy foreshore** facies sand-plains covering estuarine back swamp, seagrass flats, intertidal samphire and mangrove flats, and supratidal samphire facies sediments.
	6	Open grass plain and scrub	Below 20 cm of the surface	Sulfuric, hypersulfidic and hyposulfidic materials	Very high	Very high	Negligible	VH	XH	XXH	**Coastal barrier and sandy foreshore** facies sand-plains covering estuarine back swamp, seagrass flats, intertidal samphire and mangrove flats, and supratidal samphire facies sediments.
	7	Bare, scalped, salt scalded sand flats	At the surface	Sulfuric, hyposulfidic and hypersulfidic materials	Very high	Very high	Negligible	VH	XH	XXH	**Topsoil removed from** estuarine sand-plains, back swamps, seagrass flats, intertidal samphire and mangrove flats, and supratidal samphire flats.
	8	Artificially filled areas and embankments	Generally below 1 m of the surface	Hyposulfidic, hypersulfidic materials and monosulfidic materials	Low	Low	Negligible	L	XXH	XXH	**Buried** estuarine sand-plains, back swamps, seagrass flats, intertidal samphire and mangrove flats, and supratidal samphire flats.
	C.	Subsurface shell grit layer	Within 25 cm of the surface	Hyposulfidic materials	Very low	Very low	Very low	N	N	N	**Estuarine** sand-plains, back swamps, seagrass flats, intertidal samphire and mangrove flats, and supratidal samphire flats.
Intertidal	9	Water	At the soil-water interface	Hypersulfidic, hyposulfidic and monosulfidic materials	Low to moderate	Low to moderate	Low to moderate	N	H	H	**Subaqueous soils** (bottom sediment) of tidally influenced wetlands, lagoons, drains and creeks.
	10	Mangrove woodlands	At the surface	Hypersulfidic, hyposulfidic and monosulfidic materials	High to moderate	High to moderate	Very low	N	VH	VH	**Estuarine** back swamps, intertidal samphire and mangrove flats.
	11	Low growing salt marsh plants	At the surface	Hyposulfidic, hypersulfidic and monosulfidic materials	High to moderate	High to moderate	Very low	N	VH	VH	**Estuarine** back swamps, intertidal samphire and supratidal samphire flats.
	12	Shell grit	At the surface	Hyposulfidic materials	Very low	Low	Very low	N	N	N	**Chenier ridge – carbonate barrier** covering estuarine back swamp, seagrass flats, intertidal samphire and mangrove flats, and supratidal samphire facies sediments.

*Treatment category is based on methods described by Ahern *et al.* (1998) and is an estimate of the acidity treatment level, using agricultural lime (refer to Table 7-2). In this table the treatment categorization was calculated using maximum values from Table 7-3, Table 7-4 and Table 7-5 for existing acidity, potential sulfidic acidity (PSA) and net acidity (Ahern *et al.* 2004).
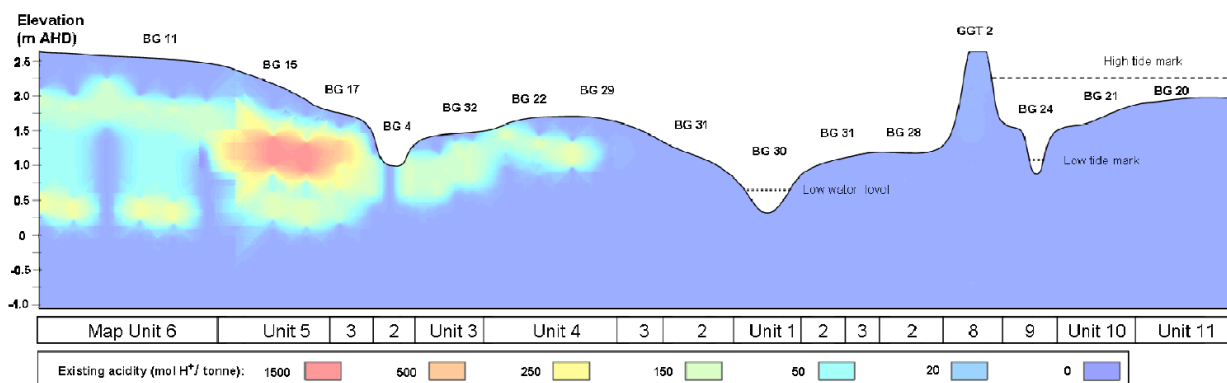
170

