Department of
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ACID SULFATE SOIL SURVEY

SUPERFICIAL GEOLOGICAL SEDIMENTS ADJACENT TO THE PEEL-HARVEY ESTUARY

SEPTEMBER 2009

Acknowledgments

This report has been prepared by Brad Degens with assistance in coring, collection of field information and management of samples by Geoff Sadgrove, Ian MacPherson, Peter Geste and Shannon Brown and processing of soil and chemistry information by Penny Wallace-Bell and Pauline Farrell. Penny Wallace-Bell is also gratefully acknowledged for providing assistance with some of the initial drafting of logs and landscape cross-sections for this report. Dr Steve Appleyard, Stephen Wong and Dr Yash Pal provided technical review and comment.

This technical report details the on-ground investigations of acid sulfate soil (ASS) materials in superficial formations adjacent to the Peel-Harvey Estuary and the subsequent use of this to develop ASS risk maps for the region. The Acid Sulfate Soils Technical Advisory Committee provided technical input into the acid sulfate soil mapping program which was made possible by Commonwealth and State funding.

The information captured in the field and laboratory is being stored in a newly developed ASS data processing module with the capacity to load and export data and produce reports. Access to ASS risk maps is now available via a web-based product using a Shared Land Information Platform (SLIP) hosted by Landgate – https://www2.landgate.wa.gov.au/idelve/bmvf/app/waatlas/.

For more information contact:

Acid Sulfate Soil Section
Contaminated Sites Branch
Environmental Regulation Division
Level 7, The Atrium, 168 St Georges Terrace
Perth WA 6000
Telephone: 6467 5377
Email: acidsulfatesoils@dec.wa.gov.au

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Cover photograph: A main drainage channel in South Yunderup leading into the Peel Estuary.

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Summary

A survey of Potential Acid Sulfate Soil (PASS) materials in superficial geological sediments adjacent to the Peel-Harvey Estuary was undertaken to:

- Evaluate the characteristics of profiles with PASS materials,
- Determine the spatial extent of this natural geochemical hazard,
- Classify and map ASS risk areas to support management of ASS in planning processes, and
- Broadly outline implications of the investigations for the management of PASS materials in the region.

PASS materials were found in at least one horizon of the superficial sediments (up to 6m depth) at 75 per cent of 177 investigation sites. Field assessment and supporting laboratory analyses indicated that shallow PASS materials occurred within 2m of the ground surface at 47 per cent of sites with a further 28 per cent containing PASS materials at 2-3mbgl. Most PASS materials commonly occurred in shallow (<2 mbgl) sand and silty sand horizons, though in areas immediately adjacent to the estuary or lower river reaches there were greater occurrences of PASS materials in silts and (occasionally) sandy clays. For representative profiles and landscapes, estimates of stored acidity within the shallowest 1m of horizons with PASS materials ranged from less than 50 tonnes H_2SO_4/ha to over 1000 tonnes of H_2SO_4/ha. It was notable that many PASS materials did not occur in horizons with significant *in situ* neutralising materials (e.g. carbonates), although on the western side of the Peel Inlet and Harvey Estuary PASS materials were commonly underlain or overlain by horizons with neutralising materials.

Thirteen per cent (22) of the sites surveyed contained evidence of actual ASS materials arising from oxidation of PASS materials. Most superficial sediment profiles with actual ASS materials were found in areas adjoining the lower Murray, though some were found in areas adjoining Robert and Boggy Bays, Lake Mealup, Black Lake (on the Serpentine River) and the margins of the Harvey River delta. Oxidation of PASS materials can be a slow natural occurrence, however, rapid oxidation can be caused by ground disturbances including excavation, lowering of ground-water tables by pumping and drainage and change in tidal regimes. Further investigations are required to determine the extent to which human-induced activities in landscapes have resulted in the recent formation of actual ASS at the sites identified in this survey. Actual ASS formation in a broad wetland depression adjoining Robert Bay and areas adjoining the Murray River mouth may be due to soil excavation, restricted tidal regime and/or drainage. The high proportion of sites with actual ASS materials (found largely by chance) indicates that there may be more (probably smaller) areas with oxidised ASS materials that remain unidentified in the superficial sediments adjoining the Peel-Harvey Estuary. The nature of the survey did not permit mapping of the extent of superficial sediments with actual ASS.

The survey identified that superficial sediments with shallow PASS materials (i.e. PASS materials within 3m of the ground-surface) occurred in significant areas of estuarine flats, low lying dunes, wetland depressions and lower floodplains of rivers adjoining the Peel-Harvey Estuary. These areas were mapped as areas with a high ASS risk where there is a high to moderate likelihood that normal land development activities would disturb shallow PASS materials (<3m below ground-level; mbgl). These areas were equivalent to over 11,500ha of the Swan Coastal Plain that adjoins the Peel-Harvey Estuary and lower

reaches of the Murray, Serpentine and Harvey Rivers. The survey identified more than double the initial area of shallow PASS materials adjoining the Peel-Harvey Estuary estimated by initial desk-top mapping using 1:50 000 urban (1997-1982) and environmental geology (1984 – 1991) mapping series published by the Geological Survey of Western Australia. Furthermore, the lower slopes of Spearwood dunes and gently undulating Bassendean sand plains adjoining the areas with shallow PASS materials frequently contained PASS materials associated with sandy clays or sand horizons at greater than 3m below ground surfaces. These were accordingly mapped as medium ASS risk where there is a medium to low likelihood of normal land development activities disturbing shallow PASS materials (<3 mbgl), but a high to moderate likelihood of these activities disturbing deeper PASS materials (>3 mbgl).

Identification of large areas of high to moderate ASS disturbance risk around the Peel-Harvey Estuary indicates that there will be a need for significant on-going investment in site-specific investigation and management of ASS materials during land development processes in the region. In particular, the survey indicates that many of the PASS materials occur in predominantly shallow, sandy horizons that will be prone to rapid oxidation if exposed to air by de-watering, drainage or excavation. Management of shallow ground-water levels in these soils will require greatest attention to ensure that inadvertent widespread oxidation of these PASS materials does not occur since most PASS materials were frequently submerged by less than 0.5m below the surface of water-tables.

Formation of actual ASS materials by oxidation of PASS materials in near estuarine landscapes indicates that further, larger areas with shallow actual ASS are likely if not managed appropriately. Impacts on infrastructure and the environment may already be occurring from existing areas with shallow actual ASS which requires further investigation to determine the extent of the area with actual ASS, major pathways for impacts on aquatic environments and infrastructure and management options to enable development of strategies for remediating or containing the impacts.

Introduction

1.1 General information

Acid sulfate soil (ASS) materials are any soil or sediment materials containing sulfuric acid stored or actively being released from sulfide minerals (Rabenhorst and Fanning, 2002). In this context ASS materials include potential ASS (or PASS) and actual ASS (AASS) materials. PASS materials contain acidity stored predominantly as microscopic grains of iron sulfides (mainly pyrite) in permanently waterlogged, frequently anoxic and submerged soil layers (Dent, 1986; Sammut, 2000) described as sulfidic layers (Isbell, 1996). Actual ASS materials are those soil materials containing sulfuric acidity from the oxidation of sulfidic minerals (forming sulfuric layers, after Isbell, 1996).

While undisturbed and under low oxygen conditions, PASS materials pose no risk to the environment and are commonly not acidic with pH generally greater than 6.5. However, if disturbed by excavation, drainage or lowering of water tables (by groundwater pumping or long-term alteration of catchment water-balance caused by vegetation and climate change), air entry to the materials causes the iron sulfides to oxidise. This oxidation releases sulfuric acid and triggers a complex array of secondary reactions and processes that can result in potentially wide-spread impacts on the environment (Dent, 1986; Powell and Ahern, 2000). In general terms, disturbance of soil or sediment materials containing PASS materials (sulfidic layers) by natural events (floods, droughts) or anthropogenic activities results in the formation of actual ASS materials (sulfuric layers) within soils. It is the formation of these soils that can lead to the development of a myriad of ASS related problems including waterway and wetland acidification, excessive black ooze formation, increased fish kills, increased mosquito breeding, proliferation of particular aquatic weeds; damage to infrastructure (e.g. corrosion of pipework and bridges and soil heaving) and nuisance odours (Dent, 1986; Sammut, 2000).

Identifying and mapping where ASS materials occur is nationally recognised as a major requirement for the effective management of acid sulfate soils (National Working Party on Acid Sulfate Soils, 2000). Until 2003, the distribution of ASS in WA was poorly understood, despite detection of problems associated with the disturbance of ASS materials in Western Australia early last century. Acidification and degradation of other aspects of water quality were reported following drainage of wetlands on the South Coast (Woodward, 1917). Later soil investigations also identified the presence of ASS materials in wetland (Teakle and Southern, 1937a, b) and near estuarine environments (McArthur and Bettenay, 1956) in southern WA.

Recognition of the environmental threat posed by ASS in WA was triggered by acute environmental impacts arising from disturbance of ASS materials in Balcatta, Perth (Appleyard et al., 2004). This event resulted in widespread acidification of ground-water and arsenic contamination (Appleyard et al., 2004) that has created on-going management problems for water resource use, drainage, infrastructure and wetland ecosystems receiving ground-water from the disturbed area.

The management response to ASS risk involves implementation of planning guidelines to avoid inappropriate disturbance of ASS materials during urban and industrial land development (Western Australian Planning Commission, 2003) and development of an overarching framework for management of ASS in WA (Department of Environment, 2004a). These processes were supported by an initial desk-top prediction of ASS occurrence in coastal regions of the state that was carried out in 2003 (see supporting maps for Western Australian Planning Commission, 2003). The map information is routinely used by state and local government planning authorities to assess whether land development proposals carry a risk of disturbing ASS materials (ASS disturbance risk) and what management response is required for each risk category (Western Australian Planning Commission, 2003, Department of Environment, 2004a). In this context, land development that involves soil and ground-water disturbance in areas with ASS disturbance risk will require a staged response to determine the presence of ASS materials, whether the land and groundwater disturbances during development risk oxidation of ASS materials and, if so, how the acidity risks will be managed.

Initial desktop mapping in WA indicated that shallow PASS materials were broadly expected to occur in superficial formations adjacent to and within estuaries and many upland wetlands of southern WA (Western Australian Planning Commission, 2003). More recent work has confirmed that ASS materials are also in superficial formations underlying extensive areas of upland wetlands and palusplains on the Scott Coastal Plain (Degens and Wallace-Bell, 2009). These formations are considered to have been deposited during the Pliocene, Pleistocene and Holocene epochs (Baddock, 1995) with the majority being more than 5m above mean sea level. Smaller areas of soils with significant PASS materials can also occur in association with salt and freshwater seeps in inland areas (Fitzpatrick et al., 2003), commonly exceeding 20m above mean sea level.

Mapping of potential ASS in many parts of Australia has been carried out with an emphasis on low-lying coastal landforms including estuarine floodplains, mangrove tidal flats, salt marshes and back-swamps (Atkinson et al., 1996; Smith et al., 2000; Merry et al., 2003; Rampant et al., 2003). This approach is based on the model that many PASS materials, particularly in eastern Australia, are considered to have formed since the last major sea level rise (during the Holocene epoch) largely as a result of the slow recession of sea levels and generally occur in landscapes within 5m of the current mean sea level (Graham and Larsen, 2000; Powell and Ahern, 2000). It is for this reason that most PASS materials in many landscapes are considered to occur in superficial layers deposited during the Holocene epoch (over the last 10,000 years). It is thought that PASS materials do not occur within superficial sediments deposited during the Pleistocene epoch mostly because the materials are considered to have oxidised during periods of low sea levels occurring after deposition (Atkinson et al., 1996). Despite this, there is evidence that PASS materials can occur in Pleistocene aged sediments (Malcolm et al., 2006) and certainly some evidence in WA that PASS materials can occur in sediments more than 5 m above mean sea level in sediments deposited before the Holocene epoch (Appleyard et al., 2004; Degens and Wallace-Bell, 2009). PASS materials in these older, higher elevation sediments have presumably either remained unoxidised since deposition or have authigenically formed (or reformed) in waterlogged conditions created by higher sea levels during the Holocene epoch.

That there can be considerable variation in the depth and extent of PASS materials within landforms (Dent, 1986; Naylor et al., 1998; Graham and Larsen, 2000) which can constrain delineation of ASS mapping units. This variation can limit the extent to which uniform areas of superficial formations with PASS materials can be distinguished without carrying out high intensity investigations. The expectation of local variation in where PASS materials may have formed (and remain preserved) combined with the possibility of materials not being confined to Holocene aged sediments forms the main backdrop for the mapping approach developed for this survey.

1.2 Report context and objectives

Planning measures to manage ASS in the land development process are dependent on spatial information about the risk of ASS disturbance associated with development activities. In the Peel region, a rapid increase in the rate of development is projected to occur over the next 20 years in line with increasing population growth (Peel Development Commission, 2001). This increasing development pressure is matched by growing actions to achieve sustainable development (Peel Development Commission, 2002) and management of the risks posed by acid sulfate soils has been recognised as an important factor in sustainable environmental management (South West Catchment Council, 2005). Greatest urban development pressure is focused on low lying land surrounding the Peel-Harvey Estuary including damplands, wetlands, floodplains and low lying dunes. These areas are typical environments in which soils with PASS materials are most likely to occur and therefore provided the main focus areas for improved mapping of ASS disturbance risk used in land-use planning processes.

The current work was initiated to improve existing ASS disturbance risk maps (Western Australian Planning Commission, 2003) for use in regional planning targeted at low-lying landscapes around the Peel-Harvey estuary. These areas typically consist of the landscapes between 0 and 10m above mean sea-level (m AHD) within 5 km of the estuary and major tributaries to the estuary (Figure 1; Figure 2). Mapping has focused on determining ASS disturbance risk which indicates the likelihood that ASS materials could be encountered and disturbed by normal land development activities. The required map product is intended to be a point-of-assessment map in which the underlying physical distribution of PASS materials (which is the main focus of the on-ground mapping reported here) is incorporated, though not explicit. Regional level land-use planning can generally be met by mapping at scales of 1:50 000 and greater where the smallest mapped units are generally 5 hectares in size (Gunn et al., 1988). These specifications have guided the intensity of on-ground investigations and, more importantly, define the limits of interpretation of the final map products (Gunn et al., 1988). In contrast, for local scale planning and management of disturbance activities with land development at specific sites, detailed information on the spatial occurrence of PASS materials is required and commonly demands mapping at greater than scales of 1:25 000 (Gunn et al., 1988). These maps are more reliable to identify changes in ASS risk within 0.25 hectare units and smaller, however they will require considerable amount of on-ground investigation.

This report presents the characteristics, distribution and management implications of ASS materials in superficial formations adjacent to the Peel-Harvey Estuary. The document provides the background to improvements in ASS risk map datasets (published in February 2005) on which state planning processes are based.

1.3 Regional setting – geomorphology, geology, soils

The Peel-Harvey Estuary and associated low-lying landscapes occur on the western edge of the Swan-Coastal Plain. This plain is the Quaternary surface of the Perth Basin is comprised of distinct landforms that correspond with the main superficial geological formations and soil associations in the region (Bettenay et al., 1960; Playford et al., 1976; Semeniuk and Semenuik, 1990). The landform units are largely arranged sub-parallel to the Darling Scarp on the eastern boundary and sub-parallel to the coast, except where intersected by major rivers (McArthur and Bettenay, 1960; Semeniuk and Semenuik, 2005). The most easterly feature of the plain is the Ridge Hill Shelf consisting of a series of laterite covered spurs at the foot of the Darling Scarp, about 2 to 3km wide. Stretching from the foot of the Ridge Hill Shelf is the flat to gently undulating Pinjarra Plain consisting generally of unconsolidated alluvial deposits (McArthur and Bettenay, 1960). The Pinjarra plain is generally about 5km wide west of the colluvial slopes, but along the Serpentine River is about 15km wide (from east to west). Much of the Pinjarra plain corresponds with outcrops of the Guildford superficial formation (Davidson, 1995; Gozzard, 2007) which is broadly described as consisting of pale-grey and blue clays through to brown silty and sandy clays with lenses of conglomeritic and shelly sands (Davidson, 1995).

A series of coastal dunes occur along the western edge of the alluvial terrain consisting of a series of sand dunes, the Bassendean Dune System, being the most easterly, followed by Spearwood Dune System and Quindalup Dune System fringing the present coastline. These dunes also decrease in age from east to west (McArthur and Bettenay, 1960).

The Bassendean Dune System lying mainly in the east of the study area consists of mainly deep leached sands that have variable drainage and depth to groundwater. The Bassendean sand geological formation broadly consists of pale grey to white sands frequently containing iron cemented layers referred to as coffee rock (Davidson, 1995; Gozzard, 2007). The Bassendean formation is considered to have been deposited during the early to mid Pleistocene (Playford et al., 1976; Gozzard, 2007). Soils within this geomorphic unit include iron podsols and iron-humus podzols. The iron podzols, sometimes containing a hardened cemented coffee rock layer in the B horizon, are commonly found in well drained sites on crests and upper slopes of low ridges (McArthur, 1991). In the lower landscapes where watertable rises to within 2m of surface, iron-humus podzols are formed, often with the B horizon partly cemented (McArthur, 1991). These soil profiles generally show evidence of extreme leaching with negligible silt, clay, nutrient and organic carbon.

The Spearwood Dune System is mainly comprised of aeolianite (Tamala Limestone) with hard capping of secondary calcite overlain by variable depth of sand, likely blown inland to form dunes (McArthur and Bettenay, 1960; McArthur, 1991). This dune system broadly corresponds with the Tamala Limestone formation (Davidson, 1995; Gozzard, 2007), considered to have been deposited during the late Pleistocene (Playford et al., 1976; Gozzard, 2007). The western part has soils consisting of yellow sandy soils often with coastal limestone (Cottesloe Association; McArthur and Bettenay, 1960; McArthur, 1991) while the eastern part consists of podzols with yellow and grey sands within undulating sand hills (Karrakatta Association; McArthur and Bettenay, 1960; McArthur, 1991).

The Quindalup Dune System consists of coastal calcareous dunes (McArthur and Battenay, 1960), beach ridge plains, tombolos and cuspate forelands; underlain by quartzo-calcareous sand. This dune system is associated with the Safety Bay Sand superficial formation (Davidson, 1995) and is considered to have been deposited during the Holocene epoch (McArthur, 1991). The formation has been described as being typically white, calcareous sands with shell fragments and occasional black, heavy minerals (Davidson, 1995).

The Peel-Harvey estuary dominates the study area and consists of the Peel inlet, which lies between the Spearwood and Bassendean dune systems, and the Harvey estuary, which lies to the south between Spearwood dunes (Brearley, 2005). The estuarine system is connected to the sea by a natural, narrow channel at Mandurah and, after 1994, an also by a large artificial channel at Dawesville (Brearley, 2005). The estuary is considered to be a shallow basin estuary, with limited tidal exchange with the sea and that has gradually been accumulating sediments over the late Holocene (Hodgkin and Hesp, 1998; Brearley, 2005).

Several rivers feed into the Peel-Harvey estuary, which are flanked to varying extents by local clay and silt rich floodplain deposits (McArthur, 1991). The Serpentine River flows into the Peel Inlet from the north, entering between Spearwood and Bassendean dunes and forming a delta that merges with that of the Murray River. The Murray River flows into the Peel Inlet from the east, mainly transecting the Pinjarra Plain (and upper Guildford formation). The Murray-Serpentine delta consists of a few main channels flanked by levees, lakes, abandoned channels, lakes and flats with a complex series of interlayered muds and sands (Semeniuk and Semeniuk, 1990). The only major natural flow into the Harvey estuary is the Harvey River, which enters from the south-east after transecting Bassendean dunes and the Pinjarra Plain. The Harvey River delta consists of multiple channels, levees, abandoned channels and flats with a similar series of complex soils to that in the Serpentine-Murray delta (Semeniuk and Semeniuk, 1990). The Peel-Harvey estuary is also flanked by numerous peripheral wetlands being more extensive on the eastern side of the estuary (Semeniuk and Semeniuk, 1990). Depending on proximity to the estuary, the soils in these wetlands have been described as being predominantly muds and sandy muds (Semeniuk and Semeniuk, 1990).

Figure 1: Northern extent of the Peel-Harvey study area with main geographic features (rivers, points, lakes, wetlands).

Figure 2: Southern extent of the Peel-Harvey study area with main geographic features (rivers, points, lakes, wetlands).

Figure 3: Initial ASS risk map (based on 1:50 000 scale environmental and urban geology mapping) and superficial formation investigation sites (Peel inlet, Serpentine and Murray Rivers). Note: map not printed to scale.