Existing acidity

Figure 7-5 Conceptual diagram showing the position of existing acidity within the Gillman landscape.
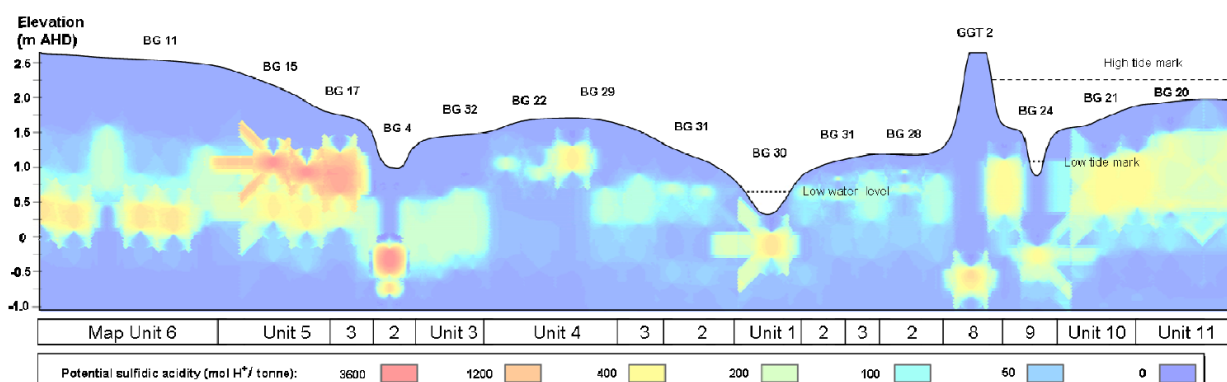
Potential sulfidic acidity

Figure 7-6 Conceptual diagram showing the position of potential sulfidic acidity within the Gillman landscape.
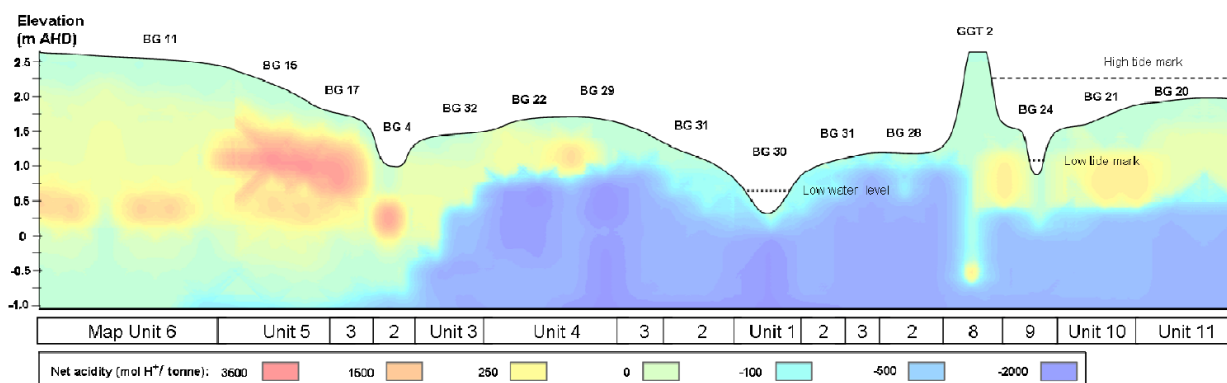
Net Acidity

Figure 7-7 Conceptual diagram showing the position of net acidity within the Gillman landscape.

Method for constructing conceptual cross-sections of landscape acidity:

The spatial distribution of acidity within the Gillman landscape is represented along a 1.8 km long conceptual transect that crossed each of the map units and main landscape features identified in the focus areas at Gillman (refer to Chapter 6). Soil profiles were positioned along the conceptual transect according to their surface elevation. The soil profile data is displayed using the circular kriging function in ArcGIS 9.1.

171

7.6. Geomorphic control on the development and distribution of acidity in the Gillman landscape

Since the last glacial maximum (about 18000 years B.P.), it is estimated that sea level rose about 25 m to reach its approximate present day level about 6000 years B.P. and has since been fairly consistent for most of the eastern coastline of Australia (Thom and Chappell 1975). Because coastal acid sulfate soils are associated with sulfidic soils and sediments occurring between the mean high water level and the mean low water level, the extent of acid sulfate soils occurring along the north-eastern coastline of Australia has been mapped using the 5 m or 10 m AHD contour interval on 1:250000 topographic maps (Powell and Martens 2005). Below these elevations it can be assumed that conditions have been favourable for formation of sulfidic material. However, sea level history has not been consistent around the coastline of Australia (Kinsela and Melville 2004).

In the northern parts of St Vincent and Spencer Gulfs on the South Australian coast, sea levels reached a maximum about 6700 years B.P and then dropped by about 2.5 m before stabilising about 1500 years B.P. (Belperio *et al.* 2002; Belperio *et al.* 1995; Hails *et al.* 1984). This apparent sea level fall was attributed to regional tectonic uplift and has left coastal sediments stranded 2.5 m above the present day mean high water level. In the Gillman and Port Adelaide region of Barker Inlet local geological subsidence has caused (apparent) sea level rise since the Mid Holocene high stand (Belperio 1993b). Anthropogenic influences have accelerated subsidence (over the past 150 years) in this area (Belperio 1993a; Belperio 1993b). In regions with dynamic and contrasting sea level histories, the use of a map contour for approximating the extent of acid sulfate soil is likely to either under estimate or over estimate the acidification hazard. It also highlights a (natural) existing acidity hazard for stranded coastal dune systems. Geomorphology is, therefore, considered a more useful tool for predicting the distribution and condition of acid sulfate soils for coastal plains of Spencer and St Vincent Gulfs.