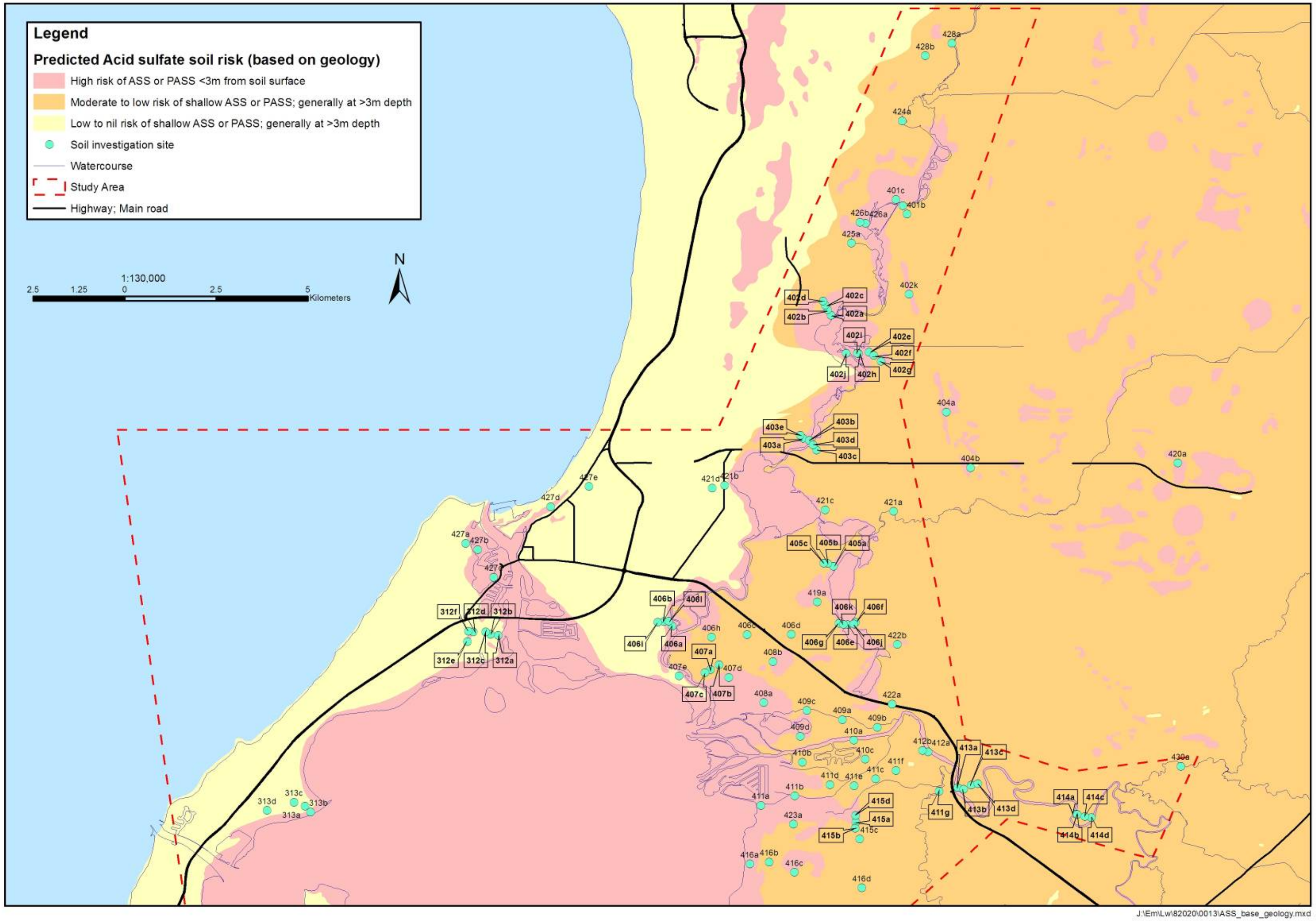
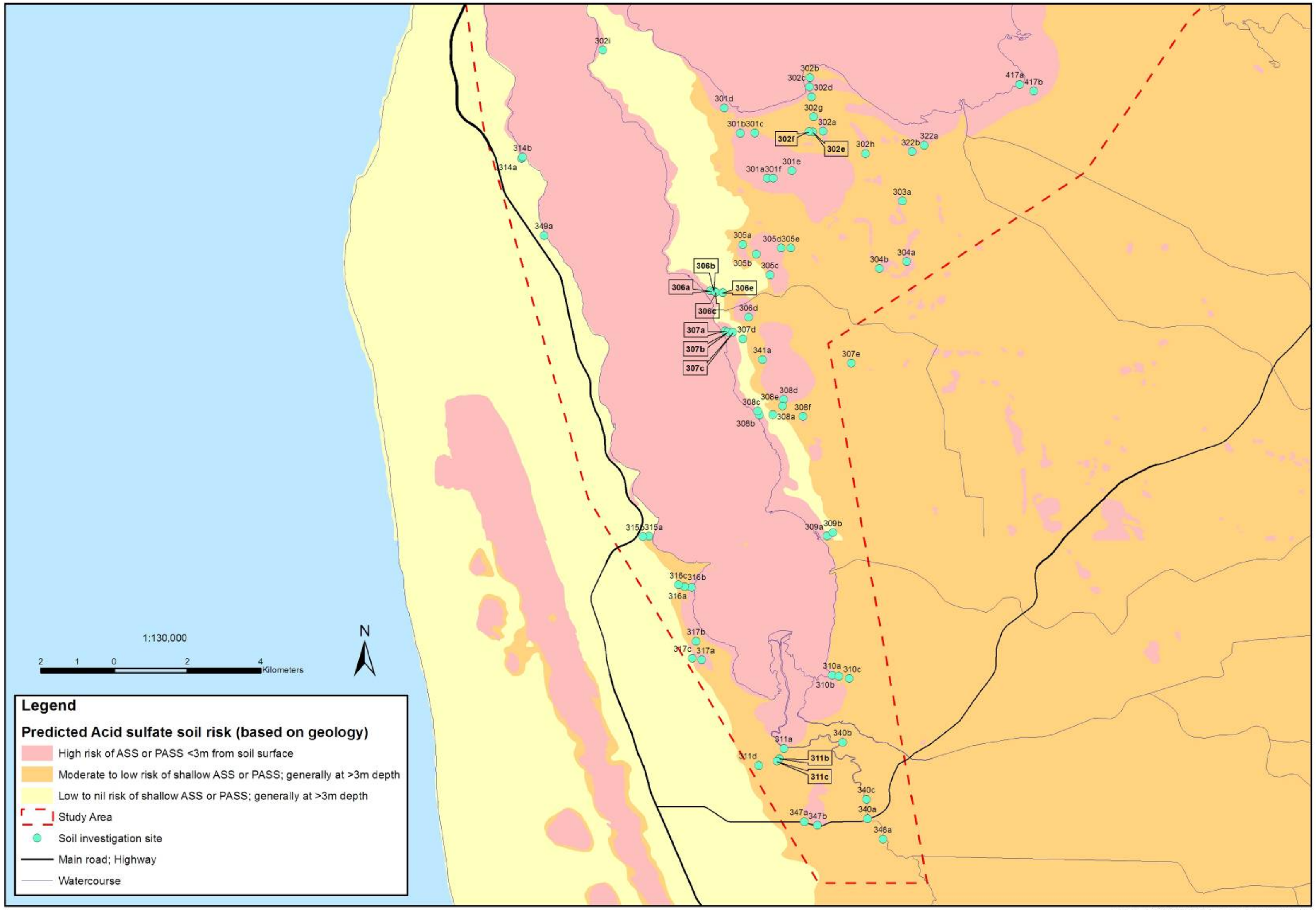


Figure 4: Initial ASS risk map (based on 1:50 000 scale environmental and urban geology mapping) and superficial formation investigation sites (SE Peel inlet, Harvey Inlet and Harvey River). Note: map not printed to scale.



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2 Investigation and mapping methods

On-ground investigations of ASS involved strategic coring to identify broad relationships between shallow lithology, the occurrence of ASS strata, geomorphology and existing map units. This approach followed the standard soil mapping techniques to ensure mapping at 1: 50 000 scales as detailed in Gunn et al. (1988). Information from the on-ground work and supporting sampling and analysis was used to describe the general characteristics of ASS (PASS and Actual ASS) adjacent to the Peel-Harvey Estuary, including the geo-hydrological context of the materials. This formed the basis for classifying the landscape according to ASS disturbance risk levels and is described in the sections below.

2.1 Preparation of base map - Analysis of existing spatial information and development of regional conceptual models of ASS occurrence

An initial base map of expected shallow (<3mbgl) and deeper (>3mbgl) ASS risk was developed (Figure 3, Figure 4) by identification of geological mapping units where ASS materials were expected to occur in the superficial formations, principally based on existing 1:50 000 urban (1977-1982) and environmental geology (19884-1991) map series published by the Geological Survey of WA (see Appendix 1). Digital datasets of specific map sheets examined for this study included:

- Rockingham -Environmental Geology map (index nos. part sheet 2033 II and 2033 III), 1985;
- Mandurah – Urban Geology map (index no. 2032 IV), 1977;
- Pinjarra – Urban Geology map (index no. 2032 I), 1978;
- Lake Clifton-Hemel – Environmental Geology map (index nos. part sheet 2032 II and 2302 II), 1987.

Initial identification of areas with a likelihood of shallow PASS materials occurring was based on the precept that PASS materials occur in and near environments with permanently waterlogged sediments (but not devoid of oxygen) with an abundance of iron, organic matter and a source of sulfate (Dent, 1986). Sulfate sources for superficial formations could be oceanic (via present or former tidal influence), meteoric, discharge of sulfate containing groundwater from deeper aquifers and/or slow oxidation of pyrite minerals in underlying Cretaceous sediments (where these are near surface).

Classification of the ASS risk for geology map units involved broadly evaluating whether map units were likely to contain landforms that would result in the persistence of PASS materials, if not formation of the materials. These included permanently waterlogged, shallow ground-water, wetland/dampland environments, floodplains with likely previous or present hydrological connection to estuarine waters and tidal flats (supratidal, extratidal, intratidal). Geology mapping units with these environments were identified and/or verified using soil-landform (McArthur et al., 1959; McArthur and Bettenay, 1960; van Gool, 1990), geomorphic wetlands (Department of Environment, 2003), vegetation and geomorphology (Heddle et al., 1980 as captured by DEP, 2002). Soil-landscape mapping (van Gool, 1990) was a compilation of land resource mapping for Rockingham (Wells et al.,

1985) and Mandurah-Murray (Wells, 1989). The suitability of existing urban and environmental geology (broadly corresponding to landform units) negated the need to prepare new maps of landform units from aerial photography (as is the standard for mapping programs; Gunn et al., 1988).

2.2 Identification of target sites for ASS investigation:

Target sites for on-ground characterisation and investigations of ASS were identified using the base map of expected ASS risk (Figure 3, Figure 4) and local interpretation of where PASS materials might be expected during on-site reconnaissance. Sites were broadly located as transects across dominant, mainly east-west, landscape patterns (), though individual site placement was determined by local landscape conditions that would determine highest likelihood of ASS occurring (i.e. predominance of wetland vegetation, surface organic accumulations, evidence of shallow and/or at least a semi-permanent water table; see Department of Environment 2004b). Details of site locations are listed in Appendix 2.

Locally significant areas of interest for ASS mapping were identified as a compromise between:

- Representativeness of potential risk areas (including relationship with regional occurrence of units and expected ASS formation pattern)
- Legal and safety access constraints: minimal number of cadastral units accessed (for a transect) and land-holders engaged for site access to facilitate speed of on-ground investigations. IT was also necessary to avoid underground power, gas or telephone services (and overhead power lines).
- Physical access for coring: access tracks with minimal vegetation, trafficable paths and limits of vehicle access
- Potential for additional sites to compliment target sites to provide full representative cross section of geomorphic units.

Problems in meeting safety and physical access criteria meant that it was not possible to conduct in-depth superficial formations investigations in all desired areas. In such situations, observations of surface features were used to evaluate ASS risk complimented with inspection of shallow soil profiles using a hand auger and selected field-testing.

Additional sites were often selected based on the results on initial coring, usually where further information was needed to confirm the presence or absence of ASS in particular areas, clarify relationships with geomorphic features or verify ASS distribution within a map unit.

2.3 Site description, superficial sediment description and ASS sampling.

Investigations involved initial description of site characteristics (dominant vegetation, when identifiable and landform) followed by description and field-testing of soil cores with selected sampling and laboratory analysis of superficial horizons/layers. Superficial sediment investigations were carried out using standard ASS investigation methods described in Appendix 3. These involved description of lithology, textures, colours (including mottling using the 2000 edition Munsell Soil colour charts), concretions, consistency, organic materials and depth of standing water table, where encountered.

Superficial formations were typically cored to 6m using the Department of Environment's Geoprobe^{TM} soil coring system where discreet, sequential 38mm diameter x 1 m length cores were collected within Teflon liners. Geoprobe core-catchers were used within the core barrels for recovery of soft, poorly consolidated materials (frequently encountered in areas immediately adjoining the estuary). Where site access for the drill rig was poor, shallow layers of the superficial formation were cored using a 100mm-diameter stainless steel hand auger to 1-2.5m (depth of coring depending on the depth of water-table and whether the bore hole remained stable during coring).

Field-testing for ASS was carried out at standard 0.25m depth intervals and samples were collected at 0.5m depth intervals for future analysis (Appendix 3). Field testing for PASS materials involved determination of field pH (pH_F), pH after peroxide oxidation (pH_{H2O2}) and the strength of reaction (Appendix 3). The collected samples were sealed in air-tight zip lock bags, with as much air as possible excluded, and immediately frozen in field refrigerators prior to transport to a storage freezer.

2.4 Sample handling and analysis

Selected samples were submitted for preparation (80°C drying for 24 hours, 2mm sieving and grinding as per QASSIT method 22b; Ahern et al., 2004) and/or further analysis for ASS characteristics by commercial laboratories on the basis of interpretation of field descriptions and field ASS testing. Sub-samples of all prepared samples were retained (and archived) in air-tight vials flushed with nitrogen gas. The decision to carry out laboratory analysis of samples was primarily guided by the need to verify field-testing results (both positive and negative indications of ASS) and provide representative information on the chemical characteristics of ASS materials within horizons.

Laboratory analysis of prepared samples involved determining potential and actual acidity (if present). Potential acidity in un-oxidised sulphides was estimated by the chromium reducible sulphur method (QASSIT method 22B; Ahern et al., 2004). Determination of actual acidity involved a combined measurement of pH (pH_{KCl} determined in 1M KCl extracts) and actual acidity (total actual acidity or TAA; QASSIT methods 23A and 23F; Ahern et al., 2004). Using this approach, actual acidity includes exchangeable acidity, acidity associated with organic matter and soluble acidity (Ahern et al., 2004) not accounted for by pH measurement alone (which only determines H+ acidity). TAA was determined when pH_{KCl} was less than 6.5, although since conducting the work the methods have been updated such that TAA should be determined for samples with $pH_{KCl} \geq 5.5$ and ≤ 6.5 when there is evidence of sulfides (Ahern et al., 2004).

PASS materials in this survey identified by chromium reducible sulphur analyses were unlikely to include assay of many mono-sulfidic materials because sample handling and preparation processes were likely to have resulted in the oxidation of these prior to analysis.

Samples with initial laboratory pH less than 4.5 were analysed to determine acid soluble sulfate minerals (QASSIT methods 23C and 20B; Ahern et al., 2004), providing an indicator of iron and/or aluminium-hydroxy sulfate minerals (stores of insoluble sulfate acidity) formed under acidic conditions (McElnea et al., 2002). The presence of such fractions (expressed as %S) in soil and sediment samples was evidence of formation of actual ASS materials (McElnea et al., 2002). Briefly, sulfate present as acid soluble sulfate minerals (S_{nas}) were estimated by S_{HCl}-S_{KCl}, where - S_{HCl} is 4M HCl extractable sulfate-S and S_{KCl} is 1M KCl extractable sulfate-S (see Ahern et al., 2004). These results were only reported where there were no obvious accumulations of organic matter that could be considered to bias such measurements (Ahern et al., 2004). Analysis of acid soluble sulfate fractions is generally only determined when pH_{KCl} <4.5. However, in this survey were also occasionally determined on samples where there were strong indications of actual ASS materials in field pH (pH_F<4) and profile indicators, since pH_{KCl} determined after sample preparation occasionally resulted in pH values that were more than 2 units greater than field pH values.

Measurements of actual acidity (TAA) were expressed in terms of equivalent amounts of H_2SO_4/tonne soil (oven dry weight) whereas acid storage is commonly expressed as units of S (%S w/w) either as reduced S (determined by chromium reducible S) or as oxidised S in acid soluble sulfate minerals (see S_{nas} above). Measurements of acid fractions expressed as %S can be related to equivalent amounts of sulfuric acid by: 1 %S (w/w) = 30.59 kg H_2SO_4/tonne (Ahern et al., 2004).

Samples with initial pH exceeding 6.5 were analysed to determine acid neutralising capacity (QASSIT method 19A1; Ahern et al., 2004). This measurement indicates the readily available alkalinity present in carbonate, organic matter, clay minerals and reactive surfaces in soil materials that might offset acid generated by oxidation of PASS materials (Ahern et al., 2004).

2.5 Data storage, quality assurance and quality control

All site, lithology descriptions, field testing and laboratory analysis results are stored in the Water Information Database, the corporate relational database designed to manage data from environmental sampling programs. Sites were identified by a unique site number with the general code: XXXYYYZZ where XXX denoted the AWRC hydrographic basin number (614 or 613 in this context), YYY denote the transect number and ZZ denoted the site number within each transect.

For this report, the site code has been simplified to XYYz, where X is either 3 or 4, where 3 is the code for sites in the western Peel, Harvey Estuary and Harvey River region (AWRC hydrographic basin number 613) and 4 is the code for sites in the Serpentine and Murray River region (AWRC hydrographic basin number 614). The second part of the site code (YY) denotes the transect number and “z” indicates the site within the transect (as either a=1, b=2, c=3 etc). For example: site code 401d represents the fourth site in transect number one in the Serpentine-Murray basin (see Appendix 2).

Development and implementation of a data management strategy at the commencement of the state-wide ASS risk-mapping project ensured that data collected and stored for the project were of a high quality (Greenbase Consulting, 2003; also see Appendix 3). This strategy involved data and sample tracking technique using chain of custody and field observation forms where sites and samples were identified and linked by unique reference numbers. Validation and verification processes involving cross-checking against superficial lithology descriptions and related data were also used during capture and entry of data to achieve high data quality standards.

All improvements to the ASS disturbance risk map datasets were carried out using ArcGIS where modifications to existing base-geology mapping units were initially identified on hard-copy 1:12 000 map sheets using a combination of aerial photo-interpretation, contoured elevation data (supplied by Department of Land Information), available vegetation and soil-landscape mapping. Digitising of modified ASS risk map units was carried out at 1:12 000 with all changes independently verified against hard-copy mapping on completion of the digitising. Attribute information for the map units was also verified similarly.

Details for quality assurance and control standards applied in the field are outlined in Appendix 3.

2.6 Analysis of field and laboratory data to support mapping of ASS risk

Data from field surveying, soil coring and subsequent laboratory analyses were analysed to determine characteristics of PASS materials within map units, interrelationships with various landforms and the suitability of initial base-map units in defining areas of high PASS risk. This process was carried out with reference to available aerial photography for the study area (Department of Land Information aerial photography Swan Coastal Plain: 2000 – 2005) and is outlined below.

The characteristics of PASS materials for superficial geological sediments were evaluated at each investigation site and classified according to ASS disturbance risk. Field ASS test results and laboratory analyses for each profile were evaluated in conjunction with lithological information (texture, colour, mottling, water table depth) to arrive at an overall characterisation of PASS presence or absence within each profile. This involved assessing whether field-testing indicated the presence of PASS materials (Department of Environment, 2004b), evaluating the extent to which the field test results indicated PASS materials within horizons and within a profile by comparison with laboratory analysis results for selected depths and determining the extent to which the PASS assessments could be applied to identifiable horizons. In the assessment, chromium reducible S analysis results exceeding 0.03% sulfide-S were considered to pose an environmental hazard. The Department of Environment trigger limits for management of ASS materials are set at 0.03% S or acidity (potential or actual) equivalent to 0.9kg H_2SO_4/tonne (Department of Environment, 2004b).

Horizons with actual ASS materials were identified using multiple lines of evidence from field descriptions, field testing and laboratory analyses. Primary evidence of actual ASS materials (formation of sulfuric horizons) was the presence of low field pH (pH_F<4) generally in unsubmerged layers and either jarosite mottling or underlying horizon with PASS materials (Isbell, 1996). Jarosite mottling was evident by formation of pale yellow mottles (Munsell Colour 2.5Y-5Y 8/3-8/6; Van Breemen, 1982; Isbell, 1996). Secondary information was also used to confirm that actual ASS materials were present in horizons with jarosite mottling including pH_{KCl}<4.5 and evidence of actual acidity and acid soluble sulfate minerals (i.e. TAA>0.9kg H_2SO_4/tonne, S_{nas}>0.03% S; Department of Environment, 2004b). When jarosite mottles were not evident, horizons with significant actual acidity (>3.5kg H_2SO_4/tonne) and/or other corroborating evidence of sulfide oxidation (e.g. intense iron mottling, colour, proximity to other PASS materials in profile, field ASS test results) were also considered to contain actual ASS materials (Fanning et al., 1993; Ahern et al., 2004).

The presence of actual ASS materials is considered to indicate a disturbed ASS (Dent, 1986; Fanning et al., 1993; Ahern et al., 2004). We have conservatively constrained our description to the materials present in the profile rather than describing the materials as disturbed ASS, although it is acknowledged that some degree of disturbance (anthropogenic or natural) of PASS materials precedes formation of actual ASS materials.

Classification of ASS disturbance risk was applied using the approach outlined in Appendix 4. This involves evaluating whether shallow ASS are within a depth from surface likely to be disturbed by normal land-use development activities, including excavation, dewatering, drainage and any other activities that may alter water table regimes. Shallow ASS materials are those materials within 3m of the ground-surface that have the capacity to influence near-surface environment and economic resources.

Soil profiles were not classified according to the Australian Soil Classification Scheme (Isbell, 1996) because many profiles contained PASS materials (sulfidic horizons) at >1.5mbgl and the scheme is presently intended for soils with PASS materials at <1.5mbgl (Wilson, 2005). Proposals for changes in the classification scheme (Wilson, 2005) could be used for retrospective classification of these soils since many contained sub-sulfidic horizons, where PASS materials occur at >1.5mbgl (Wilson, 2005), and those with actual ASS materials could be regarded as containing supra-acidic horizons (Wilson, 2005).

The association between sites with shallow PASS materials (for transects of sites) and existing environmental geology, soil, landform, vegetation and hydrological features were assessed to determine whether existing geology map units were sufficient to map areas with shallow ASS hazard (PASS and actual ASS materials). Particular attention was paid to capacity for mapping units to identify areas with shallow PASS in areas with contrasting ASS risk (particularly where high risk units adjoined low risk units, and to a lesser extent where high risk units adjoined moderate risk map units). Where the existing map units were not considered sufficient to capture high ASS risk areas, further assessment was carried out to alter mapping units using either soil (van Gool, 1990), vegetation (Heddle et al., 1980 as captured by DEP, 2002), geomorphic wetland mapping (Department of Environment, 2003), land-surface contours or any other landscape features identifiable by aerial photography that provided improved definition of ASS risk areas.