The distribution of existing and potential sulfidic acidity in the Gillman landscape is largely controlled by the natural sea level history. The former back barrier sand ridge

and sandy shore face facies sediments that formed during the Mid Holocene high stand, about 6700 years B.P. (Belperio *et al.* 1995) were sulfidic and hosted mangrove vegetation. During the following period of regression (between 6600 and 1500 years B.P.) the upper 1 to 2 m of these elevated coastal dune systems were largely oxidised, with sulfuric material forming. Acidity and oxidation products that leached from the upper portion of the dunes (map unit 6 and 7) moved vertically to the redox boundary and laterally to groundwater discharge sites (map unit 5 at that time). This process re-distributed iron and sulfur to form a halo of iron sulfide enrichment that surrounded the back barrier sand ridge. Iron sulfide contents became particularly elevated in reduced soil layers that contained high organic matter content. Over the past 1500 years or so, the Gillman area has been subsiding at a rate of 0.5 mm per year, equating to about 75 cm (Belperio 1993a; Belperio 1993b). This depth is consistent with jarosite mottles being observed at about 80 cm below the lowest recorded water table height for the profile BG 11 (Figure 7-4). The local subsidence and artificial lowering of the groundwater table moved seepage sites to lower positions in the landscape (e.g. map unit 3).

The Gillman area has never had a formal acid sulfate soil management plan. For the past 50 years or so the area has played a vital part for stormwater management of the local area. The low lying nature of the site enables it to be used as a stormwater ponding basin during times when stormwater cannot be discharged directly to the Barker Inlet (during high tide). Fortuitously this role has managed the acid sulfate soils through a number of strategies that have together protected the Barker Inlet. Existing acidity is essentially being managed by 'containment' of acidity within the soil profiles. Low lying, normally flooded areas fringe the main store of existing acidity and provide a sink for acidity and sulfide oxidation products in a wetland environment. The main functional wetland area is located at the northern end of the major store of acidity, and does not discharge directly to the Barker Inlet as there is no tidal gate. Water is lost from this ponding basin by evaporation. Soils with excessive carbonate content are located in these recessive areas and aid acid neutralisation. In some areas the latent reflooding of the Gillman study area has caused very high concentrations of reduced inorganic sulfur and AVS to accumulate.

7.7.   Pedogeophysical Survey

At Gillman, in soil profiles that contain buried hypersaline layers, there was a positive correlation between soil salinity and very high sulfide (% S_{CR}) and high existing acidity contents (as retained acidity). This relationship was most evident at Focus area A for the sandy textured profiles where leaching was evidenced by the development of an E horizon (e.g. profiles BG 15, BG 17, BG 4, BG 5 and BG 11). For this reason a pedogeophysical survey was conducted over Gillman Focus area A using:

(iv)   a magnetic susceptibility (MS) meter to measure the ferromagnetic properties of the soils, and

(v)   an electrical conductivity meter (Geonics EM38 instrument) to map the apparent EC (EC_a) of soils at varying depths.

The following section describes the acquisition and interpretation of these data-sets, which were correlated to observed soil characteristics within the study area. The correlation between soil properties, MS and EC_a was used to improve map unit boundaries (Figure 7-2; includes improved map unit boundaries).

7.7.1. Magnetic susceptibility

High resolution MS mapping of the recent soils at Gillman provided an opportunity to relate the magnetic mineralogy to pedogenesis, including the impact of drainage and disturbance. Magnetic susceptibility is a method to estimate the amount of magnetic mineral particles (e.g. magnetite, maghemite, haematite, goethite, greigite and pyrrhotite) present in a soil, sediment or rock (Mullins 1977; Thompson and Oldfield 1986). The method measures the ratio of induced magnetisation versus the applied magnetic field and is a function of magnetic particle size, grain shape and mineralogy (Grimley *et al.* 2004). The nature, content and grain size of each magnetic mineral phase reflect the physico-chemical conditions of the soil, such as availability of iron and its valency state, mineral formation, pH and Eh (Mathé *et al.* 2006; Schwertmann *et al.* 2005). The MS of soils can be correlated to other pedogenic factors such as climate, topography, hydromorphic processes, fire history and time (Fine *et al.* 1992). Low magnetic anomalies in the spatial distribution of ferromagnetic mineral phases may therefore reflect land drainage and tillage patterns (Mathé and Lévêque 2003), and has

174

implications for assessing redox processes. Field measurements of MS are termed volume susceptibility (κ) and are typically reported in non-dimensional volume units (SI units). Laboratory MS measurements are reported in mass-dependent units (χ m^3/kg) (SI units), which is equivalent to volume susceptibility divided by sample density, and therefore allows direct comparisons in MS between different samples.

Data acquisition: The MS survey was conducted with the EM38 survey across Gillman Focus area A, at roughly 5-10 m intervals. Volume MS determinations were made in the field using a Barington magnetic susceptibility instrument model MS2 (Barrington Instruments Ltd., Oxford, England) equipped with a MS2D probe. This instrument determined concentrations of magnetic minerals to a depth of 1-2 mm. A differential GPS was used to position the 267 data acquisition sites allowing the data to be imported into ArcGIS 9.1 for interpretation by ordinary kriging. The resultant GIS surface was draped over aerial photography and previously mapped soil units. Kriged MS data is shown in Figure 7-8. Site-specific geophysical measurements are provided in Appendix D.

Results and discussion

There was one κ anomaly (high) located in the southern third of Gillman Focus area A (Figure 7-8). The high κ readings measured up to 123 x 10^{-5} SI, and were predominantly located within the map unit 8 (Artificially filled area and embankments) that forms a earthen mound about 2 m higher than the surrounding landscape. The mound was built during the construction of the Range wetlands in 1996 from predominantly clayey soils excavated from adjacent wetland ponds. Prior to excavation these soils would likely have contained hyposulfidic minerals that have since oxidised, in the top 80 cm of the soil profile, with soil pH values remaining circum-neutral. The crest of the mound is covered by grasses. Bare, salt scalds patches occur on the slopes with samphire vegetation fringing the toe of the mound. The soil types associated with map unit 8 were classified as Haplic Xerarents (Soil Survey Staff 2010); and Sulfidic, Dredgic Anthroposols (Isbell 2002) and contained hyposulfidic materials (Figure 7-4 and Table 6-17).
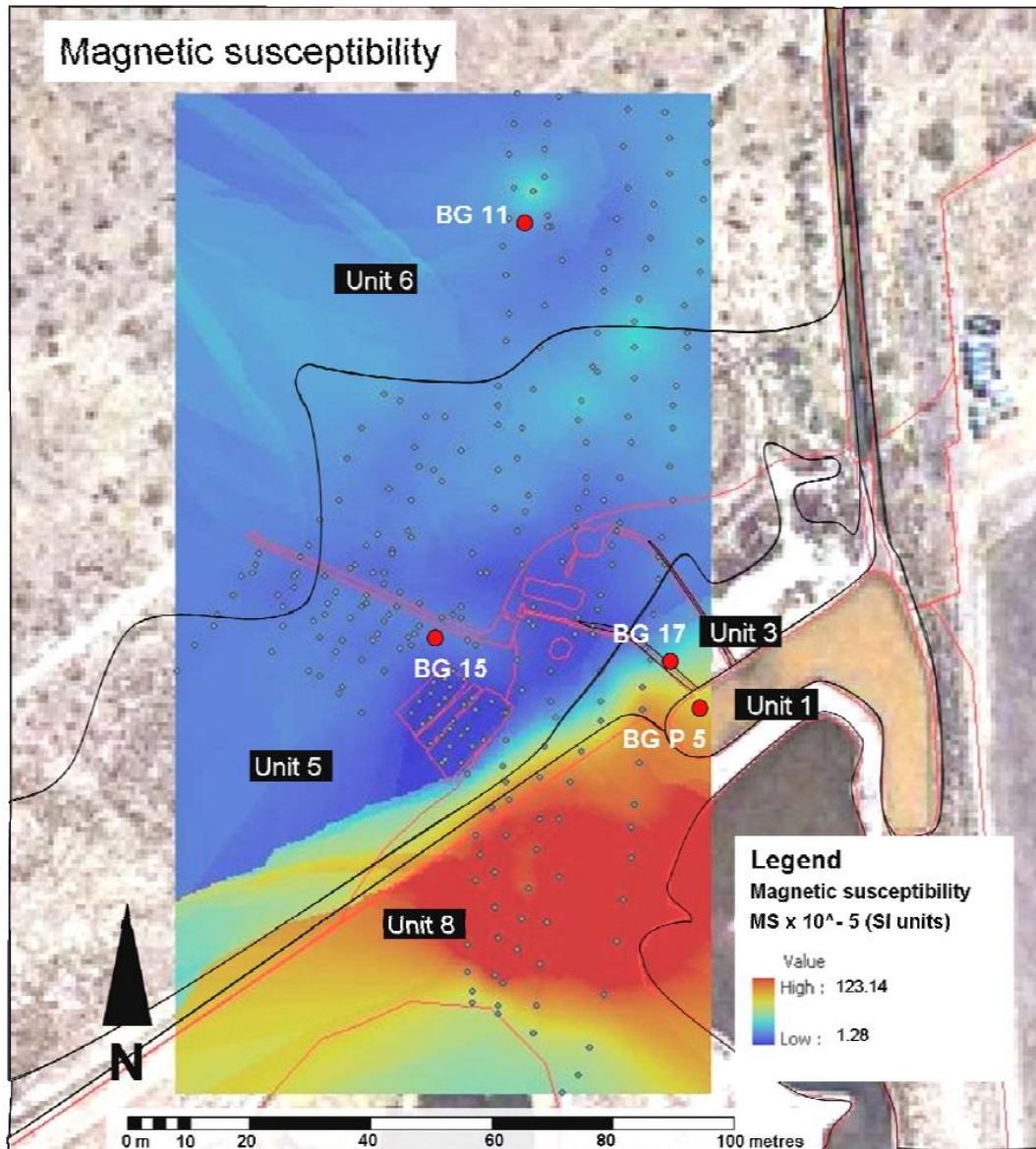
Figure 7-8 Kriged κ data overlaid on aerial photography for Gillman Focus area A. Dots show κ data collections points, red dots indicate type soil profiles, and the black lines demarcate the map units. Red lines outline drains and mounds. Note that the kriged data set is only reliable for the area between data points.