3 Results

3.1 Characteristics of potential acid sulfate soil materials

3.1.1 Dominant soil materials containing PASS materials

PASS materials predominantly occurred in gley coloured (e.g. greenish- and bluish-grey) silty sands and sands (Figure 5) reflecting the dominance of sandy superficial formations with shallow water-tables adjoining the Peel-Harvey estuary (see also Appendix 5). With increasing elevation and distance from the estuarine environment, PASS materials increasingly occurred in sandy horizons of either deep sandy profiles or sands overlying clays/sandy clays that were brown, olive and occasionally white and gleyed in colour. There were few incidences of shallow silts or clays with PASS materials (see Appendix 5) with many being generally confined to tidal flats (intertidal and supratidal), salt marshes and lower-level floodplains of the Harvey, Serpentine and Murray Rivers. Shells and other carbonate materials were not widely encountered in many superficial sediment horizons containing PASS materials, however, could occur in underlying or overlying horizons. This was common in low-lying Spearwood dunes on the western, north-western and northern side of the estuary (e.g. sites 327a-327e).

Few peat and peaty horizons were encountered in the investigations of superficial sediments adjacent to the Peel-Harvey estuary. These generally occurred only in the surface sediments (<0.5mbgl) of wetlands and marshes and invariably contained PASS materials (e.g. the wetland at North Yunderup, site 409d). There were also few occurrences of sub-surface horizons with any visible residual organic materials (for example peaty sands or peaty silts) except for indications of buried profiles in back-swamps of the Serpentine River (e.g. Dunkerton Rd 419a) and coastal dunes (e.g. Shannon Rd 427d and south Mandurah bridge 412d).

The greatest concentrations of PASS materials occurred in horizons with clay and silt textures, as indicated by % S concentrations of representative sample analyses for a range of horizons (Figure 5). Median sulfide-S concentrations for clay and silt materials were 0.04% and 1%, respectively, however, clays could contain up to 3.4% sulfide-S (equivalent to 104 kg of H_2SO_4/tonne), whereas silts could contain up to 2.4% sulfide-S (equivalent to 73 kg of H_2SO_4/tonne). Where PASS materials occurred in coarse textured horizons, these were generally less than 1% sulfide-S (Figure 5), particularly the silty sands and sand materials that were most frequent in the profiles investigated around the Peel-Harvey Estuary. Sands with PASS materials identified in this survey contained a median of 0.05% sulfide-S (exceeding that of clay horizons with PASS materials), but could be up to 0.85% sulfide-S. Similarly, silty sands with PASS materials generally had similar sulfide contents (median of 0.06% sulfide-S) though could be up to 3.1% sulfide-S in some cases (Figure 5). Although infrequently encountered in this survey, ferruginous sands and coffee rock materials contained up to 0.1% sulfide-S (median of 0.06% sulfide-S).

The occurrence of PASS materials within profiles broadly corresponded with patterns of horizonation in many profiles, although there were examples where this was not the case. For example, in some profiles detectable concentrations of PASS materials occurred in the lower part of a horizon, but not in the remainder, with no visual or textural distinctions of this difference (for example profiles 305b and 306b near Lake Mealup). Similarly, for some clay, sandy clay and clayey sand horizons overlaid by sand horizons containing PASS materials, there were PASS materials in the shallowest part of these horizons, but not at greater depth in the same horizon (e.g. north Austin Bay profile 416a, Robert Bay profile 301d and Lake Mealup site 305d). PASS materials also appeared to occur sporadically in some horizons (particularly clayey sands) as evidenced by field-test results or sulfide analyses (for example the profile 310a north of the Harvey River delta). There were commonly no visual or textural indications that PASS materials were irregularly distributed, though some horizons where this occurred were heavily mottled (e.g. east Yalbanberup pool site 402e).

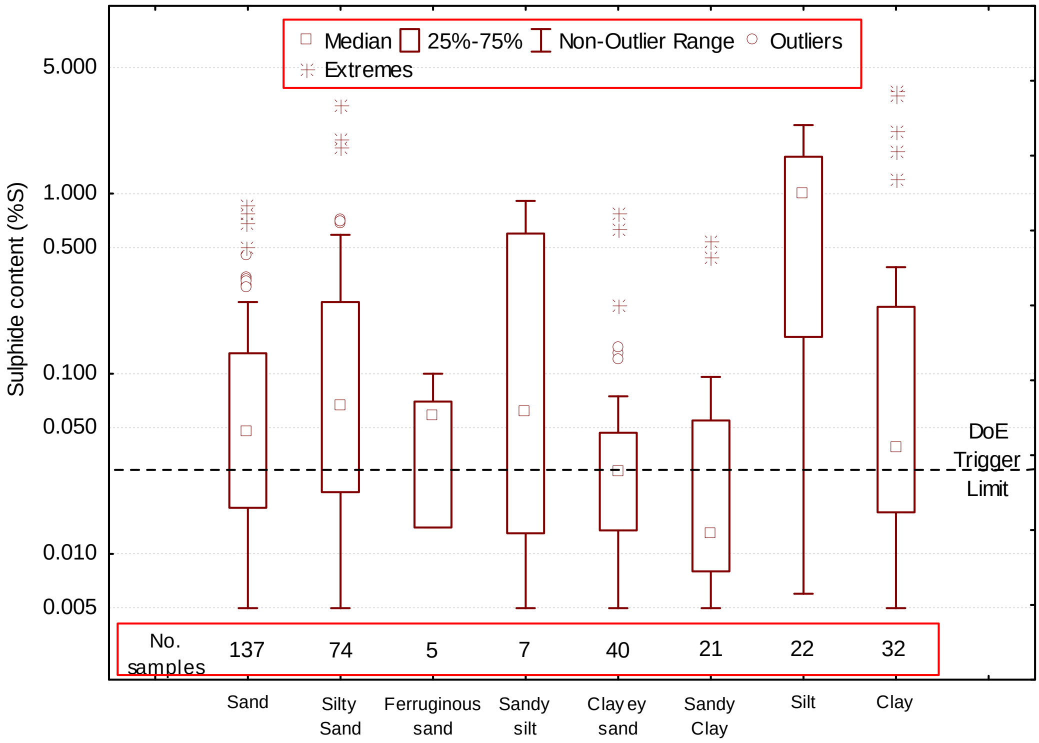


Figure 5: Concentrations of PASS materials (as indicated by % sulfide-S on a logarithmic scale) for representative samples of horizons (grouped by dominant soil texture).

3.1.2 Distribution with depth

The depth of PASS materials in superficial sediments varied widely from immediately beneath topsoil horizons (<0.1mbgl) to horizons occurring at over 5mbgl (with no overlying PASS materials). PASS materials were within 3m of ground-surface in over 75 per cent of profiles investigated with 48 per cent of these containing materials within the surface 2m and 28 per cent containing PASS materials 2-3mbgl (Figure 6). PASS materials could occur deeper in superficial sediments (>3mbgl), overlaid by thick horizons that did not contain PASS materials, however, these were not extensively investigated in this study.

There were few profiles investigated where PASS materials occurred within 0.5m of the ground-surface (Figure 6), but this does not indicate that there were no areas with very shallow PASS materials. Few shallow PASS materials were found because most investigations were carried out where drill rig access was possible, thereby largely excluding tidal flats and wetland basins. Significant concentrations of PASS materials were frequently found within 0.5m of the ground-surface where hand-auger investigations were carried out in wetland basins and tidal flats (particularly supra-tidal flats).

Profiles with shallow PASS materials (<3mbgl) were typically associated with PASS materials throughout a number of underlying horizons, particularly those dominated by sandy horizons (see

Appendix 5). It was common for superficial sediment profiles to contain shallow PASS materials concentrated in up to 2m of sandy horizons or a mixture of sand and silt horizons but with minor or no PASS materials in deeper sandy or clay horizons (see example profiles in Figure 7a and b, Figure 8b and Figure 9a). These were common in areas not immediately adjacent to the estuary or rivers (e.g. Austin Bay profile 302b and profile 411d inland of south Yunderup).

Near to the estuary, rivers, lakes or wetlands, PASS materials could frequently occur in sand and silty sand layers within 1 m of the ground-surface and throughout all underlying horizons to depths exceeding 6mbgl (see example profile in Figure 8a). An area where this is best illustrated was on the western shore of the estuary (profiles 317a, 317b and 316a south of Island Point and 313b near Ward Point;) where PASS materials up to 0.35 per cent sulfide-S occurred in olive or grey silty sand horizons at less than 1.5mbgl and throughout underlying horizons to 6mbgl. Similarly, sand dominated superficial sediments in areas adjoining lakes and wetlands and throughout the lower Serpentine could also contain PASS materials in shallow surface horizons and all underlying horizons (see example profile in Figure 8b). This occurred in many profiles in the Furnissdale-North Yunderup area (e.g. 408a, 407b, 409d, 470b and 470c) including the Barragup wetland profile (408b) as well as profiles near Lakes Mealup and Lake McLarty (305a and 306d).

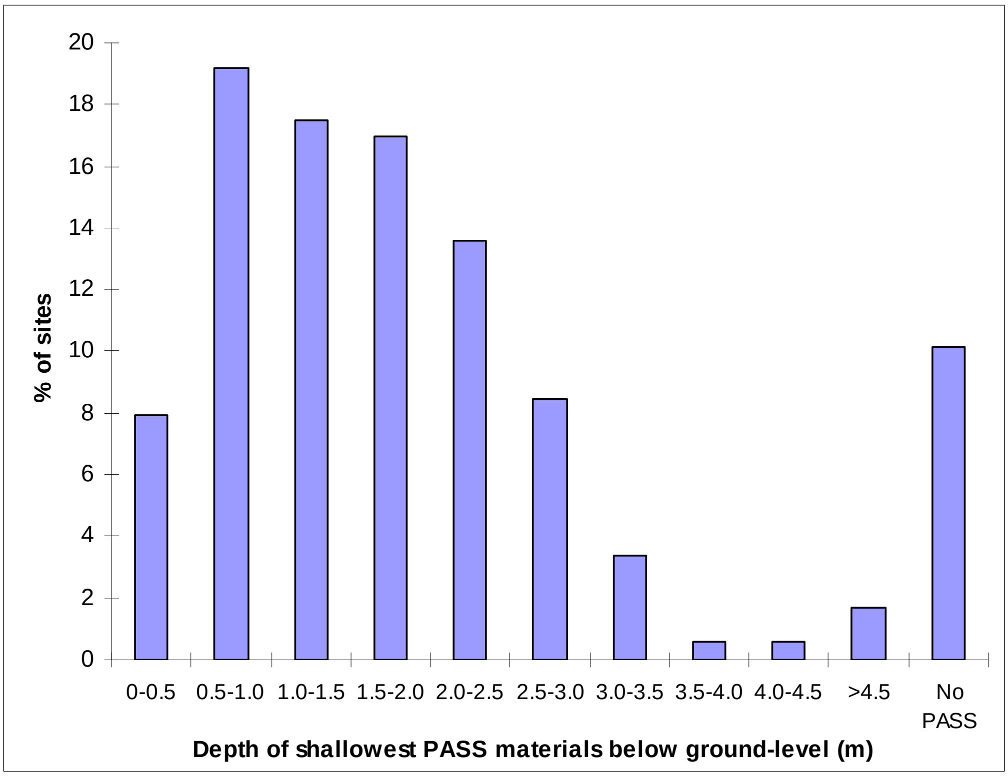
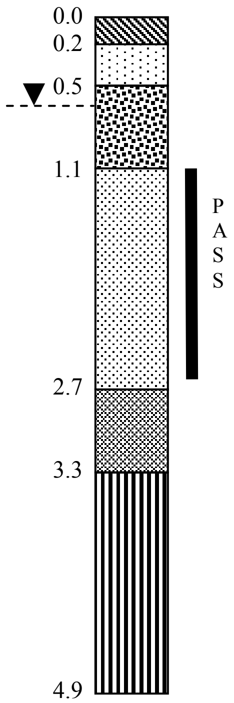


Figure 6: Distribution of sites classified by depth of shallowest PASS materials below ground-level.

Where PASS materials were only present in deeper horizons of the superficial sediments (>3mbgl) these were generally sporadically distributed in thin lenses interspersed among soil materials containing small concentrations (<0.02 per cent sulfide-S) of PASS materials (see example profile in Figure 9b). This pattern was common where mottled bluish-grey and green sandy clay or clay materials occurred at depth (which was most likely the upper part of the Guildford formation). Typical profiles included those in the Murray

Figure 7: Examples of common profiles in low-lying land adjoining the Peel-Harvey Estuary with PASS materials only in (a) shallow silty sand or (b) sand and silt horizons but not underlying deeper horizons (pH_F, pH_{FOX} and reaction as per Appendix 3; S_{Cr}=laboratory analysis of Chromium reducible S).

(a) Site: 302b Location: East Robert Bay, Austin Bay Conservation Reserve



Description

Top soil and sand very fine to coarse vegetation, roots, poorly sorted

Sand, white/grey, organic material very fine to medium sub-angular to sub-rounded, moderately sorted.

Sand, light pale brown, very fine to medium, sub-angular to sub-rounded, well sorted, mottled dark brown (5Y 8/1)

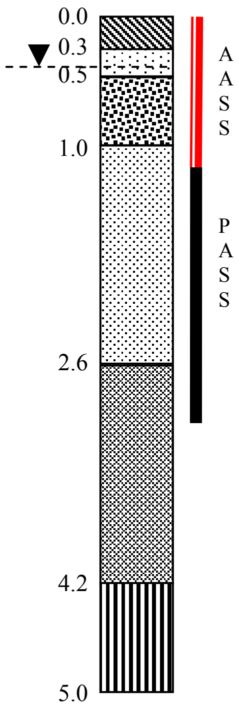
Silty sand, brown/olive (fine), medium with minor large grains, sub-rounded, well sorted (5Y 5/4)

Silty sand, dark olive/green very fine to fine, sub-angular to sub-rounded, well sorted (2.5Y 8/2)

Calcareous sand, cemented lenses, very coarse (5Y 5/4)

Depth (cm)	pH_F	pH_{FOX}	Reaction	S_{Cr} (%)
0.25	4.7	4.0	-	
0.50	5.1	3.8	-	
0.75	4.8	3.2	-	
1.00	4.5	3.9	L	0.01
1.25	6.4	4.4	L	
1.50	6.8	1.7	X	
1.75	7.0	1.9	X	
2.00	7.1	2.0	X	0.59
2.25	7.2	2.1	X	
2.50	7.5	2.9	M	
2.75	7.5	6.0	M	
3.00	7.7	6.2	M	0.02
3.25	7.6	6.3	L	
3.50	8.3	6.7	L	
3.75	8.3	6.7	L	
4.00	8.5	6.6	L	
4.25	8.3	6.7	L	
4.50	8.4	6.7	L	
4.75	8.3	6.7	L	

(b) Site: 409d Location: Murray River Backswamp, North Yunderup



Description

Peat sand with organics

Sand, white, very fine to medium, angular to sub-angular, mod. sorted

Sand with silt lenses. Ferruginous at water-table surface

Silt, black, shell grit, very soft with sulfide odour (Gley 1 2.5/N)

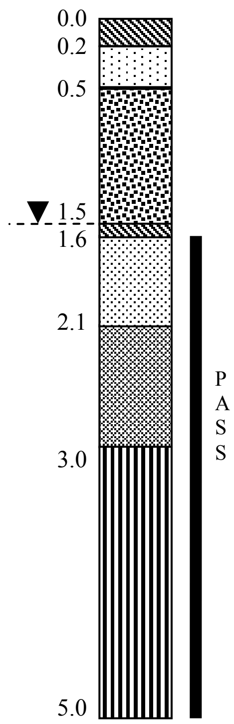
Clay with iron mottling at first, change olive green to dark olive green (5Y 4/3)

Clay very stiff dry mottled red olive green with carbonate nodules coated by red iron oxide (possibly hematite)

Depth (cm)	pH_F	pH_{FOX}	Reaction	S_{Cr} (%)
0.25	3.6	1.6	H	
0.50				
0.75				
1.00				
1.25	3.5	1.6	M	
1.50				1.40
1.75				
2.00	6.4	1.0	X	1.90
2.25	6.7	1.0	X	
2.50	6.8	1.8	X	2.10
2.75	7.0	3.6	H	
3.00	7.3	3.9	H	
3.25				
3.50	7.3	7.0	H	0.03
3.75				
4.00	7.3	7.0	H	
4.25				
4.50				
5.00	7.3	7.0	H	

Figure 8: Examples of common profiles in low-lying land adjoining the Peel-Harvey Estuary with PASS materials throughout profiles dominated by silty sands (a) or sands (b) (pH_F, pH_{FOX} and reaction as per Appendix 3; S_{Cr}=laboratory analysis of Chromium reducible S) .

(a) Site: 317b Location: North Harvey Delta, Off Sthrn Estuary Drive

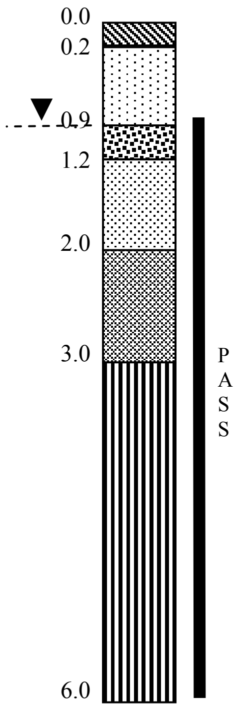


Description

- Top soil black, roots, organics, dark fine to medium, moderately sorted, rounded (2.5 Y 3/1)
- Sand, grey, very fine to medium, sub-rounded to rounded, moderately sorted (10 YR 7/1)
- Sand, grey, very fine to medium, sub-rounded to rounded, moderately sorted (10 YR 8/1)
- Silty sand, mottled brown, iron cemented (10 YR 3/3)
- Silty sand, dark olive, very fine to medium, sub-rounded, poorly sorted (5 Y 4/2)
- Silty sand, greenish grey, very fine – medium, rounded, moderately sorted, some minor heavy minerals (5 Y 5/2)
- Silty sand, grey fine to medium, rounded to well rounded, well sorted, some minor heavy minerals (5 Y 5/2).

Depth (cm)	pH_F	pH_{FOX}	Reaction	S_{Cr} (%)
0.25	5.9	4.1	L	
0.50	6.0	4.3	L	
0.75	6.2	5.2	L	
1.00	6.2	5.1	L	
1.25	6.4	5.2	L	
1.50	6.1	3.3	X	0.20
1.75	5.7	1.4	X	
2.00	5.4	1.4	X	0.30
2.25	5.0	1.4	X	
2.50	5.4	1.4	X	0.35
2.75	5.6	1.4	X	
3.00	6.2	1.5	X	0.17
3.25	5.6	1.5	X	
3.50	5.8	1.5	X	0.24
3.75	5.8	1.6	X	
4.00	5.9	1.6	X	
4.25	6.0	1.6	X	
4.50	6.0	1.5	X	
4.75	5.9	1.6	X	
5.00	6.0	1.7	X	

(b) Site: 407b Location: Off Ronlyn Road, Furnissdale



Description

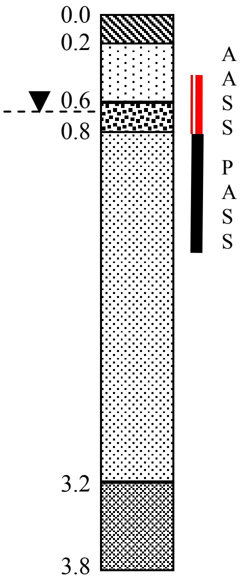
- Top soil, minor organics
- Sand very fine to medium angular, moderately sorted
- Sand light brown, iron, angular to subrounded, fine to coarse, poorly sorted
- Sand olive green/grey, subangular to rounded fine to very coarse, moderately sorted. Minor silt (Gley 1 5/N)
- Sand, grey, subangular to rounded fine to very coarse, moderately sorted. Minor silt (Gley 1 6/1)
- Sand grey, fine to coarse, subrounded to rounded, moderately sorted (Gley 1 6/1)

Material reaction peroxide
L – slight effervescence
M – moderate reaction
H – vigorous reaction
X – volcanic, very vigorous reaction

Depth (cm)	pH_F	pH_{FOX}	Reaction	S_{Cr} (%)
0.25				
0.50				
0.75	5.8	2.9	M	
1.00				
1.25	5.7	1.5	L	
1.50				0.12
1.75	5.6	1.5	X	
2.00				
2.25	4.8	2.1	X	
2.50	5.1	1.9	M	
2.75				
3.00	5.1	2.1	M/H	0.02
3.25				
3.50	5.9	1.8	L	
3.75				
4.00	6.1	1.7	L	
4.25	6.1	2.1	L	
4.50				
4.75	6.3	2.1	X	

Figure 9: Examples of common profiles in low-lying land adjoining the Peel-Harvey Estuary with PASS materials only in shallow silty sand (a) or sand and silt horizons (b) but not underlying deeper horizons (pH_F, pH_{FOX} and reaction as per Appendix 3; S_{Cr}=laboratory analysis of Chromium reducible S).

(a) Site: 305d Location: East Lake Mealup



Description

Top soil, loam minor, organic roots, vegetation

Sand, minor silt, very fine to coarse, angular to sub-angular, poorly sorted, roots,

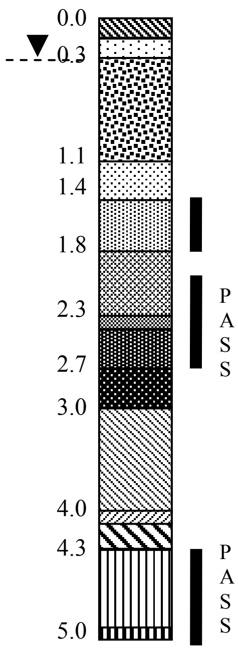
Sand, minor silt, light pale brown, yellowish red mottles, very fine to medium, poorly sorted (Gley 1 7/5 GY)

Sandy clay, mottled olive/grey/brown sand, very fine to coarse angular to sub-angular, poorly sorted (Gley 1 7/5 GY)

Clay, lenses of red and yellow-red mottles (Gley 1 7/N)

Depth (cm)	pH	$pH_{(FOX)}$	Reaction	S_{Cr} (%)
0.25	3.9	2.6	L	
0.50	3.4	1.7	L	0.01
0.75	3.4	2.2	L	
1.00	3.6	1.8	X	0.54
1.25	5.7	2.3	H	
1.50	6.1	2.6	H	0.06
1.75	6.3	2.8	H	
2.00	6.6	6.5	X	0.01
2.25	6.8	6.7	X	
2.50	7.0	6.8	X	
2.75	7.0	7.1	X	
3.00	7.0	5.6	X	
3.25	7.1	6.1	H	
3.50	7.1	6.1	H	
3.75	7.0	6.5	H	

(b) Site: 307e Location: McSwann Road, Lake McLarty



Description

Top soil. Peaty sand, grey, fine medium, sub-rounded (10 YR 2/1)

Sand, grass, minor peat, nodules of peat, fine coarse, sub-angular, sub-rounded well sorted (10 YR 4/1)

Sand, loamy grey, fine coarse, sub-angular to sub-rounded, moderate sorted, minor clay (7.5 YR 7/1)

Sand, minor clay, slight cemented, mottled, brown/dark grey, sand -fine coarse, rounded to sub-rounded, poorly sorted, (7.5YR 3/1)

Sand, iron cemented, mottled brown, minor clay, fine to very coarse, rounded to well rounded, very poorly sorted (7.5 YR 5/8)

Clayey sand, saturated brown, cemented fine clay nodules, fine to very coarse, rounded to well rounded, poorly sorted (7.5 YR 3.3)

Clayey sand white, fine to medium, rounded to well rounded (7.5 YR 7/1)

Clayey sand, white, cemented, very fine to fine sand, rounded (Gley 3 8/10 B)

Clay, white, dry cemented, minor iron mottling (Gley 2 8/10B)

Clayey sand, gravel nodules, yellowish-red mottles (7.5 YR 8/1)

Clayey sand, medium to gravel rounded, poorly sorted (Gley 2 8/5 PB)

Clayey sand, mottled olive/grey, gravel, sub-rounded (2.5 Y 7/3)

Clayey sand, olive (3.5Y 6/8)

Depth (cm)	pH	$pH_{(FOX)}$	Reaction	S_{Cr} (%)
0.25				
0.50	6.5	5.1	L	0.06
0.75	7.0	5.8	L	
1.00	7.0	5.9	L	
1.25	6.6	5.3	L	
1.50	6.4	3.6	L	0.01
1.75	6.1	4.3	H	
2.00	6.2	3.5	X	0.03
2.25	6.2	3.8	X	
2.50	6.3	3.7	M	0.01
2.75	6.5	3.9	L	
3.00	6.2	4.1	L	0.02
3.25	6.2	3.5	L	
3.50	6.3	4.6	L	
3.75	6.2	4.5	L	
4.00	6.2	3.6	L	
4.25	6.3	3.5	L	
4.50	6.2	3.7	L	0.02

River delta (e.g. sites 411e and 416b) and dunes east of the Serpentine River (e.g. sites 402e and 402g) and Lake McLarty (site 307e) where sporadic and minor PASS materials occurred in mottled clay and sandy clay layers below generally sandy surface horizons of variable thickness. Exceptions to this pattern of PASS occurrence occurred in the lower-level floodplains of the Harvey River in particular (e.g. Harvey River sites 311a – 311c). Mostly black and greenish-grey clay horizons occurring at below 1.3mbgl in these profiles contained significant PASS materials throughout the depth of investigation (up to 6mbgl).

3.1.3 Depth of submergence of PASS materials

A high proportion of superficial sediments contained PASS materials that were only marginally below the surface of water-tables. Over 35 per cent of superficial sediment profiles contained PASS materials at less than 0.5 metres below the water-table (Figure 10). This applied to only those profiles where both water-table levels and PASS materials were detected and PASS materials were within 3.5m of the ground surface. A further 14 per cent of profiles contained PASS materials submerged between 0.5m and 0.75m below the water-table (Figure 10). These results exclude profiles where PASS materials were <0.5mbgl or 0.5 – 0.75mbgl and PASS would naturally be near the water-table unless the land is submerged (i.e. the water-table is above the ground surface).

A number of profiles (23 per cent) contained PASS materials above the watertable, as indicated by negative submergence values in Figure 10 (e.g. south Mandurah bridge site 312d). Where this occurred PASS materials occurred in horizons with organic rich horizons, clay, actual ASS materials or extensive iron mottling in the horizon above the water-table.

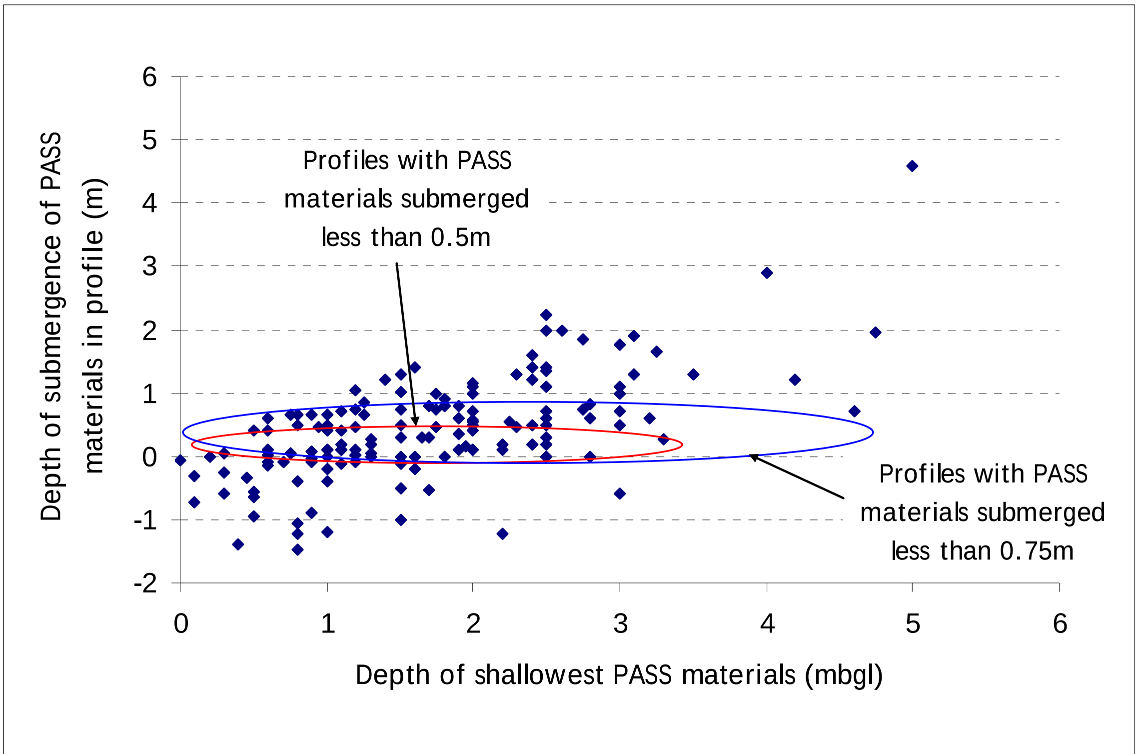


Figure 10: Plot of the depth at which shallowest PASS materials occurred in superficial sediment profiles (mbgl) in relation to the depth that the materials were submerged below the water-table (measured at the time of coring), for profiles where both PASS materials occurred and a water-table measurement was available (145 sites).

Some PASS materials could also occur well below the surface of the water table – at up to 4.6m (e.g. South Yunderup Rd site 411g). This generally corresponded with the shallowest PASS layers being more than 2m below ground-level. However, some sites contained deeper PASS materials (>4mbgl) could still be within one metre of the water-table (e.g. Southern Estuary Drive site 311d and South Mandurah Bridge site 311d).

3.1.4 Acid storage in PASS materials

The storage of acidity in PASS materials was calculated on an area basis for selected sites to provide an indication potential acidity (as equivalent tonnes of sulfuric acid) in the similar landform immediately surrounding the site. Estimates of acid storage were applied to the shallowest 1 m of the profiles judged to contain PASS materials (see section 2.6) using estimates of sulfide content determined by the chromium reducible S method. A depth of 1 m was used in the calculations to normalise estimates and allow comparisons to be made between sites.

Since only selected samples of horizons were analysed to estimate sulfide-S content a number of assumptions were employed to calculate acid storage:

- Analysis results were applied across horizons where these could be associated with consistent field-testing results or morphological characteristics (colour, texture, etc.);
- In some instances, information from only a single sample was collected, in which case the result was averaged across the estimation interval (1m);
- Every 1% S (weight S per weight soil material) was equivalent to 30.59 kg H_2SO_4/tonne (Ahern et al., 2004).
- Estimates were restricted to layers of less than 1 m thickness where the shallowest PASS materials were <1 m thickness or where there was insufficient analysis information to enable reliable estimation of acid storage for all horizons with PASS materials;
- Bulk density of all sediment horizons was assumed to be an average of 1.2 tonnes/m^3, since many contained fine sandy to silty sand materials (that generally have a similar average bulk density). This was used to calculate the weight of soil materials per hectare containing PASS materials and then the weight of acidity stored within these. It was possible that the bulk densities for profiles with clays were likely to have exceeded that of silty sands and sands, which indicates that the stored acidity for such profiles were likely to be slightly over-estimated (up to 20 per cent).

Acid storage ranged over three orders of magnitude from less than 10 tonnes H_2SO_4/ha to more than 1,000 tonnes H_2SO_4/ha (Figure 11). Superficial sediments with PASS materials occurring in mainly coarse textured materials (sands and silty sands) could contain as much acid storage as those with PASS materials in mainly finer textured materials such as silts and clays, though there were fewer of the latter (Figure 11). This result broadly reflected the patterns of sulfide contents for soil materials (Figure 5), and confirms that a similar pattern also occurs for whole profiles (where acid storage is considered across horizons). There was only one profile where peat was the dominant soil material containing PASS materials (Mandurah town site, 427d) and the acid storage from the 0.2m layer of this was estimated to be equivalent to 56 tonnes H_2SO_4/ha (not shown in Figure 11).

Greatest concentrations of acid storage generally occurred in superficial sediments closest to the estuary or rivers draining to the estuary (Figure 12, Figure 13), however were not limited to these landscapes. Significant shallow storage of potential acidity occurred in the floodplains of the Serpentine River (between 354 up to 1235 tonnes H_2SO_4/ha), floodplain terraces of the Murray River (257 – 367 tonnes H_2SO_4/ha) and low lying wetlands and dunes immediately adjoining the Peel-Harvey estuary (e.g. Robert Bay, Falcon Point and north of Island Point). Storage of more than 100 tonnes H_2SO_4/ha also could occur in superficial sediments adjoining wetlands some distance from the estuary, including Lake Mealup (at least 156 tonnes H_2SO_4/ha), Lake McLarty (at least 128 tonnes H_2SO_4/ha) and the Barragup Swamp (at least 118 tonnes H_2SO_4/ha). Given that these assessments are based on cores not taken within the sediments of the wetlands it was likely that much greater acid storage occurred in these environments. Acid storage in many low-lying areas without obvious wetland features and not adjoining the estuary was generally between 10 and 100 tonnes H_2SO_4/ha (Figure 12 and Figure 13).

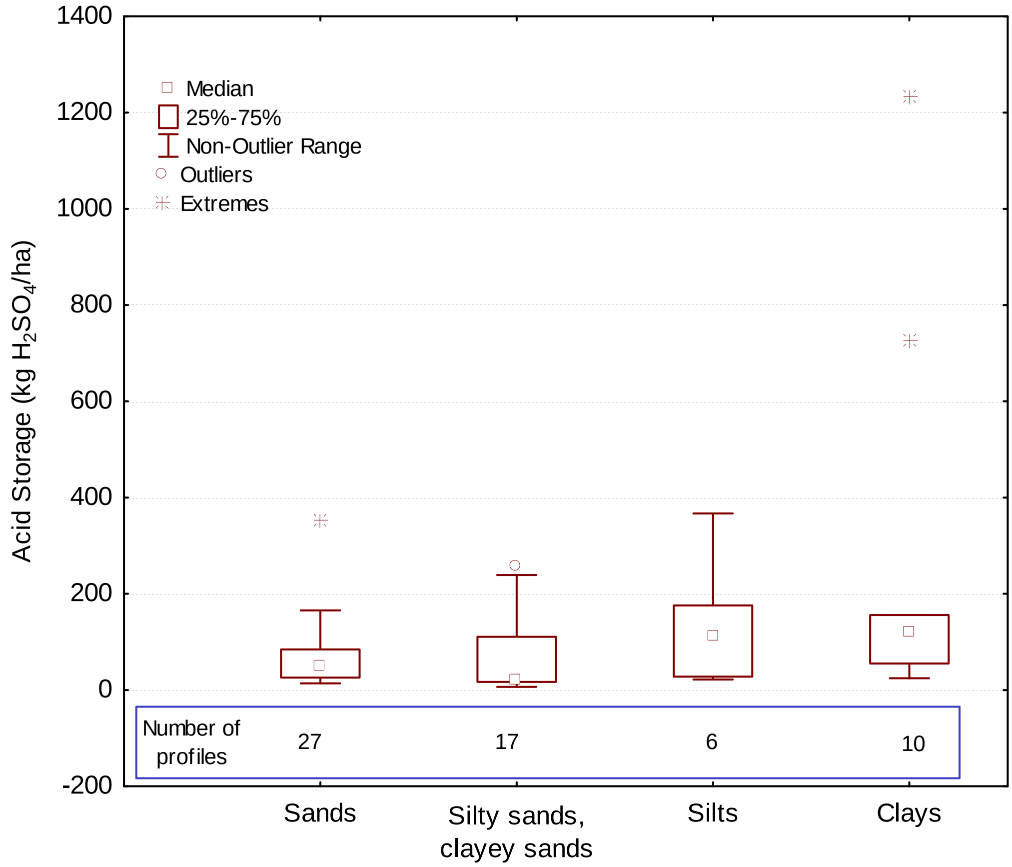


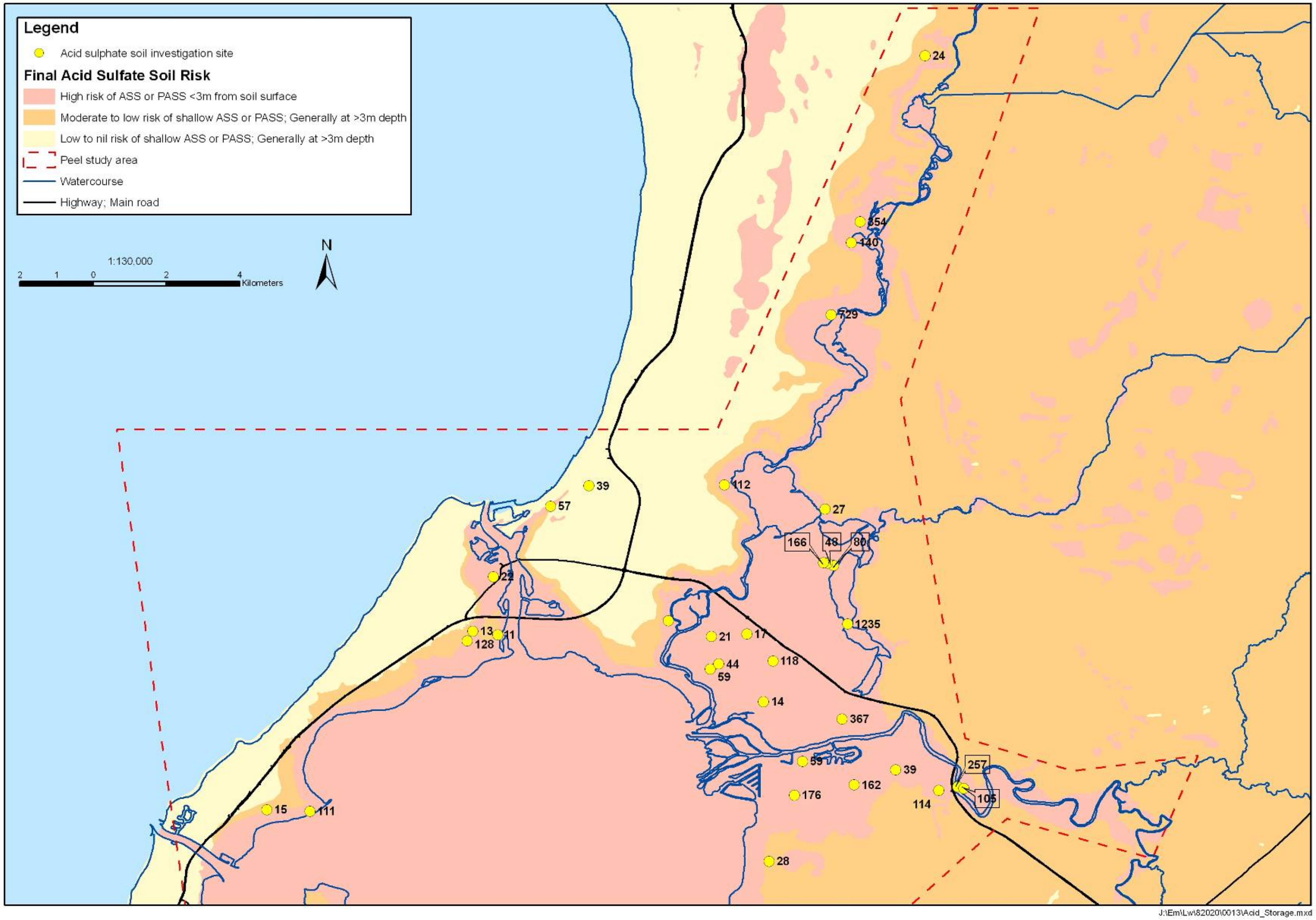
Figure 11: Estimation of acid storage within the shallowest PASS materials (up to 1 m thickness) categorised by the dominant textures in which the PASS materials occurred.

3.1.5 Characteristics of Actual ASS materials

Actual ASS materials were identified in thirteen percent (24) of the 177 profiles investigated, despite the focus of this survey on identifying and mapping superficial sediments with PASS materials. These occurred mainly on the eastern side of the Peel-Harvey estuary in low-lying areas predominantly adjoining the lower Murray (Murray River delta), though actual ASS materials also occurred in some profiles near Robert and Austin Bay, Lake Mealup, Black Lake (on the Serpentine River) and the lower Harvey River (Table 1).

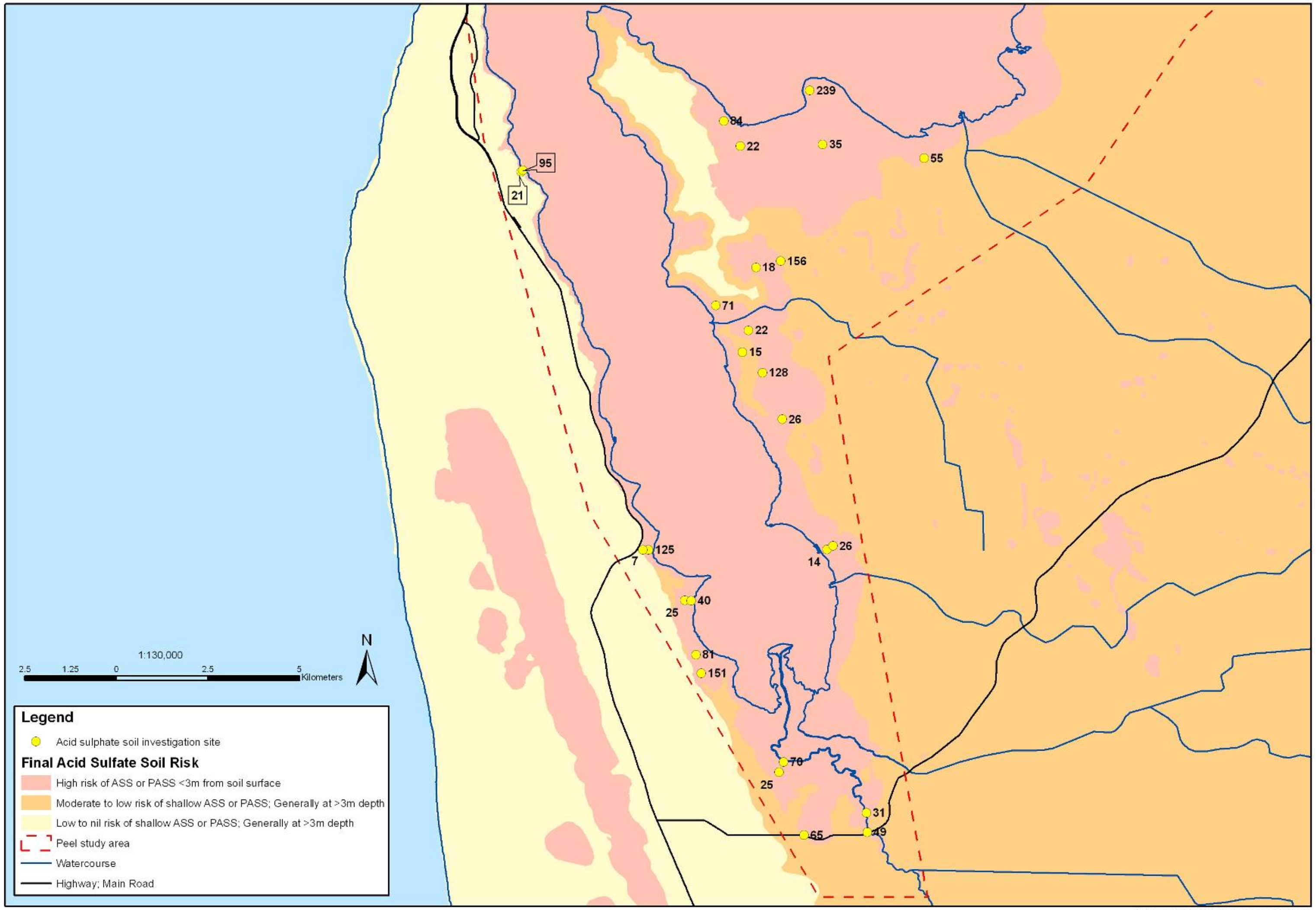
Visible pale yellow mottling (Munsell Colour 2.5Y-5Y 8/3-8/6) indicative of jarosite formation (Figure 14) and field pH less than 4 indicated the presence of actual ASS materials in five profiles. These profiles were Lake Amarillo site 426a, Black Lake site 406j, South Yunderup profiles 411f and 410c and Austin Bay profile 322a (Table 1). Except for sites 406j and 410c (where no laboratory data was available), this was corroborated pH_{KCl} being less than 4.5, significant actual acidity (determined by TAA) and acid soluble sulfate minerals (indicated by $\%S_{nas}$; Table 1). Actual acidity in these horizons exceeded

Figure 12: Estimated storage of potential acidity (tonnes H_2SO_4/ha) within the surface 1m of shallow PASS materials encountered at Acid Sulfate Soil investigation sites in



superficial sediments around the Peel Inlet, Serpentine River and Murray River. Note: map not displayed to scale.