Slightly elevated κ readings were recorded on flat, bare salt scalded area, proximal to the base of the soil mound. These slightly elevated κ readings are likely to be associated with magnetic clay materials that washed onto the salt scalded flat areas as anti-ferromagnetic minerals, such as goethite, hematite and schwertmannite. These minerals were identified as the dominant iron oxides found at the surface (upper 2 mm) of the salt scalded areas (refer to Chapter 10). The salt scalded areas were mapped as unit 3 and associated with soils that contained sulfuric material in the near surface layers and

hypersulfidic, hyposulfidic materials and minor monosulfidic material at depth (e.g. profile BG 17 and BG 32, refer to Figure 7-4 and Table 6-17).

Volumetric MS readings within map units 5 and 6 produced very low MS responses. The soils from these two map units contained sulfuric material, hypersulfidic and hyposulfidic materials (e.g. profiles BG 15 and BG 11, refer to Figure 7-4 and Table 6-17).

The type of iron oxide mineral formed from aqueous solutions is pH dependent. In moderately alkaline solutions (pH > 8) oxidation of Fe^{II} solutions proceeds via $Fe(OH)_2$ and usually yields magnetite (David and Welch 1956; Sidhu 1988; Sidhu *et al.* 1977). Ferrihydrite forms under moderately acidic conditions (pH < 5) (Schwertmann and Thalmann 1976). Slow oxidation rates also promote magnetite formation (Schwertmann and Taylor 1977; Taylor and Schwertmann 1974). The high κ response from soil mounds (artificially filled areas) may therefore be due to a relatively high carbonate content maintaining alkaline soil solutions during oxidation of the hyposulfidic materials, and slow oxidation reaction rates due to the high clay content. The occurrence of monosulfidic material (e.g. soil containing greigite) in soils surrounding and within the wetland pond (e.g. profile BG P 5) is likely contributing to the positive magnetic anomaly. Magnetic susceptibility may therefore be a useful mapping tool to distinguish between 'hyposulfidic' and 'hypersulfidic' materials in the near surface of drained acid sulfate soil landscapes. Anti-ferromagnetic iron (hydr)oxide minerals generally form when pH is below 7 following iron sulfide oxidation. (Grimley and Vepraskas 2000) used κ to identify hydric soil boundaries to delineate wetland soils.

7.7.2. Electrical conductivity (EM38) survey

Soils conduct electrical current mainly through the moisture-filled pores between individual soil particles, and from particle to profile either: i) through the crystal or ii) via the crystal surface. Bulk soil apparent electrical conductivity (ECa) is a measure of electrical conductivity through the soil, which allows differentiation of various soil characteristics e.g. (Aimrun and Amin 2009; Sudduth *et al.* 2001). The ECa relates to soil texture and other factors including salinity, clay mineralogy, temperature, soil pore size and water conductivity and soil moisture (Kachanoski *et al.* 1990; Moore *et al.* 1993). (Wolcott and Moore 2001) found a very high correlation between electrical conductivity of soils and clay content as well as between electrical conductivity and organic matter. (Williams and Baker 1982) found that in areas with salt affected soils, 65-70% of the variation in ECa measurements could be attributed to soluble salt concentrations.

In this study, ECa was determined by measuring electromagnetic induction (EMI) using a Geonics EM38 instrument (Geonics Limited, Canada). The EM38 works through the emission of a primary electromagnetic field and measuring the soil-induced response (secondary field). The intensity of the received signal depends on the electrical conductivity of the bulk soil (ECa) (Herrero *et al.* 2003). The ECa generated response is a depth weighted combination of the EC of the individual soil layers (McNeill 1990). Measurements with the EM38 can be carried out in the vertical (ECav) or horizontal (ECah) dipole mode. In the vertical dipole orientation approximately 70% of the measurement is from the upper 1.5 m, while in the horizontal orientation approximately 70% of the measurement is from the upper 0.75 m of the soil profile (McNeil 1992). The units of measurement for ECa are decisiemens per metre (dS/m). For a detailed summary of the principles and applications of electromagnetic induction and soil conductivity refer to (Allred *et al.* 2008).

Data acquisition: Both vertical and horizontal EM38 measurements were taken at grid locations with 5-10 m intervals across Gillman focus area A (Figure 7-9 and Figure 6-2). A differential GPS was used to position the 267 data acquisition sites allowing the data to be imported into ArcGIS 9.1 for interpretation by ordinary kriging. The resultant GIS surface was draped over aerial photography and previously mapped soil types. Site-

specific measurements are provided in Appendix D. Kriged horizontal dipole EM38 data is displayed in Figure 7-9. Kriged vertical dipole EM38 data is displayed in Figure 7-10.