Figure 13: Estimated storage of potential acidity (tonnes H_2SO_4/ha) within the surface 1 m of shallow PASS materials encountered at Acid Sulfate Soil investigation sites in superficial sediments around the SE Peel Inlet, Harvey Inlet and Harvey River. Note: map not displayed to scale.



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3.8 kg H_2SO_4/tonne whereas concentrations of acid soluble sulfate minerals were as much as 0.2% S (equivalent to 6.1 kg H_2SO_4/tonne). For reference, the Department of Environment and Conservation trigger limits for management of ASS materials are set at 0.03% S or acidity (stored or actual, including acid soluble sulfate minerals) equivalent to 0.9kg H_2SO_4/tonne (Department of Environment, 2004b). Jarosite mottling was also identified visually (and with field pH<3.5 for soil scrapings from jarosite mottles) at three sites in profiles exposed by drain construction (Bens Rd site 415d, Robert Bay drain sites 301e and 301f; Table 1).

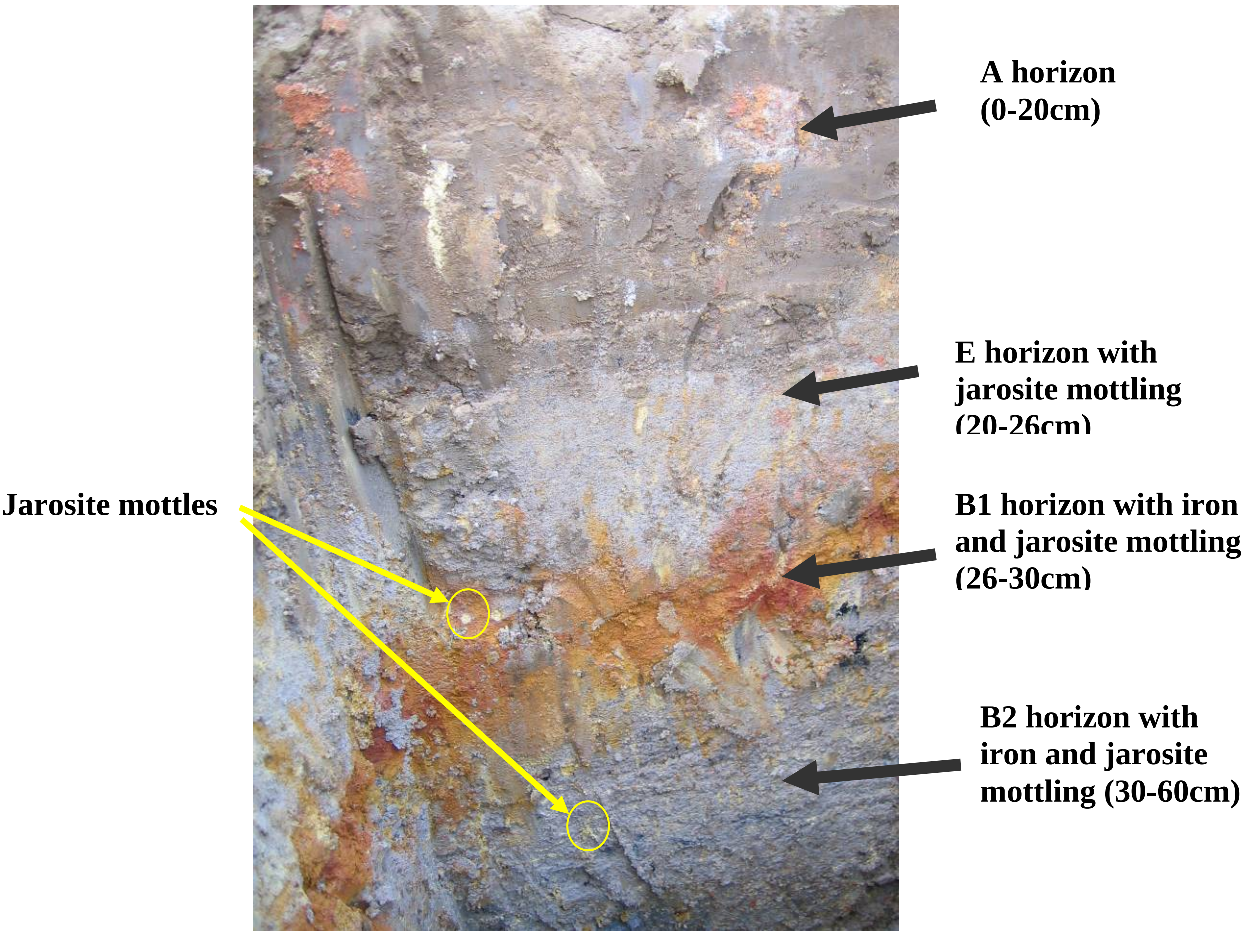


Figure 14: Jarosite evident as pale yellow mottling (Munsell Colour 2.5Y 8/3) within an actual ASS profile in South Yunderup site 411f

Many profiles were assessed as containing actual ASS materials, however did not contain visible jarosite mottling (e.g. Murray River Site 414a and Harvey River mouth site 311b; Table 1). These profiles contained horizons with significant iron mottling, pH_F less than 4, pH_{KCl} frequently less than 4.5, actual acidity generally greater than 3 kg H_2SO_4/tonne and the presence of acid soluble sulfate minerals (S_{nas}>0.03%). These chemical characteristics were typical of actual ASS materials (McElnea et al. 2002; Ahern et al., 2004) and exceeded regulatory trigger limits of 0.03% S or acidity equivalent to 0.9kg H_2SO_4/tonne (Department of Environment, 2004b).

Field pH testing and significant iron segregations (evident as mottling; see Fanning et al., 2003) in horizons overlying horizons with PASS materials were considered evidence of actual ASS materials in some profiles (after Dent, 1995; Isbell, 1996), despite a lack of support in pH_{KCl} results (Table 1). Determination of pH_{KCl} after sieving, drying and grinding of such samples resulted in increases in pH by more than 2 units to pH values exceeding 5 (e.g. Lake Mealup site 305d and Murray River site 414c). This was also associated with actual acidity being less than 0.5 kg H_2SO_4/tonne, though is not generally considered to be significant for samples exceeding pH 4.5 (Ahern et al., 2004).

Actual ASS materials in all profiles were frequently associated with residual PASS materials either in the same horizons or as unoxidised materials immediately below these horizons (Table 1). This was additional evidence that actual ASS materials had been derived from the oxidation of PASS materials and is a key factor in evaluating presence of actual ASS materials (Isbell, 1996). Where laboratory analyses were undertaken, PASS materials in association with actual ASS materials could range from less than 0.02% sulfide-S to more than 1% sulfide-S. PASS materials of up to 2.4 % sulfide-S (equivalent to 73 kg H_2SO_4/tonne) occurred with actual ASS materials in silty sand and silt layers in one profile alongside a flood drain (South Yunderup site 411b; Table 1). By contrast, there were horizons in some profiles that contained actual ASS materials with no detectable PASS materials though were directly underlain by horizons with PASS materials.

Actual ASS materials occurred at a range of depths from ground surfaces within layers of between <0.2m up to 1.7m in thickness (Table 1). Where near surface actual ASS materials occurred (<1mbgl), such as in South Yunderup, there were classical surface indications of intense soil acidification at the sites such as scalding, salt efflorescences, bare ground or surface iron precipitates (Fanning et al., 2002; Rosicky et al., 2004). For many sites with actual ASS materials however, there were generally no surface indications of this occurring in the immediate landscape surrounding the investigation sites, particularly at sites with sandy profiles. The thickness of horizons with actual ASS materials varied from thin sandy or silty sand lenses overlying PASS materials (at Lake Mealup and Ravenswood bend; Table 1) to more than 1.2m in thickness (e.g. lower Harvey River site 311b and South Yunderup site 423a; Table 1). Thick layers of actual ASS tended to occur in horizons with fine textures (i.e. silts and clays).

Consistently reliable identification of actual ASS materials could not be made on the basis of laboratory analyses alone. During laboratory analysis of over 300 samples for the survey (usually in batches of 30-40 samples), problems in sample preparation were found to occasionally result in oxidation of PASS materials, which caused significant bias in subsequent laboratory analyses of sample acidity. In particular, pH_{KCl} was found to have decreased by more than 2 units relative to pH_F in some samples, was associated with existing acidity (indicated by TAA) of more than 6kg H_2SO_4/tonne and (occasionally) significant concentrations of acid extractable sulfate minerals (S_{nas} > 0.03%). While this result correctly identified actual ASS materials within the soil samples – the result falsely indicated the condition of the original soil profile from which the samples were taken. In many cases, there was no other supporting evidence by way of low pH_F and lithological characteristics (e.g. iron or jarosite mottling) of actual ASS materials being present in the soil horizons.

Consultation with the laboratory analysts identified that drying of individual samples as sometimes large clods (>0.4kg) without breaking these up was most likely responsible for causing oxidation during the drying process. Under these conditions, it was likely that the samples reached 80 degrees C rapidly, but remained moist (due to limited surface area for moisture loss), creating ideal conditions for oxidation of PASS materials. It is widely accepted that preparation of samples is the stage most likely to cause changes in soil chemistry of with PASS materials that could result in significant bias in subsequent measurements (Hicks and Bowman, 1996; Ahern et al., 2004).

Table 1: Sites with actual ASS layers, description of the horizons, chemical evidence of actual ASS materials and thickness of the layer.

Location	Site code	Actual ASS horizons	Evidence of actual ASS materials
Hill Top Rise, Karnup (lower floodplain terrace, mid-Serpentine River)	428a	Extensively mottled (>75%) dark greenish grey clays and sands (0.5-1.0mbgl)	Extensive iron mottling in shallow horizons with 0.07-0.1% sulfide-S. However, pH_F>4.9, pH_{KCl}>5, TAA[a] up to 3.9 kg H_2SO_4/tonne
Lake Amarillo (lower floodplain terrace, Serpentine River)	426a	Dark grey peaty silt-clay with significant reddish-yellow to brownish-yellow mottles and occasional pale yellow (jarosite) mottles (0.1-0.35mbgl) and dark grey clayey silt (0.35-0.5 mbgl)	pH_F 4.0-4.2, pH_{KCl}<4.3, TAA between 1.9-3.4 kg H_2SO_4/tonne and S_{nas} 0.07-0.2%S. No residual PASS materials (<0.002%S), however underlain by PASS materials (>0.8mbgl)
Black Lake East, Rogers Rd West (low lying dunes)	406j	Brownish-grey sand with significant yellowish-red and occasional pale yellow (jarosite) mottles (1.0-1.5mbgl). Grey silty sand with occasional mottles (1.5-1.7mbgl)	Jarosite mottling (Munsell Colour 5Y 8/6), pH_F<3.7. No laboratory analysis data for profile.
Murray River Backswamp, North Yunderup (margin of seasonal wetland depression)	409d	Black peaty sand and silty sands (0-1.0mbgl)	pH_{KCl} and pH_F<4, TAA up to 8 kg H_2SO_4/tonne, S_{nas} of 0.09% S with residual PASS materials of 1.4% sulfide-S.
Banksia Terrace, South Yunderup (lower Murray River floodplain)	410a	Mottled (yellow and grey) silty sand (0.75-1.75mbgl)	pH_F<4, but pH , but no TAA or S_{nas}.
South Yunderup flood drain (Murray River delta)	411b	Mottled grey silty sand (1.1-1.4mbgl) and light bluish-grey silt (1.4-1.6mbgl)	pH_F and pH_{KCl}<3.8, TAA of 5 kg H_2SO_4/tonne, S_{nas} of 0.09%S and residual PASS materials of up to 2.4% sulfide-S
Delta Crescent, South Yunderup (Murray River delta)	410c	Mixed mottled clay and sand horizons (fill materials, 0-1mbgl)	pH_F 3.6-3.7, no laboratory analysis data. PASS materials in underlying horizons (<1mbgl)
Murray River backswamp, South Yunderup Rd (seasonal wetland depression)	411f	Grey silty clay with yellowish-red, reddish-yellow and occasional pale yellow (jarosite) mottles (0.3-0.6mbgl) and grey sandy silty clay (0.6-0.8mbgl)	Jarosite mottling (Munsell Colour 2.5Y 8/3) pH_F<4 and pH_{KCl} <4.1, TAA between 3.8-4.3 kg H_2SO_4/tonne, S_{nas} up to 0.2%S and residual PASS materials of up to 0.26% sulfide-S.
South Yunderup Rd, Ravenswood (seasonal watercourse)	411g	Dark grey silty clay (0.8-1.6 mbgl)	pH_F 3.8, pH_{KCl} 4.3, TAA at least 6.5 kg H_2SO_4/tonne (however, no iron mottling evident)
Beecham Rd north, South Yunderup (Murray River floodplain delta)	423a	Light greenish-grey mottled clayey sand (0.25-0.6mbgl), light greenish grey clay with reddish-yellow and pale yellow (jarosite) mottles (0.6-0.9mbgl) and reddish-yellow clay with yellowish-red and grey mottles (0.9-2.3mbgl)	pH_F<3.9, pH_{KCl}<4.1, TAA between 2.8-3.9 kg H_2SO_4/tonne and S_{nas} up to 0.26%S. Minor residual PASS materials (<0.01% sulfide-S), however underlain by PASS materials (>2.3mbgl)
Ravenswood bend (lower floodplain terrace, Murray River)	413a	Brownish grey silty sand (thin lens 1.5-1.75mbgl)	pH_F = 3.8, no laboratory analysis data for horizon. Immediately underlaid by PASS materials of up to 0.7% sulfide-S
Old Sarun Lodge, East Ravenswood (lower floodplain terrace, Murray River)	414a	Brown clayey sand (1.7-2.3 mbgl) and mottled greyish brown sand (2.3-2.8mbgl)	pH_F<3.7, TAA 3.4-3.5 kg H_2SO_4/tonne with residual PASS materials of up to 0.85% sulfide-S (however pH_{KCl}<4.7)

Location	Site code	Actual ASS horizons	Evidence of actual ASS materials
Old Sarun Lodge, East Ravenswood (lower floodplain terrace, Murray River)	414b	Brown, ferruginous sand with iron cementations (2.5-2.8mbgl)	pH_F<4, but no other laboratory analysis data for horizon. Immediately underlain by PASS materials (up to 0.5% sulfide-S).
Old Sarun Lodge, East Ravenswood (lower floodplain terrace, Murray River)	414c	Mottled grey clay (2.2-3.0mbgl) and silt (3.0-3.4mbgl)	pH_F<4, TAA up to 1.8 kg H_2SO_4/tonne and residual PASS materials (up to 0.78% sulfide-S). However, pH_{KCl}>5.
Bens Rd, South Yunderup (margin of Murray River delta)	415d	Yellowish-red and pale yellow mottling in grey sandy clays of exposed drain wall (0.5-1mbgl)	Jarosite mottling (Munsell Colour 2.5Y 8/3) confirmed by field pH<3.5. No laboratory analysis data
Boggy Bay (low lying dunes)	322a	Dark grey sandy silt with brownish yellow and pale yellow (jarosite) mottles (0.8-1.0mbgl) overlying dark grey silty clay with minor pale yellow (jarosite) mottles (1.0-1.3mbgl)	pH_F 3.6-3.7, pH_{KCl} 4.1-4.2, TAA 4.5-4.6 kg H_2SO_4/tonne and significant S_{nas} 0.11-0.22%. Residual PASS materials of up to 0.5% sulfide-S in actual ASS horizon.
Austin Bay Nature Reserve, Robert Bay (margin of broad seasonal wetland depression)	301b	Grey sand with iron mottling (0.4-0.5mbgl) and dark grey silt with yellow and yellowish-red mottles (0.5-1.4mbgl).	pH_F 3.6-3.9, pH_{KCl} <4.3 and TAA >2.5 kg H_2SO_4/tonne and S_{nas}= 0.02% S (at 1.0mgbl). Residual PASS materials of up to 0.78% sulfide-S.
Robert Bay Drain, Austin Bay Nature Reserve (broad seasonal wetland depression)	301e	Light grey clayey sand with yellowish-brown and occasional pale yellow mottles (0.5-0.75mbgl)	Jarosite mottling (Munsell Colour 2.5Y 8/3) confirmed by field pH<3.5. No laboratory analysis data
Robert Bay Drain (NE), Austin Bay Nature Reserve (broad seasonal wetland depression)	301f	Grey clayey sand with yellowish-brown and occasional pale yellow mottles (0.25-0.5 mbgl)	Jarosite mottling (Munsell Colour 2.5Y 8/3) confirmed by field pH<3.5. No laboratory analysis data
East Lake Mealup (low lying dunes)	305d	Pale brown silty sand with heavy iron mottling (0.6-0.8mbgl) and upper part of light greenish grey sandy clay with iron mottling (0.8-1mbgl)	pH_F = 3.5 with heavy iron mottling, but pH_{KCl} = 5.5 and TAA<0.5 kg H_2SO_4/tonne after drying and grinding. Immediately underlain by PASS materials (up to 0.54% sulfide-S)
Lower Harvey River (floodplain terrace)	311a	Brownish grey silty sand (1.0-1.3mbgl) and underlying mottled greyish brown silt (1.3-1.8mbgl)	pH_F 3.5-3.9 and TAA = 1.8 kg H_2SO_4/tonne (at 1.5 mbgl), but pH_{KCl}>4.6. Immediately underlain by PASS materials (up to 0.2% sulfide-S).
Lower Harvey River (floodplain terrace)	311b	Black clay (1.1-1.8mbgl) overlying and greyish brown clay (1.8-2.3mbgl)	pH_F 3.6-3.8, pH_{KCl} <4, TAA between 3.4-4.5 kg H_2SO_4/tonne, S_{nas} up to 0.16%S. Residual PASS materials (up to 0.02% sulfide-S) and immediately underlain by PASS materials.
Lower Harvey River (floodplain terrace)	311c	Grey clay (1.0-1.6mbgl) overlying greyish brown clay with yellow and grey mottles (1.6-2.3mbgl)	pH_F 3.7-4.0. At 1.5 mbgl, pH_{KCl} 4.1, TAA 3 kg H_2SO_4/tonne and S_{nas} 0.16%S.
Lower Harvey River (floodplain terrace)	340b	Lower layer of dark grey clay with mottles (1.15-1.3mbgl) and iron cemented clay (1.3-1.4mbgl)	pH_F=2.5 at 1.25mbgl and residual PASS materials at 1.0mbgl (0.07% sulfide-S). No other laboratory analysis data

[a] TAA = total titratable acidity (QASSIT method 23F; Ahern et al., 2004)

Figure 15: Mapping of high risk of potential Acid Sulfate Soil materials occurring within the superficial sediments (<3 mbgl) surrounding the Peel Inlet, Serpentine River and Murray River and classification of ASS disturbance risk for the superficial formations at various sites (see Appendix 2 for details on risk classification).

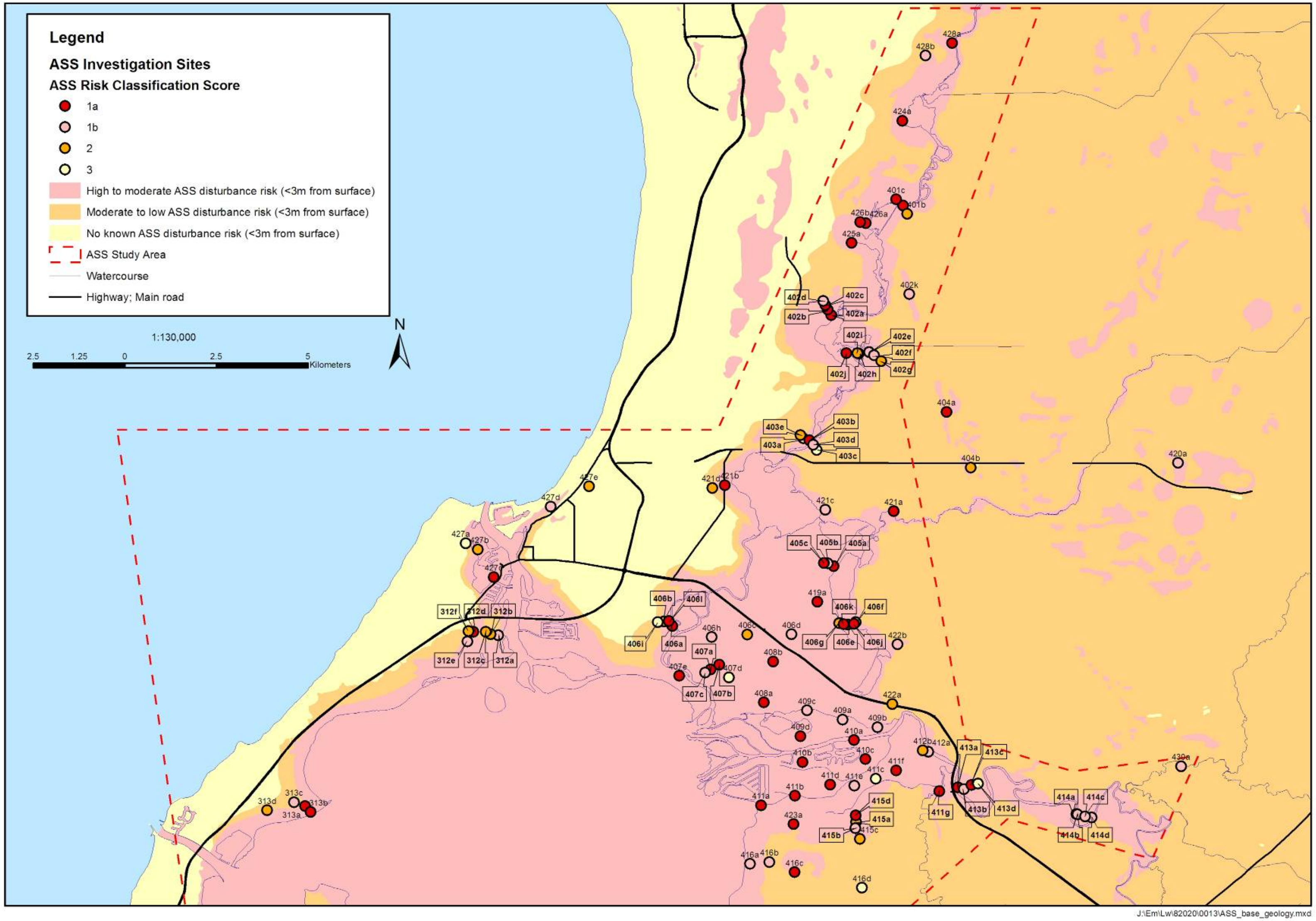
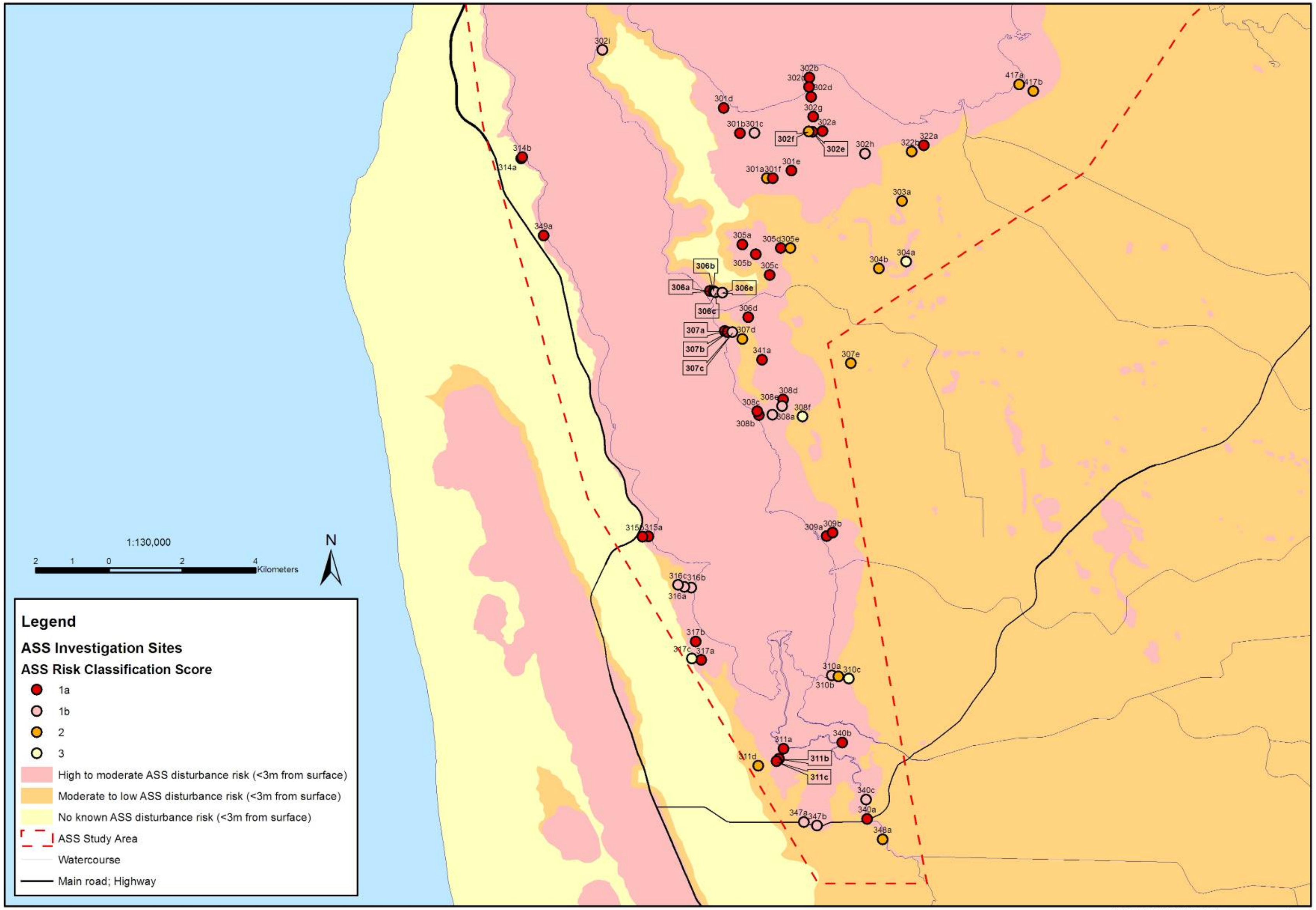


Figure 16: Mapping of high risk of potential Acid Sulfate Soil materials occurring within the superficial sediments (<3mbgl) surrounding the SE Peel Inlet, Harvey Inlet and Harvey Rive and classification of ASS disturbance risk for the superficial formations at various sites (see Appendix 2 for details on risk classification).



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3.2 Landscape patterns and mapping ASS hazard

Mapping of ASS disturbance risk areas was carried out by identification of landform patterns where PASS materials were likely to occur in the superficial formations and relating these to existing geology and soil mapping units. To facilitate description of this process the study area was divided into areas with generally similar landforms and geology and is presented in Table 2.

In general, existing lagoonal and estuarine geology map units (e.g. Mp/Qhg/Qhbg) consistent with low-lying landforms adjoining the estuary and tributaries could be used to broadly map areas with high-moderate ASS disturbance risk occurring in superficial sediments (where PASS materials were generally <3 mbgl). Alterations were made to selected geology units using soil mapping units, elevation contour information or aerial photo-interpretation where this provided a better capture of areas with high-moderate ASS disturbance risk. Final mapping of ASS risk based on this approach is shown in Figure 15 and Figure 16**.**

Areas of moderate-low ASS disturbance risk were generally identified by expected transition of PASS materials in map units adjoining high ASS disturbance risk areas (i.e. whether PASS materials are likely to occur in horizons >3mbgl). This was mapped either using existing geology units or new units defined as buffer zones adjoining high ASS disturbance risk areas (Table 2). Evidence of sporadic or minor PASS materials either shallow (<3mbgl) or deeper within the superficial formation was considered to be indicative of moderate-low ASS disturbance risk. Although the ASS disturbance risk at such sites was not definitive evidence of significant ASS disturbance risk, the evidence indicated the likelihood of the presence of such materials in the adjoining superficial sediments and the possibility of localised accumulations of PASS materials in near-surface horizons were water-logged and/or organic rich environments occur.

Over 115km^2 of the low-lying superficial sediments adjoining the Peel-Harvey Estuary was mapped as having a high probability of shallow PASS materials (<3mbgl; see Figure 15 and Figure 16). This area is considered to carry a high to moderate risk that normal land development activities will disturb these materials (i.e. high ASS disturbance risk) and represents an increase of more than double the area of high to moderate ASS disturbance risk identified using initial desktop mapping (determined as 54km^2, see Figure 3 and Figure 4). High ASS disturbance risk areas are commonly adjoined by landforms (over 112 km^2 of land within the study area) where PASS materials are generally deeper in superficial sediments (>3 mbl; see Figure 15 and Figure 16), hence normal land development activities are considered to carry a moderate to low risk of disturbing these ASS materials (i.e. moderate ASS disturbance risk).

The intensity of site investigations in the study area was marginally less than the minimum 1 per km^2 recommended to ensure reliable 1:50 000 mapping (Gunn et al., 1988). However, for many areas along the western shoreline and tributaries of the Peel-Harvey estuary (where the investigation intensity was least) the patterns of superficial formation with shallow PASS materials were sufficiently uniform and readily predicable to have not required further investigation. Therefore mapping of ASS risk in these areas can be considered to be reliable at 1:50 000 scale. The production scale of the map should be strongly borne in mind when using GIS viewers, since interpretation of risk boundaries at scales of greater than 1:50 000 (for example 1:25 000 or 1:10 000) increases the likelihood that incorrect interpretation of ASS disturbance risk will occur.

It was not possible to determine the geological age of the superficial sediments sampled in this survey without carrying out detailed dating analyses. Although many of the surface horizons were most likely in either in Holocene or Pleistocene sediments (based on environmental and urban geology mapping), reliable determination of the whether deeper horizons were Pleistocene in age (from descriptions alone) was not possible, particularly on the margins of river deltas where it appeared that shallow horizons were Holocene sediments and deeper underlying horizons may have been Pleistocene sediments.

Table 2: Summary descriptions of relationships between landform units and superficial sediments with shallow PASS materials and superficial geology and soil mapping units associated with PASS materials.

<table>
<tr><th>Summary of occurrence of shallow PASS materials in relation to landform and superficial sediments</th><th>Geology and soil mapping units[1]</th></tr>
<tr><td colspan="2">Mid Serpentine floodplain (Kerulup Pool and Lake Amarillo to Goegrup Lake)</td></tr>
<tr><td>PASS materials associated with a range of waterlogged silty and sandy horizons in superficial formations on the lower floodplain terraces of Serpentine River, including adjacent backswamps in gently undulating dunes and adjoining plains. On the low-level floodplain terraces of the mid-Serpentine between Kerulup Pool and Lake Amarillo, patchy PASS materials also occurred within black silty clays with occasional actual ASS in some seasonal wetlands (e.g. sites 428a, 426a). Significant PASS materials (>0.04-1.3% sulfide-S) can occur in deep sandy sediments (with occasional silt lenses) along the western margin of the mid-Serpentine floodplain, typically in low elevation (<5mAHD) gently undulating dunes (e.g. site series 426, 425 and 402). On lower slopes of major Spearwood dunes, PASS materials occurs in deep sandy horizons at the surface of the water-table of the deep sandy superficial sediments in this landform (conferring moderate disturbance risk). This tends to be more prevalent where dunes occur immediately adjoining floodplain.

On the eastern margin of the mid-Serpentine River, low elevation gently undulating dunes could contain superficial formations PASS materials typically occasionally associated with shallow sandy horizons (overlying clay horizons with generally minor or sporadic PASS materials). Minor seasonal wetlands (with perched water-tables) contain evidence of PASS materials (e.g. 402k, 402g). PASS materials (>0.04% sulfide-S) also occur in deep (>3mbgl) sandy horizons of larger gently undulating dunes along the eastern bank of the Serpentine (e.g. site 401b), though likely to be spatially variable in distribution (local geochemical processes have a greater influence on PASS material occurrence than regional geomorphology and soils).</td><td>Geology: Cp, Spm, low-lying S7, S8

Soil: Vasse series, low lying B4, B3, B2 and S4a, B5, swamps</td></tr>
<tr><td colspan="2">Mid-Lower Serpentine floodplain (Goegrup Lake to Coodanup, including Black Lake)</td></tr>
<tr><td>Lower floodplain terraces of the Serpentine River, including adjacent backswamps, contain PASS materials in predominantly sandy horizons (below water-table) of generally sandy profiles. With increasing proximity to the river channel, PASS materials increasingly occur in silty horizons (exceeding 2% sulfide-S). Significant PASS materials (> 0.2-0.5% sulfide-S) occur in sandy profiles (with occasional minor silt) on the western margin of the Serpentine floodplain in areas of low elevation (<5mAHD) gently undulating dunes (e.g. transect 421). Deeper PASS materials (>0.05% sulfide-S) can occur in association with sandy horizons below the water table in some lower slopes of major Spearwood dunes conferring moderate disturbance risk (see Figure 17). This tends to be more prevalent where dunes immediately adjoin the floodplain.

On the eastern margin of Lake Goegrup and Black Lake, PASS materials can occur in shallow sandy horizons with occasional silt lenses typically in areas of gently undulating dunes adjacent to river terraces (e.g. site series 421 and sites 406f, 406j; see Figure 17). The lower floodplain terraces of the Nambeelup Brook also contain shallow PASS materials (>1% sulfide-S) associated with sandy horizons (e.g. site 421a). Extensive areas of shallow PASS materials do not appear to occur in gently undulating dunes (overlying clays) east of lower Serpentine River, except for minor closed wetland depressions where PASS materials were associated with grey or brown sandy horizons.

Low gently undulating dunes between Black Lake and the main Serpentine channel frequently contain PASS materials in sandy horizons (with occasional clayey sands) generally at >1.5mbgl below ground (see site series 406 and 405 and Figure 17). The thickness and concentration of PASS materials in the superficial formations of this area varies significantly (e.g. sulfide content varies between <0.02 to >0.5% sulfide-S) in</td><td>Geology: Mp, Spm, low-lying S7, S8, S10

Soil: Vasse series, low-lying B4, B3, B2 and S4a, B5, swamps</td></tr>
</table>

commonly sandy profiles. The depth of PASS materials from the natural ground surface (being a key factor controlling risk of disturbance by land development) appears to be linked with local topography where slightly higher elevation areas have greater depth of sands (with no PASS materials) overlying the permanently submerged sandy layers with PASS materials. Closed seasonal wetland and dampland depressions in this area (including low level sandplain west of Black Lake) frequently contain sandy horizons with considerable PASS materials (in thickness and sulfide content e.g. site 408b contained up to 0.3% sulfide-S in >1 m layer).	
Serpentine-Murray R Delta (South Furnissdale, South and North Yunderup)	
Low elevation seasonally flooded wetlands, damplands, intertidal flats, supratidal flats and low-level beach ridge dunes of the Murray and Serpentine deltas contain PASS materials within a range of superficial sediments. In the Serpentine delta and northern part of the Murray delta (south Furnissdale), PASS materials up to 0.5% sulfide-S occur in deep sandy profiles interspersed with areas of predominantly thin sands over mottled clays with no PASS materials (eg. site series 407 and 408, part of series 406). Increasing silt and clay materials occur in the superficial formations towards the southern extent of the Murray delta (from Wilgie Creek southwards). Shallow PASS materials can occur in inter-layered silt and sandy horizons (often >2 m thickness with up to 3% sulfide-S) and occasionally clay and sandy clay horizons (e.g. site series 409 and 411). Actual ASS materials occur sporadically (<1 mbgl) in the superficial formations of the southern part of the river delta (South Yunderup area). These were most evident in wetland depressions and minor drainage lines (e.g. site series 411). The occurrence of shallow PASS materials within the superficial formations becomes increasingly spatially variable and confined to seasonal wetland depressions and local drainage lines with transition to gently undulating plains south and SE of the Murray Delta (toward Beecham Rd). Shallow PASS materials are likely to be rare in the area of broad alluvial plain and gently undulating dunes SE of the lower Murray River floodplain and flood channels.	Geology: Mp, Spm, low-lying S7, S8, S10 Soil: B2, B3, Vasse series, swamps, P2, P7
Lower Murray River floodplain (upstream of Hougham bend)	
Low and mid-level floodplain terraces on the lower Murray River contain PASS materials in predominantly alluvial sandy horizons (beneath the water-table) occasionally overlying deeper silty and clayey horizons with PASS materials (between 0.2-1% sulfide-S). Thin alluvial loams and clays (1-2 m) commonly overlay these PASS containing layers (e.g. site series 414 and 413). With distance upstream, PASS materials are generally limited to increasingly deeper horizons (>3 mbgl) and appear to become increasingly spatially patchy, particularly in mid-level floodplain terraces upstream of the Dandalup-Murray River confluence. Adjoining upper level floodplain terraces and gently undulating plains and dunes contain superficial formations with few PASS materials with occurrences either greater than 3 mbgl or confined to small (<2 ha) seasonal wetland and dampland depressions (therefore carrying conferring moderate to low disturbance risk).	Geology: Msc1 Soil: swamps, low-lying P10 and P6a.
Eastern Peel Inlet - Austin Bay, Boggy Bay, Robert Bay	
Superficial formations of the beach ridge dunes adjoining estuary and eastward gently undulating sandplain contain spatially variable occurrences of PASS materials. PASS materials with up to 0.8% sulfide-S can occur in sandy horizons of sandy superficial sediments south of the Murray delta, with increasing sporadic occurrence in the mainly clay dominated superficial formations of the supratidal and extratidal flats and seasonal wetland depressions south to Boggy Bay. There are limited occurrences of shallow PASS materials east of the beach ridge dunes.	Geology: Mp, low-lying S10, Ms2 Soil: swamps, Vasse series, B4, low

Gently undulating dunes south of Boggy Bay and Robert Bay extending to the flat sand plains inland contain substantial, frequently shallow PASS materials (>0.1% sulfide-S). Most PASS materials occur in predominantly silty sand horizons, interspersed with occasional sandy clays and silts and are commonly overlaid by thin sand horizons (e.g. site series 302). In the flat plains inland of the dunes, PASS materials in the superficial formations becomes increasingly confined to <1.5 m of sands overlying clays in minor seasonal wetland depressions. An area of broad wetland depression lying inland of Robert Bay (also referred to in 1:50,000 Urban Geology map sheet for Mandurah, Geological Survey of WA, 1977) contained predominantly sandy clay superficial sediments with sporadic PASS materials flanked by low-lying dunes with PASS materials (up to 0.2% sulfide-S) in shallow silt and clayey sand horizons (>0.5mbgl; see site series 301). Actual ASS materials were found by soil coring and observed in excavated soils alongside drains. Hand auger inspections indicated little indication of PASS materials in the superficial formations in the eastern and south-eastern extent of the depression (with transition inland to the gently undulating plain). Low-lying beach ridge dunes on the margin of the Peel estuary around the Point Grey peninsular south to Mealup Point contain extensive PASS materials frequently in sandy horizons with increasing occurrence in silt horizons in superficial formations on the edge of the estuary. The superficial formations of lower slopes of Spearwood dunes in this area contained minor shallow PASS materials, with significant concentrations mainly constrained to minor dampland depressions.	lying S4a, B2
North eastern Harvey Estuary– Point Grey, Lakes Mealup and McLarty to Harvey River Delta	
Foreshores and sediments of Lakes Mealup and McLarty and surrounding minor wetlands and gently undulating dunes contain superficial formations with extensive PASS materials. Sulfides of up to 0.5% are associated with peat, sandy and silt horizons in the lake sediments and predominantly sandy horizons in surrounding areas often concentrated within upper layers of the water-table (see series 305 and 341). Actual ASS materials were encountered at one site on the eastern side of Lake Mealup, occurring within a <0.4m sand layer at the surface of the water-table in a predominantly sandy clay profile. The deep sands of the dunes adjoining the lakes and estuary contained thin layers of PASS materials in deep sandy horizons (>3mbgl) associated with the upper layers of the water-table. In gently undulating landforms east of Lake Mealup and McLarty, PASS materials in the superficial formations (see Figure 18a) become increasingly confined to sandy horizons in minor seasonal wetland depressions, therefore conferring moderate to low ASS disturbance risk. Low-lying, beach ridge dunes adjoining the Harvey Estuary and gently undulating dunes inland of these (particularly south of Lake Mealup) contain extensive areas of shallow sandy superficial sediments with PASS materials (see series 306, 307, 308 and 309 and Figure 18a). PASS materials with up to 0.2% sulfide-S predominantly occur in sandy horizons (varying in thickness) overlying sandy clays with no or minor PASS materials. South of Lake McLarty, shallow PASS materials could occur in iron cemented sands and deeper brown sands of profiles consisting of sands overlying clay horizons.	Geology: Mp, low-lying S10, Ms2 Soil: swamps, Vasse series, B4, low lying S4a, B2
Harvey River delta and lower Harvey River floodplain	
Low elevation seasonally flooded wetlands, damplands, tidal flats, supratidal flats, and low level beach ridge dunes in the lower Harvey River delta frequently contain superficial formations with PASS materials in a range of superficial formations materials. On the eastern margins of the delta, PASS materials were found in	Geology: Mp, Spm, low-lying S8 and Ms2

predominantly deep sandy superficial sediments with minor silt and clay horizons (e.g. site series 310). In the centre and towards the western margin of the delta, alluvial clays and sandy clays dominated the superficial sediments with PASS materials generally occurring in clay horizons (e.g. site series 317) with occasional silts interspersed with minor sandy horizons. On margins of the delta, low-level gently undulating dunes (and lower slopes of major dunes) with deep sandy superficial sediments can also contain PASS materials in shallow sandy horizons (e.g. sites 310a, 310b and 311a). Localised actual ASS materials occur in clay profiles of some seasonal damplands and wetlands in the margins of the river delta (e.g. site 340b). Lower level floodplain terraces (<5mAHD) of the lower Harvey River and adjoining seasonal and permanent wetlands commonly contain predominantly shallow sandy superficial sediments with PASS materials occurring in near surface sand and silty sand horizons. Deeper PASS materials can also occur in clays and silt horizons in these areas. With increasing distance up-stream towards the mid-Harvey River, PASS materials are increasingly deeper and spatially sporadic in the lower-level floodplain landforms. Mid- to upper-floodplain terraces of the delta with predominantly clay sediments can frequently contain significant PASS materials at depth (>3mbgl) in sandy clay and sand horizons. ASS disturbance risk of adjoining undulating plains is highly dependent on depth of excavation and proximity to minor seasonal wetlands (where there is a likelihood of PASS materials occurring in the superficial formations).	Soil: Vasse series, swamps, low-lying P10a, B2, P5 and B6
Western Peel Inlet, Mandurah Estuary and Harvey Estuary	
Shallow mainly sand dominated superficial sediments in the tidal flats, supratidal flats, seasonal wetlands and low elevation gently undulating dunes on the western margin of the estuary and inlet contain extensive PASS materials (Figure 18b), with some occurrences containing substantial acid storage within 2m of the ground surface (e.g. transects 312, 313 and 315). PASS materials commonly occur in deep sandy profiles in silty sand horizons in occasionally large concentrations (>0.5% sulfide-S). PASS materials in silt horizons become more prevalent in the superficial formations adjoining the Harvey Estuary (Figure 18b), particularly areas just north of the Harvey River mouth. Substantial PASS materials (up to 0.45% sulfide-S) can also occur in shallow silty sands and silts underlying minor non-saline damplands, seasonal wetlands and gently undulating dune landforms (e.g. transect 317). Low-lying land (including former tidal and supratidal flats) adjoining the Mandurah Estuary commonly contain shallow sulfides in <0.5m sandy horizons frequently overlying limestone (see transect 427). These horizons can be occasional more significant in areas closer to the channel. The tidal flats (inter, supra and extratidal) and low elevation gently undulating dunes to the north of the Mandurah Estuary and channel contain PASS materials commonly in sandy and silty horizons within a mosaic of shallow, mainly sandy, superficial sediments. The PASS materials are highly spatially variable in depth and extent, ranging from shallow calcareous marls overlying limestone (with limited PASS materials) to deep sands with >3 m of PASS materials layers. Dune ridges and steeply sloping dunes to the west of the Peel Inlet and Harvey Estuary contain no evidence of shallow (<3mbgl) PASS materials. However, in the north-west of the Peel Inlet, the lower slopes of more gentle gradient dunes can be underlain by PASS materials layers (up to 0.05% sulfide-S) in association with water-tables (generally >3 m below ground-level; see transect 312 and 313). These characteristics confer a moderate ASS disturbance risk classification.	Geology: Mp, low-lying S7, S8 Soil: B2, Vasse series, S4b, swamps, low-lying S4a

[1] Soil mapping unit codes obtained from Department of Agriculture (WA) soil landscape mapping codes (van Gool, 1990) for the Coastal Plain soil-landscape mapping dataset.