Results and discussion

The Gillman Focus area A was a saline environment with groundwater salinity ranging from 39 dS/m in the southern portion to 58 dS/m in the northern portion of the focus area. Near surface (0 to 5 cm) soil salinity (ECse) ranged from less than 1 dS/m in relatively elevated soil profiles BG 11 and BG 15 to 12 dS/m in profile BG 17 where salt efflorescence has precipitated at the surface. Near surface soil salinity (ECse) measured 5 dS/m in subaqueous soil profile BG P 5. In these saline environments 65-70% of the variation in ECa can be attributed to soluble salt concentrations (Williams and Baker 1982). Comparing the EM38 data acquired in the two different modes (horizontal dipole mode and vertical dipole mode) can be used to compare relative salt accumulation in the near surface (upper 0.75 m) to that at slightly deeper depths (upper 1.5 m), and is usually displayed as kriged horizontal minus vertical EM38 data.

In areas where surface elevations were natural, both the vertical and horizontal dipole EM38 modes measured a similar pattern of ECa distribution across the focus area, and corresponded to visible micro-topographical variations. In the higher, naturally elevated, areas (map units 5 and 6), ECa measurements were relatively weak (represented by the cooler colours) and ranged from 1.0 to 1.3 dS/m (Figure 7-9 and Figure 7-10). Strong ECa measurements (represented by warm colours) were also recorded (ranging from approximately 2.0 to >3.0 dS/m) within map units 5 and 6 and correspond to lower lying areas formed by a subtle, open erosional depression (Figure 7-9 and Figure 7-10). This slight depression is evident on aerial photographs by the occurrence of samphire vegetation. The EC_a measured using the horizontal dipole across map units 5 and 6 were stronger at depth suggesting that salinity in these areas was predominantly controlled by proximity to the shallow, hypersaline groundwater table. The sandy texture of soils under these two cover types would limit the transport of salts to the surface by capillary rise from groundwater, as well as aiding leaching. White salt efflorescence was commonly observed in areas represented by map unit 3 (Bare salt scalded mud flats). In these low lying areas the groundwater table was generally within 50 cm of the surface

and the soils were usually finer textured. The EM38 data for these salt scalded areas showed that ECa response was usually stronger near the surface than at depth (Figure 7-9 and Figure 7-10).

In areas where surface elevations were man-made (map unit 8), ECa patterns reflected topography and relief, but also had soil textural influence. Near-surface ECa measurements determined using the horizontal dipole mode indicate salt has leached from the top of constructed soil mounds and washed out around the toe of the mounds (Figure 7-9). This is evidenced by salt efflorescence occurring at the break in slope. On the top of mounds ECa concentrations determined using the horizontal dipole mode were weak indicating that the salt concentrations were deep (Figure 7-10). This suggests soil texture was strongly influencing ECa in this modified area, which is expected given that these mounds were predominantly constructed using clays, excavated from below the saline water table.

Salt scalds have developed in areas where clay has been washed from mounds (artificial fill, map unit 8) onto flat, low lying areas. Slight adjustments were made to map unit boundaries to account for this artefact, and better reflect the soil type and acid sulfate characteristics of the underlying soil profile.