Figure 17: Schematic landscape cross-section illustrating occurrence of PASS materials in relation to landscape position and dominant lithology in the lower Serpentine River area (representing the landscape from Coodanup to Black Lake).

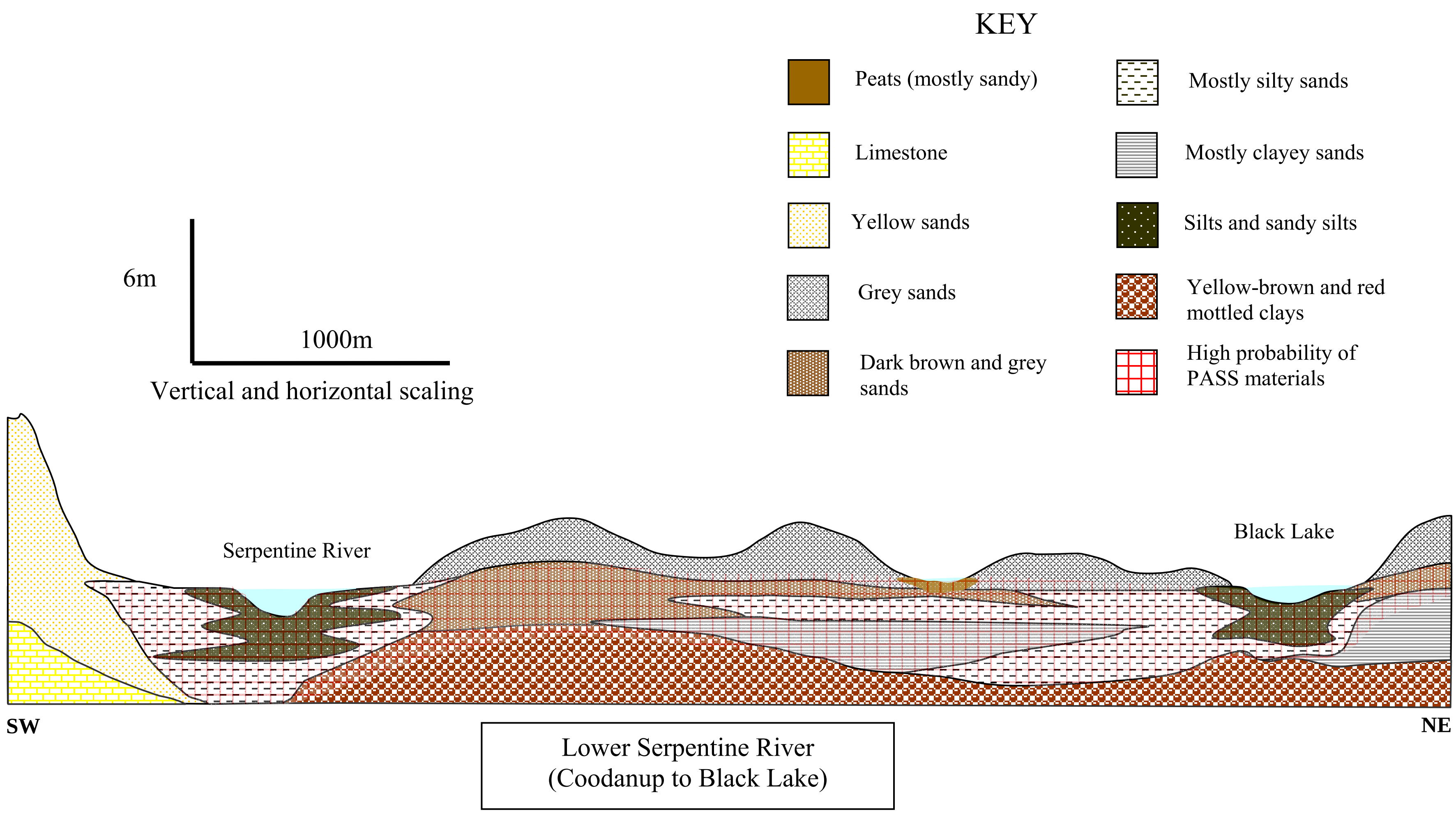
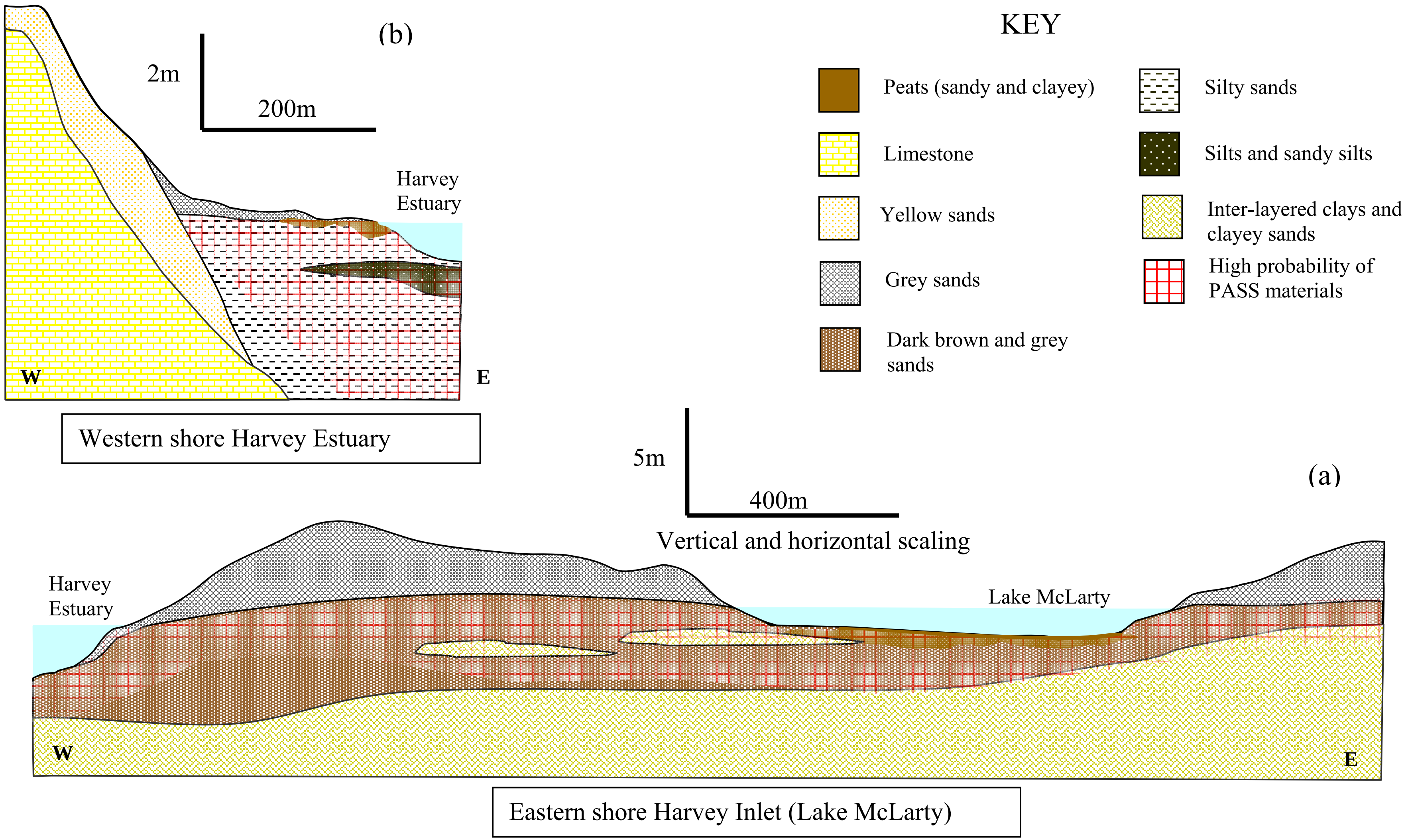


Figure 18: Schematic landscape cross-sections illustrating occurrence of PASS materials in relation to landscape position and dominant lithology for the (a) the eastern margin of the Harvey Estuary and (b) western margin of the Harvey Inlet near Lake McLarty.



4 General discussion

4.1 Potential ASS materials in superficial geological sediments adjoining the Peel-Harvey estuary

4.1.1 General characteristics and distribution of superficial geological sediments with PASS materials

PASS materials were frequent among investigation sites, with over 85 per cent of the 177 sites containing evidence of PASS materials within at least one horizon. At the majority of these sites (80 per cent or 133 sites) PASS materials were within 3m of the ground-surface. The soil materials at these sites were regarded as being representative of the superficial sediments in the low-lying landscapes (<5 m AHD) adjoining the Peel-Harvey estuary. Only a few profiles provided an indication of superficial sediments with PASS materials in inland and higher elevation areas (>10 mAHD). In the superficial sediments at most sites, PASS materials occurred in sand and silty sand horizons generally submerged less than 0.75m below water-tables. Few profiles contained PASS materials in clay or silt horizons and these were generally on the margins of the estuary or river deltas.

Over 115km^2 of the low-lying landforms adjoining the Peel-Harvey estuary and tributaries were mapped as containing PASS materials within 3 m of the ground-surface and therefore carry a high to moderate ASS disturbance risk. This mapping result represents an increase of more than double the area of high to moderate ASS disturbance risk identified using initial desktop mapping (determined as 54km^2 from initial mapping; Western Australian Planning Commission, 2003). There were strong associations between the occurrence of shallow PASS materials and landform that generally corresponded with existing Environmental and Urban geology map units, although a number of these units were initially considered to contain medium to low ASS disturbance risk, particularly Bassendean sand units (Urban Geology Series map unit code Qpb or Environmental Geology Series map unit codes S8 and S10). Where existing map units did not adequately identify high ASS risk areas, modifications were made to the boundaries of the mapping units to achieve a more reliable final risk map. These were made primarily to capture shallow ASS disturbance risk in wetlands adjoining floodplains, the lower, mainly eastern, slopes of Spearwood dunes containing PASS materials in association with shallow ground-water tables and areas of low-lying, gently undulating Bassendean dunes. It is notable that PASS materials were not confined to geological map units considered to be Holocene-aged sediments and also could also occur in many map units with Pleistocene-aged sediments (particularly the Bassendean dunes and Guildford clays).

Acidity stored in shallow PASS materials in superficial sediments varied from less than an equivalent 5 tonnes H_2SO_4/hectare to more than 1000 tonnes H_2SO_4/hectare (for the shallowest 1 m of horizons with PASS materials). The largest concentrations of stored acidity (more than 100 tonnes H_2SO_4/hectare) generally occurred in areas immediately adjoining the estuary and estuarine lakes on the Serpentine River, commonly in superficial sediments containing silts and clays. These areas were typical of where long-term, significant accumulation of PASS materials were most likely to have occurred under depositional conditions facilitated by the combination of tidal saline/brackish waters, organic inputs from fringing vegetation and inputs of iron from catchments (Pons et al., 1982; Powell and Ahern, 2000). Iron sources in this context could include ground-water discharge from surrounding superficial aquifers, which can contain significant dissolved iron concentrations (Davidson, 1995) or deposition of iron oxide containing sediments (eroding from the Darling Scarp) by the Serpentine, Murray or Harvey Rivers.

Less acidity is generally stored in shallow PASS materials in superficial sediments associated with many mainly low-lying Bassendean dunes in the study area, compared with near estuarine areas, but are more extensive in area. Furthermore, these areas could also contain localised, but significant acid storage (exceeding 100 H_2SO_4/hectare) in the superficial sediments adjoining wetlands. Given that there were no investigations of sediments within wetlands (with investigations being carried out on the margins of wetlands), it was likely that much greater acid storage occurred in the central basins of wetland environments than is indicated by this survey. Other studies have also found similar amounts of acid storage in sandy profiles with PASS materials, although this occurred in high elevation wetland and palusplain environments (10 – 45 mAHD) on the Scott Coastal Plain (Degens and Wallace-Bell, 2009).

Limited PASS materials occurred in the sandy superficial sediments in areas inland of the estuary and tributaries possibly because of the absence of tidal interaction (limiting the supply of SO_4^{2-}) and lower rates of organic matter inputs in the surface soils. Authigenic formation of sulfides (PASS materials) is most likely to have occurred in many sandy profiles inland of the estuary and major tributaries. This is concluded on the basis that since there were no significant patterns in sand grain distribution, sorting or appearance between horizons containing PASS materials and those without PASS materials that would indicate an evolution through various fluvial deposition events. The non-fluvial origin of many sandy superficial sediments in the study areas is also consistent with other studies reporting that many low-lying dunes surrounding the estuary are considered to have been of aeolian origin (McArthur et al., 1959; McArthur and Bettenay, 1960; Semeniuk and Semeniuk, 1990).

The authigenic formation of PASS materials was most likely the result of result of *in situ* biogeochemical processes within the upper parts of the superficial aquifer perhaps facilitated by high dissolved iron and organic carbon in shallow groundwaters (particularly in areas around wetlands). Soluble iron would not be limiting in many areas inland of the estuary and estuarine tributaries because this can be as much as 16 mg/L in many superficial ground-waters (Davidson, 1995). Organic matter and sulfate in shallow groundwater are likely to be most limiting in many areas, hence would have greatest control over where PASS materials would have formed. Most sandy horizons below water-tables contained little evidence of organic matter in this investigation and subsoils of similar Bassendean and Spearwood sands are reported to contain less than 0.2 per cent organic C (McArthur, 1991). However, shallow groundwaters in areas adjoining wetlands may contain significant soluble organic carbon, since wetlands hydrologically connected with the water-tables in the area can be rich in dissolved organic compounds (Wrigley et al., 1988). Furthermore, ground-water fed waterways can contain high concentrations of dissolved organic C (Petrone et al., 2009). The dissolved organic C may be sufficient to sufficient to support microbial reduction of sulfate (from rainfall inputs or oxidation of sulfides in deeper geological deposits) to the extent of enabling the gradual accumulation of sulfide minerals in the superficial sediments.

Some of the landscapes in the study area contained superficial sediments with sporadic or low concentrations of PASS materials in mottled clays of areas. These generally corresponded with shallow Guildford clay formations on urban or environmental geology mapping (e.g. sites 402g and 307e). The PASS materials in these sediments were not considered to constitute a significant environment hazard due to the minimal quantities of PASS materials present and protection within heavy clay profiles (which are unlikely to rapidly generate significant acidity if disturbed). However, this did not exclude the possibility that wetland depressions within these areas or deeper horizons containing PASS materials. Deep PASS materials (>3mbgl) are not thought to pose a significant environmental risk because of minimal likelihood that these could be disturbed in significant volumes by normal land development activities. However, the possibility of deep PASS materials will need to be considered in management of mining operations or regional water-table levels (where large volumes or areas can be disturbed simultaneously). Earlier investigations have already noted that PASS materials can occur deep within the superficial formations of the Swan Coastal Plain (e.g. Environmental Protection Authority, 2005).

4.1.2 Submergence of PASS materials

PASS materials in the Peel-Harvey region are likely to be sensitive to any regional or local decline in water-table levels since almost half of the investigated sites contained PASS materials submerged no more than 0.75m below the water-table. The close connection between water-table levels and depth of PASS materials indicates that should local or regional water-tables decline in many areas by any cause, this is likely to expose PASS materials and trigger oxidation processes that generate acidity. Activities that could cause declines in local water-tables include short-term intensive ground-water pumping for dewatering or ground-water use and longer-term activities such as drainage and increased ground-water abstraction. The results of this survey indicate that a depth of 0.5m depth of submergence of PASS materials may be a suitable interim guideline value when establishing management trigger limits for water-table levels in broad areas with shallow PASS materials (also see Degens, B.P. and Wallace-Bell, 2009). For specific wetland basins and tidal areas, the safe margin for decreases in water-tables that would prevent oxidation of PASS materials would be less considering that the materials in these environments were generally shallower and frequently less than 0.5m below water-table levels at the time of investigation.

PASS materials could occur up to 1.5m above the water-table at some sites, but these were generally associated with actual ASS materials or extensive iron mottling indicating oxidation of ASS. Where this was not the case, either measurements of water-tables were incorrect or PASS materials could occur in an unoxidised state above the water-table. It was more likely in many cases that water-table measurements contained some errors (that is, were under-estimated) at some sites thereby erroneously giving the false impression that horizons with PASS materials were not submerged. Errors in measurement of water-tables were most likely to have occurred in superficial sediments with significant clay or sandy clay horizons due to difficulty in determining a true reading during some investigations. This was mainly because of poor or slow recovery of water-levels after coring. Determination of water-table levels were only intended to be an indicator of the water-table and the reliable determination of water-table levels can only be achieved by installation of appropriately installed ground-water observation wells.

There were a few cases where PASS materials evidently occurred above the water-table possibly aided by the high organic or clay content of the horizons (for example Lake McLarty site 307a and North Yunderup site 426a). These soil factors may have facilitated capillary rise of the water-table (i.e. maintaining saturation of horizons with PASS materials), remained saturated and maintained low redox conditions and/or hindered diffusion of oxygen (due to low porosity). Similar soil conditions might be considered with managing the risk of disturbing PASS materials in site specific management of ASS.

4.2 Actual ASS materials in superficial formations.

4.2.1 Characteristics of profiles with actual ASS materials

Actual ASS materials were most frequent in superficial sediments on eastern site of the Peel Inlet, predominantly in floodplains and low-lying dunes surrounding the lower Murray River. Some sites adjoining the Harvey River delta and lower Serpentine River also contained incidences of actual ASS materials. These chance findings may belie a greater number of sites with actual ASS than reported here since the survey was designed to identify the spatial distribution of shallow formations with PASS materials and not the extent of superficial formations with actual ASS materials.

There was evidence of actual ASS materials forming at twenty two sites (13 per cent of all investigated sites) with the horizons containing these materials varying widely in depth, thickness and acidity characteristics. Actual ASS materials could be immediately below the ground-level to as much as 2.5m below in layers that were as little as 0.25m in thickness up to 1.7m. This variation is not unexpected and reflected the variation in the original depth and thickness of PASS materials that occurred in the region (see section 4.1). There was also significant variation in the form of actual ASS materials. These ranged from well developed classical ASS profiles with jarosite mottling (after van Breemen, 1982) at South Yunderup (site 411f) through to what appeared to be ripened profiles (after van Breemen, 1982; Dent and Pons, 1995) with significant formation of actual ASS materials overlying residual PASS materials (e.g. Harvey River sites 311a-311c and mid-Serpentine site 426a). Ripened profiles are those where PASS oxidation is well advanced, which, in this context resulted in formation of extensive iron mottled horizons (with minimal residual acidity, though pH_F is *circum* 4), overlying horizons with significant acidity and deeper PASS materials in horizons with no acidity.

Surface expression of ASS disturbance in the Peel-Harvey region is likely to be minimal, with many impacts resulting from acid generation likely to be evident off-site rather than at the site of disturbance (where the acid is generated). This conclusion is based on the depth of most of the PASS materials in the landscape and the occurrence of actual ASS already forming at some sites.

For many profiles where disturbance has already occurred (with actual ASS materials forming), acidity was deep (>1 mbgl) within superficial sediment profiles (particularly sandy profiles) with little or no evidence of this at the surface (i.e. overlying horizons showed no signs of deeper actual ASS materials). Acidification of shallow horizons is generally associated with on-site scalding (Rosicky et al., 2004), formation of surface acid salt efflorescence (Fanning et al., 2002), iron crusting and evapo-concentration of acidic ions in near surface horizons during summer (Rosciky et al., 2006). This was typical of areas with superficial sediment profiles containing actual ASS materials in the southern Murray River delta (South Yunderup) and the broad seasonal wetland depression adjoining Robert Bay.

By contrast, acid associated with actual ASS materials that occurred in deeper horizons (>1mbgl) or in shallow horizons (<1mbgl) with little capillary connection with surface horizons (e.g. deep sandy profiles) did not result in immediately obvious surface acidity impacts. These sites are likely to result in impacts only evident where seasonal soil through-flows or ground-water flows discharge to wetlands, waterways or the estuary, although are highly dependent on whether the hydraulic conductivity of the subsoils would result in significant water movement to enable flushing of the acidity from the profiles (Ferguson and Eyre, 1996; Kinsela and Melville, 2004). This factor is likely to limit transport of acidity from the clays in which actual ASS materials occurred in the Harvey River delta (sites 311a-311c and 340b) and at a site on the Murray River (414c).