Radiometrics (K, Th, U) were used by (Bierwirth and Graham 1997) to map acidity within coastal flood plains in northern NSW. The authors used airborne collected data with varying success. A radiometric survey over the Barker Inlet would probably better distinguish between the different acid sulfate soil types in the Gillman and St Kilda areas by providing distinction between the sandy soils (with high net acidity) from clay rich and carbonate rich soils (with considerably lower or negative net acidity).
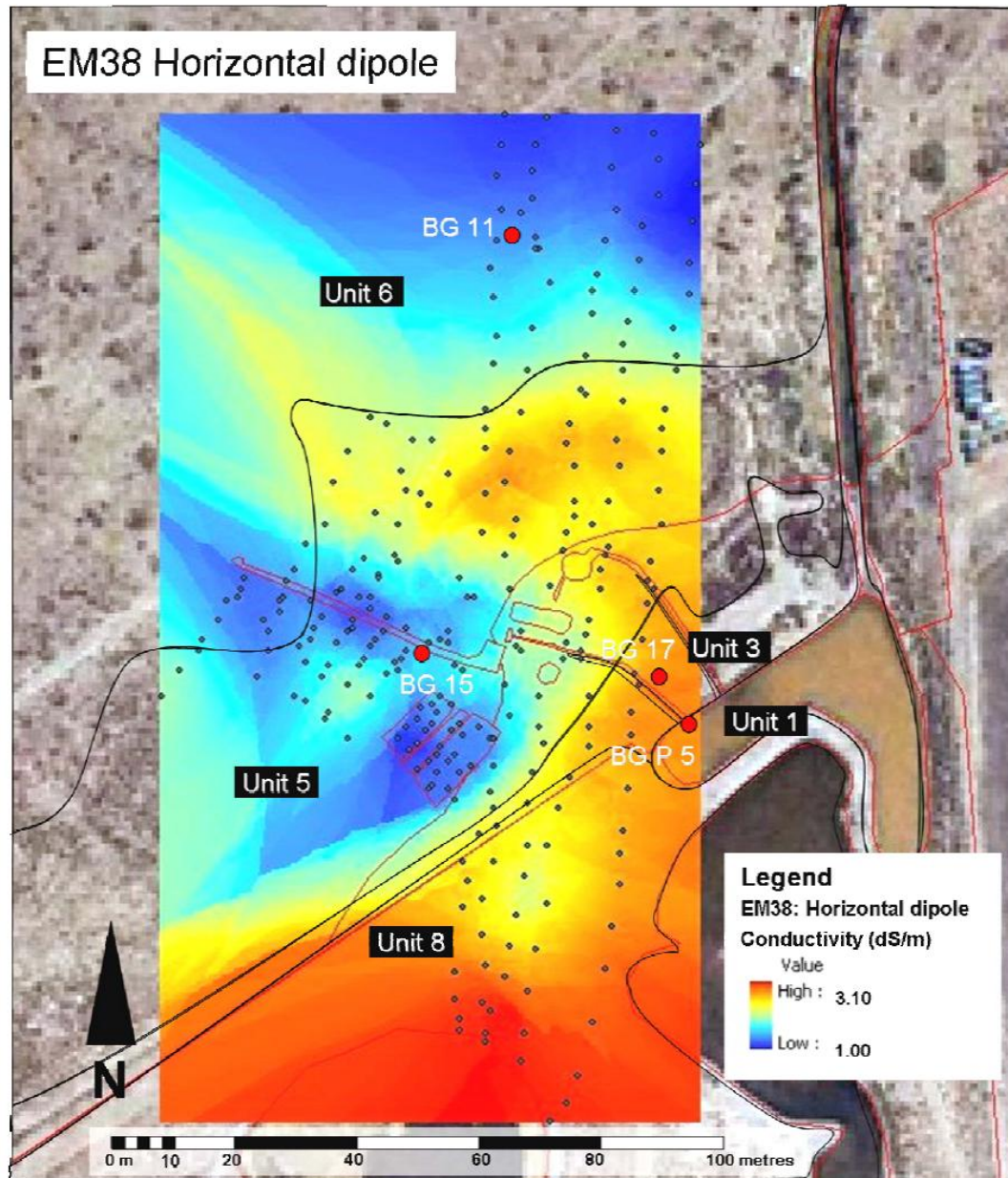
Figure 7-9 Kriged EM38 (horizontal dipole) data overlaid on aerial photography for Gillman Focus area A (depth of measurement was approximately 0.75 m). Dots show data collections points, red dots indicate type soil profiles and the black lines demarcate map units described previously. Red lines outline drains and mounds. Units are in dS/m. Note that the kriged data-set is only reliable for the area between data points.
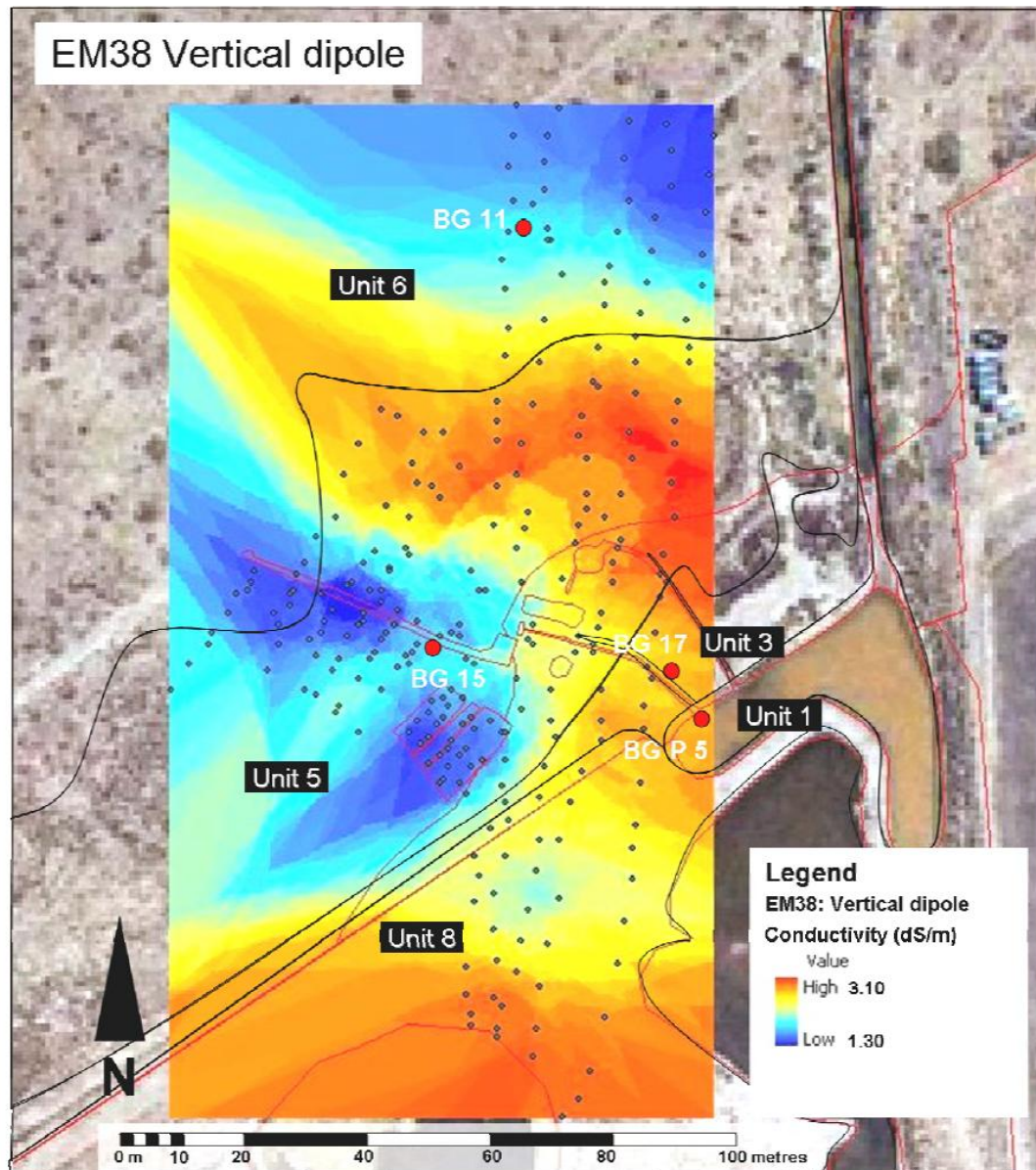
181

Figure 7-10 Kriged EM38 (vertical dipole) data overlaid on aerial photography for Gillman Focus area A (depth of measurement was approximately 1.5 m). Dots show data collections points, red dots indicate type soil profiles and the black lines demarcate map units described previously. Red lines outline drains and mounds. Units are in dS/m. Note that the kriged data-set is only reliable for the area between data points.

182

7.8. Summary

The soil-landscape maps and legends provide spatial tools to illustrate where potential hazards, such as salinity, acidity, potential acidity and monosulfides occur in the landscape. The use of geophysical techniques and historic aerial photography improved correlation between the map unit boundaries and soil morphology, and therefore hazard assessment.

The Gillman study site contained very high levels of existing and potential acidity that was predominantly associated with map unit 5. It is proposed that the apparent accumulation of acidity in map unit 5 is a reflection of the geomorphic and natural drainage history of the Gillman area. When the Gillman area was under natural tidal influence the surface of areas assigned to map unit 5 occurred approximately between the mean and high tide mark. Acidity and oxidation products from within the near surface of more elevated soils (e.g. from map units 6 and 7) has likely leached to lower areas in the landscape. Willett *et al.* (1992) noted that pyrite oxidation products can remain in the landscape for 100-1000 years before either being neutralised or leached from the system. van Oploo *et al.* (2008a) estimated the emergence of sulfidic soil profiles above estuarine waters in the Tweed River valley to be about 2000 years BP. It is therefore possible that the presence and spatial distribution and concentration of existing and potential sulfidic acidity within the Gillman landscape is linked to both:

    (i)   geomorphological features and past sea level fluctuations, and

    (ii)   recent artificial drainage and stormwater management and local land subsidence.

The export of pyrite oxidation products to Barker Inlet has probably been low since bunding due to:

    (i)   containment of oxidation products on site by bund walls,

    (ii)   low hydraulic gradient across the Gillman site which limits the movement of acidity,

    (iii)   carbonate-rich horizons fringing the main acid store and

(iv)   occurrence of monosulfides within the ponding (evaporation) basins, within the study site, that provide a sink for acidity and metals. The stormwater ponding basins form areas of permanent water (i.e. map unit 1), located inside the bund walls and down the hydraulic gradient of sulfuric material.

At Gillman, if there is no change to the current land management and drainage regime the oxidation front will deepen and pyrite oxidation will continue to produce H_2SO_4. Existing acidity, which is largely stored in the sandy shore face facies, is unlikely to move off-site unless the hydraulic or drainage regime of the area is changed.

Successful management of acid sulfate soil hazards at Gillman should take into account the specific nature of the site so that the current containment of acidity within the profile by bunds is not compromised. Unmanaged development at the Gillman study site that disturbs acid sulfate soils or changes the local hydrology could cause environmental damage by increasing the oxidation of pyrite and off-site transportation of acidity and other metal contaminants. Techniques could be implemented to minimise further pyrite oxidation and export of acidity. However, the specific development plans will dictate the remediation options available to achieve the desired environmental outcomes.

In the following chapters, soil redox characteristics (Chapter 8) and hydrogeochemical (metal and metalloid contamination) characteristics (Chapter 9) are investigated and related to the 12 map units for the St Kilda and Gillman study sites. In Chapter 10 the implications of exposing and mobilising acidity contained within the profiles of map unit 5 are explored.

Combining this additional information from Chapters 8, 9 and 10 aimed to improve understanding of the evolution, nature and interrelationships of these coastal soils. This is vital for the developing and implementing effective long-term acid sulfate soil management plans and for selecting appropriate (development-specific) remediation options.