4.2.2 Evaluating lithological horizons for Actual ASS materials

During the course of this survey, it was clear that a combination of field and laboratory analyses were necessary to evaluate soils for actual ASS materials. Jarosite mottling, being a definitive indicator of actual ASS formation (van Breemen, 1982; Isbell, 1996), was evident in only six profiles with three of these being profiles of exposed drain walls. In most cases however, multiple lines of evidence from field observations, field testing and laboratory analyses were necessary to reliably confirm the presence of actual ASS materials. The presence of actual ASS materials were initially identified by pH_{KCl}<4.5 and corroborated by significant actual and acid soluble minerals in combination with pH_F<4, significant iron mottling, presence of residual unoxidised PASS materials (within a horizon) and proximity of underlying PASS materials. The latter factors were met for all sites; however laboratory analysis results sometimes conflicted with field observations and testing.

It was found during the course of this survey that laboratory analyses alone were unable to consistently evaluate lithological horizons for actual ASS materials. Reliable assessments could only be made using the combined evidence provided by field tests, profile description and distribution of PASS materials in profiles, in addition to laboratory analyses. Laboratory analyses of some samples appeared to fail to detect the presence of actual ASS materials, despite field evidence strongly indicating that actual ASS materials were present. These occasional failures were most likely due to changes in soil chemistry that can occur during preparation of samples by drying and grinding.

Drying and griding can significantly alter the chemistry of soil samples (Hicks and Bowman, 1996; Maher et al., 2004; Ahern et al., 2004) primarily because of the exposure of mineral surfaces that would not usually be reactive with soil solutions. It was apparent that grinding of samples affected analysis of samples from Lake Mealup site 305d and Murray River site 414c where the increase in pH_{KCl} of dried and ground samples by more than 2 units relative to pH_F. Oxidation of PASS materials during soil preparation also occurred for some samples (due to poor sample handling practices), therefore giving the false indication that actual ASS materials were present.

The errors introduced by analysis artefacts could *only* be identified by comparison of laboratory results with field descriptions and testing results (which showed no evidence of ASS materials being present at the time of collection). These incidences highlight the importance of collecting sound information in the field (as base line quality assurance information) and applying caution if relying solely on interpretation of laboratory in assessing superficial sediment profiles for ASS materials.

4.3 Implications of ASS characteristics and distribution for management

Much of the high ASS disturbance risk areas identified in this survey contained PASS materials in mainly shallow sandy horizons that will require careful management to deal with the significant risks to the environment if these materials are disturbed by drainage, dewatering or excavation activities. Although investigations indicated that greatest acid storage occurred in profiles containing silts and clays, generally on the margins of the estuary, land development activities in the region are likely to encounter the more widely occurring superficial sediments with PASS materials in sandy horizons (e.g. low-lying Bassendean and Spearwood dunes).

The risk of rapid acid generation from soil or water disturbances is greatest in areas where PASS materials occur in shallow sandy horizons, with few neutralising materials and little indication of significant concentrations of organic matter. These areas are most common in low-lying Bassendean and Spearwood dunes adjoining the Serpentine and Murray Rivers and eastern Peel Inlet and Harvey Estuary (see Figure 15 and Figure 16). Drainage or de-watering of sand horizons containing PASS materials would result in rapid air entry and initiation of oxidation processes. The porosity of the soils would also facilitate prolonged high rates of oxidation (since oxygen diffusion is enhanced, see Cook et al., 2004) and would result in rapid acidification, given the general lack of potential *in situ* neutralising materials (carbonates or detectable acid neutralising capacity) in many horizons with PASS materials. Soils with few *in situ* neutralising materials (pH<5.5) can acidify quickly when oxygen is not limiting (Ward et al., 2002; Ward et al., 2004a). Consumption of oxygen by microbial decomposition of organic matter can play a role in limiting rates of oxidation of PASS materials in some disturbed soils, but only initially (Ward et al., 2004a). Regardless, there were few horizons with PASS materials in this survey with evidence of organic matter concentrations where this might occur (as based on few observations of peaty or organic rich horizons).

Management of PASS materials at the source of disturbances will be important because most off-site impacts are likely to occur via ground-water flow paths that could remain undetected for some time. The pathways by which acid and ASS oxidation products can be transported from disturbed soils to off-site environments are frequently complex. Research in eastern Australia and overseas has identified that the hydrological properties of the soils (macro- and micro-porosity, infiltration characteristics etc) and connectivity of flow pathways in the landscape play a significant role in influencing transport of acidity from catchments with actual ASS (Ferguson and Eyre, 1996; Minh et al., 2002; Green et al., 2006). It was clear in this survey that, sandy soils carry a risk that acidity could accumulate in sub-surface horizons, with little surface expression, potentially resulting in impacts on aquatic ecosystems that may remain undetected until well advanced. Many of the low lying sand dunes mapped as high ASS disturbance risk areas contained PASS materials where the dominant transport pathway would be via shallow ground-water. This is also supported by evidence that where shallow (1-1.5mbgl) actual ASS materials had already formed in sandy profiles there was little surface expression of the acidity (e.g. Lake Mealup site 305d and North Yunderup wetland site 409d). The impacts from this acidity would be occurring where acid ground-waters transported from the sites interacted with waters of rivers, wetlands and the estuary.

Off-site impacts on aquatic systems of disturbed ASS are primarily related to the high concentrations of dissolved iron and aluminium that can be transported in surface or ground-waters from the site of acid generation. Short-term impacts associated with high concentrations of iron are mainly linked with smothering and suffocation of aquatic life when the iron precipitates from waters columns due to neutralisation or increased oxygenation (Sammut et al., 1996; Cook et al., 2000). Over the longer-term, greater mobility of iron and sulfate can result in problems associated with formation of monosulfidic black oozes (discussed below). Intense acidity generated by disturbance (and oxidation) of ASS materials can chemically dissolve clays (primarily containing aluminosilicates) and result in high concentrations of soluble aluminium. Soluble aluminium can be highly toxic to aquatic life (Nordstrom and Ball, 1986; Sammut et al., 1996), particularly when partially neutralised (e.g. when acid surface or ground waters mix with alkaline waters). In the Peel-Harvey Estuary this is most likely to occur when acid surface or ground waters mix with alkaline waters in estuary or the Murray, Serpentine and Harvey Rivers as well as wetlands receiving a mixture of surface and ground-waters. Soluble aluminium can also reach concentrations in shallow groundwaters that would also be toxic to plants accessing this water (Moore et al., 1999; Slattery et al., 1999). While some plants may be tolerant to high levels of soluble aluminium in soils, recruitment and establishment of new plants may be limited (Slattery et al., 1999).

Management of PASS materials in sandy profiles will need to focus on minimising mobilisation of iron and sulfate in ground-waters to prevent secondary issues of monosulfide formation in waterways. This management will need to be in addition to preventing generation and transport of acidity. Excessive iron can be transported from landscapes with disturbed ASS as colloidal iron (Sammut et a., 1996) which is highly likely even if acidity has been neutralised (Hall, 2003). Increased prevalence of iron (and often sulfate) rich surface and ground-waters in landscapes will increase the likelihood of iron monosulfide formation in the sediments of drains, rivers (Bush et al., 2004; Smith and Melville, 2004), boating channels and other environments such as tidal lakes where this would normally be limited (e.g. see Macdonald et al., 2004). Excessive formation of monosulfide minerals in unconsolidated organic rich sediments of drains and water-ways (termed monosulfidic black oozes or MBO’s) can be a substantial secondary problem arising from disturbance and oxidation of PASS materials. If sediments with MBO's are scoured or disturbed, these materials can frequently rapidly deoxygenate water columns (Johnston et al., 2003). Furthermore, in some instances, MBO's can concentrate heavy metals occurring in surface waters and, when disturbed, can release the metals in a single pulse to water-columns (Smith and Melville, 2004).

In situ neutralising materials may play a role in mitigating ASS risk in many low-lying Spearwood dunes on the western, north-western and northern side of the estuary, but the extent to which this is important is likely to be limited. PASS materials in these areas commonly occurred in profiles that could also contain *in situ* neutralising materials (including shells and carbonate inclusions). However, the neutralising materials were not consistently in the same horizons as PASS materials. It is also not possible to conclude whether neutralising materials in any profiles would contain sufficient alkalinity to address possible acid generation without making assumptions about how the soils were to be disturbed. Even under controlled conditions, the dynamics of acid generation and interaction with neutralising materials can be difficult to predict in soil materials (Ward et al., 2002; Ward et al., 2004b). Standard practice demands that more detailed site specific soil sampling and laboratory analysis is carried out prior to evaluating whether *in situ* neutralising materials could be included in management of ASS risk at a site (Ahern et al., 1994; Department of Environment, 2004c).

The discovery of a number of sites actual ASS materials occur in superficial sediments indicates that historical or on-going activities have disturbed ASS materials which urgently requires further investigation. In particular, investigations are required to determine whether human-induced changes in landscapes or declining rainfall pattern have caused some PASS materials to oxidise resulting in the formation of actual ASS materials. This information is necessary to determine management priorities for reducing impacts of these soil materials on the Peel-Harvey Estuary and the major rivers draining to this estuary (Serpentine, Murray and Harvey Rivers). Although oxidation of PASS materials can be a natural occurrence (Dent and Pons, 1995; Kinsela and Melville, 2004), rapid oxidation is frequently caused by anthropogenic disturbances including excavation, lowering of ground-water tables and change in tidal regimes (Sammut, 2000). In some areas, for example near Robert and Boggy Bays and the southern Murray River delta (South Yunderup), formation of actual ASS materials in superficial sediment profiles occur where human-induced changes in tidal regime and hydrology are also evident. However, such associations cannot easily be made for sites on Murray River floodplain terraces (e.g. sites 413a and 414a), Black Lake (406j), Lake Mealup (306d) or the Harvey River floodplain (e.g. sites 311a-311c; 340b). These deserve further investigation to determine whether changes in regional water-tables due to historical drainage of the region is the main disturbance factor or whether there are natural disturbances causing oxidation of ASS materials.

4.4 Further work

- Improved mapping to identify sub-risk areas (within high ASS disturbance risk map units) where ASS risk is very shallow (within 1.5mbgl) or in near surface horizons (1.5-3mbgl). This would improve identification of areas with an immediate risk of near surface ASS developing from any disturbance activities, as compared with those where sub-surface ASS may develop due to deeper excavations or decreases in water-tables.

- Expanded investigation of moderate ASS disturbance risk areas - in particular whether deeper PASS materials occur in the superficial formations that are at risk of disturbance from changes in deeper ground-water tables and the extent to which shallow PASS materials occur in small (<1 ha) wetlands or creeklines of medium ASS risk areas.

- Further investigation of areas with disturbed ASS to determine causes, extent, pathways of impact and management options. To achieve this it will be necessary to identify where excavations, drainage, ground-water use or tidal barriers have occurred in areas with a high likelihood of shallow PASS materials. These areas will then need to be evaluated to determine the extent of influence of the disturbances (depth and area) and used to guide follow-up on-ground surveys to determine whether actual ASS materials occur. It cannot be automatically assumed that where disturbances have occurred in areas where shallow PASS are likely to have existed that actual ASS materials are essentially widespread within the area of disturbance. This is because although PASS materials may have existed prior to any land disturbance, oxidation of the materials may not have resulted in the formation of actual ASS materials (which generally require prolonged concentration of acidity within profiles and non-neutralising conditions to prevail).

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Appendix 1: Geology map unit ASS risk classification table

Initial classification of Environmental and Urban geology map units (with descriptions taken from published map sheets) on the Swan Coastal Plain according to ASS disturbance risk (see Appendix 4). This includes 1:50 000 geology mapping from Lancelin to Dunsborough as classified by Department of Environment for the WA Planning Commission Planning Bulletin 64 (WA Planning Commission, 2003).

CLASS 1 **High risk of potential acid sulfate soil (PASS) materials occurring < 3 m of ground surface**	
Environmental Geology Map Unit Codes[a]	**Urban Geology Map Unit Codes[b]**
S26: Calcareous sand by estuarine processes, white, fine to medium grained, various depths over limestone.	**Qhws:** Re-worked swamp deposits
Cps/Cp: Peaty Clay – Dark grey and black with variable sand content of lacustrine origin	**Qhw, Qrw :** Swamp deposits
M1: Silt – Grey mottled yellowish brown, blocky, firm, variable clay content	**Qhg**: limestone associated with lagoonal/lacustrine deposits
P: Peat – Black, clayey in part, saturated fibrous organic soil	**Qhl**: limestone associated with swamps
Sp/Spm : Peat Sand – Greyish brown, medium-grained quartz, moderately well sorted variable organic of lacustrine content	**Qhg, Qg, Qhgb**: Lagoonal deposits
Scp : Clayey sand – Black, fine to medium grained, variable organic content	**Qha**: Alluvium
Cs1 : Sandy Clay – Dark grey to black, variable sand content, some silt.	
Sp1 : Peaty Sand – Grey to black, fine to medium sand, slightly peaty,	
Sp2 : Peat Rich Sand – Grey, with much brown to black organic material grading to peat patches, fine to medium sand	
Spc/Spc1 : Peaty Sand - Dark grey and black quartz sands with variable organic content and common peat lenses, variable clay content	
Mps/Mp: Peaty Silt– brownish black, soft, variable organic content (mainly upper layers), some fine to medium sand, lacustrine origin	
Msp: Peaty Sandy Silt – dark brown to black, soft, wet, variable organic content, medium grained sand, lacustrine origin	
Ms5: Sandy Silt- dark brownish grey, mottled, low lying, variable clay content, some fine sand	
S4 – Lakebed sands; greyish brown, variable silt content, medium to coarse grained, moderate sorting	

CLASS 1

High risk of potential acid sulfate soil (PASS) materials occurring < 3 m of ground surface

Environmental Geology Map Unit Codes[a]	Urban Geology Map Unit Codes[b]
M5: Calcareous Silt – dark greyish brown silts and minor clays, some organic matter, shell debris and limestone common. **M6**: Silt – brownish grey, calcareous in part, fine sand and shell debris in places, minor clay content; lacustrine origin **S27**: Sand- thin layer of calcareous and quartz sand (white) over variably thick estuarine silts and gley clays. **Sc2:** Clayey sand – grey quartz fine to medium sand, variable clay content (marginal risk class) **Sm2:** Silty sand – greyish brown, medium to coarse grained, variable silt content, common shell debris **Mc1**: Clayey silt – mottled, low lying **Ms4**: Sandy silt- light/cream to yellow-brown, mottled, low lying alluvium, clayey in parts **C1:** Clay: mid to dark grey, soft, saturated, prominent oyster shell bed layer near surface of alluvial origin **Sm1 (Swan and Leschenault variant):** Silty sand – brown, leached at surface; tidal influence. **Ms2**: Sandy Silt (Swan, Peel variant)– Strong brown to mid-grey, mottled, variable clay content of alluvial origin.	

CLASS 2

Moderate to low risk PASS materials occurring <3 m of ground surface. PASS materials generally occur at depths of >3 m from ground surface

Environmental Geology Map Unit Codes[a]	Urban Geology Map Unit Codes[b]
S12: Sand – yellow, fine to medium grained, sub-angular to rounded quartz, minor silt and clay of colluvial origin	**Qpb:** Bassendean sand
Ms2, Ms7, Msg4: Sandy Silt – Strong brown to mid-grey, mottled, blocky, hard when dry, variable clay content of alluvial origin.	**Qhgb:** reworked Bassendean sand
S11: Sand – Light grey, medium grained, alluvial origin	**Qpr:** Yoganup formation
Mgs1: Pebble silt – strong brown silt with laterite common, well weathered granite, alluvial origin	**Qpry** – Yoganup formation young element
M4: Silt – v. pale brown, low clay content, hard when dry	**Qpri** – ferrunginised ilmenite layer
Smg2: Silty Sand – greyish to brown, medium to coarse sand, occasional quartz and gneiss pebbles.	**Qpa:** Guildford formation
Sm2: Silty Sand – brown to yellow-grey, fine to medium sand	**Qpb/Qpa:** Bassendean sand over Guildford association
Cs: Sandy Clay – white-grey to brown, fine to coarse grained, gravel and silt layers near scarp	**Qha:** Alluvium

CLASS 2

Moderate to low risk PASS materials occurring <3 m of ground surface. PASS materials generally occur at depths of >3 m from ground surface

Environmental Geology Map Unit Codes[a]	Urban Geology Map Unit Codes[b]
Sc: Clayey Sand – pale grey to brown, silty in part, poorly sorted, medium to coarse grained, alluvial origin	**Qhay:** young Alluvium terraces
Mc2: Clayey Silt – dark greyish brown, mottled in part, variable clay content	**Qhao:** old Alluvium terraces
S8: Sand – very light grey at surface, yellow at depth, sub-rounded, moderately well sorted of aeolian origin	
S10: Sand over Clay-Sand/Sandy Clay– surface light grey to yellow depth (aeolian origin). Thin veneer over strong, brown silts and clays. Local variation of coffee rock at depth south of Perth (S8 over Mgs1)	
Cm2 &C2: Clay: dark strong brown, variable silt content; no sand; of alluvial origin.	
S14: Sand – white to pale grey, rounded quartz, containing shells/shell fragments, alluvial origin	
Cms: Sandy silty clay- Pale Brown, alluvium	
Msc, Msc1 &Msc2: Clayey sandy silt- Pale Brown, angular-rounded sand, low cohesion (Msc1); moderate cohesion (Msc2) of alluvial origin	
Sm1:- Silty sand – brown, leached at surface; inland with no tidal influence	
S9: Sand – Yellowish brown, some fine pisolitic laterite, lacustrine origin, medium to coarse grained sand, angular to subrounded	
M2: Silt: brown, strong, tight, fine grained sand matrix.	

CLASS 3

Low to no known risk of PASS materials occurring <3 m of ground surface or at >3 m from ground surface

Environmental Geology Map Unit Codes[a]	Urban Geology Map Unit Codes[b]
LS1: Limestone – light yellowish brown, shell debris, aeolian origin	**Qtl & Qt:** Tamala limestone
LS3 & LS7: Limestone – same as LS1 but with shallow surface layer of calcareous sand	**Qhs:** Very shallow Safety Bay sand over limestone
LS2: Limestone – same as LS1 with abundant karst structures	**Qpm:** Muchea limestone
LS4: Limestone – pale yellowish brown, weakly cemented	**Qts:** Sand over limestone
LS5: Limestone – white fine grained, algal laminated, alluvial origin (also associated with coastal lagoonal deposits on Clifton and Preston sheets)	**Qtr:** reworked sand on Tamala limestone

CLASS 3

Low to no known risk of PASS materials occurring <3 m of ground surface or at >3 m from ground surface

Environmental Geology Map Unit Codes[a]	Urban Geology Map Unit Codes[b]
S7: Sand – Pale and olive yellow, medium to coarse grained, moderately sorted of residual origin over Tamala Limestone	**Qc:** Colluvium from scarp
Smg, Smg1, Smg2 & Smg3, Smg4: Silty sand – Dark yellowish brown, mottled, gravelly (particularly Smg3). Greyish brown Smg2 overlies gravelly silty sand.	**Qhc, Qs** (for S5)
Mgs1 & Mgs2 : Gravelly Silt – colluvial origin Localisaed variation of gravel horizons near Busselton (Msg1)	**Qm:** sandy colluvium from cretaceous rocks
Sm6: Silty sand – Red brown, fine-medium sand, occasional pisolitic gravels	**Qpo:** undifferentiated sand
Msg & Mgs1 : Sandy Silt – strong brown, colluvial origin, contains gravel.	**Qa:** Alluvium
S5: Sand – very pale brown, well sorted	**Qhs:** Safety Bay sand
S6: Sand – white grey, pale to yellow, medium to coarse, moderately sorted	**Qhsm:** mobile dunes (Safety Bay sand)
S7: Sand – light grey, fine to coarse, well sorted	
Ms3 : Sandy silt – yellowish brown, some gravel	
Ms1: Sandy Silt – brownish yellow, alluvial origin, firm silt, angular to sub-rounded sand in firm silt matrix	
S1, S2, S3, S13, S26, S17: Calcareous sand, white, fine to medium grained, various depths over limestone. S26 modified by estuarine processes	

a: Codes for map units and descriptions as cited on WA Geological Survey 1:50 000 Environmental Urban Geology map series (1984-1991).

b: Codes for map units and descriptions as cited on WA Geological 1:50 000 Survey Urban Geology map series (1977-1982)

Appendix 2: Investigation site details

Note on site numbering convention: The site 4 digit site code used in this report consists of a basin number (either 4 for Murray and Serpentine Rivers or 3 for Harvey River and West Peel), transect number within the basin (two digits following basin number) and site number within a transect (last digits).

Site Code	Database ref. code[a]	Sampling date	Location	Easting[b]	Northing	Elevation (mAHD)[c]
401a	ASS61400101	06/11/03	NORTH GUANANUP POOL, GULL ROAD NORTH, SERPENTINE RIVER	388451	6409303	0.3
401b	ASS61400102	06/11/03	NORTH GUANANUP POOL, GULL ROAD NORTH, SERPENTINE RIVER	388555	6409073	2.4
401c	ASS61400103	06/11/03	NORTH GUANANUP POOL, GULL ROAD NORTH, SERPENTINE RIVER BACKSWAMP	388295	6409466	0.1
402a	ASS61400201	08/10/03	WEST YALBANBERUP POOL, SERPENTINE RIVER	386831	6406301	0.1
402b	ASS61400202	08/10/03	WEST YALBANBERUP POOL, SERPENTINE RIVER	386750	6406450	0.8
402c	ASS61400203	09/10/03	WEST YALBANBERUP POOL, SERPENTINE RIVER	386694	6406575	0.7
402d	ASS61400204	07/11/03	WEST YALBANBERUP POOL, SERPENTINE RIVER	386640	6406687	1.7
402e	ASS61400205	05/11/03	EAST YALBANBERUP POOL, SERPENTINE RIVER (OFF FOWLER ROAD)	387721	6405310	0.3
402f	ASS61400206	06/11/03	EAST YALBANBERUP POOL, SERPENTINE RIVER (OFF FOWLER ROAD)	387829	6405226	1.0
402g	ASS61400207	06/11/03	EAST YALBANBERUP POOL, SERPENTINE RIVER (OFF FOWLER ROAD)	387999	6405063	0.5
402h	ASS61400208	06/11/03	EAST YALBANBERUP POOL, SERPENTINE RIVER (OFF FOWLER ROAD)	387478	6405269	0.1
402i	ASS61400209	09/01/04	EAST YALBANBERUP POOL, SERPENTINE RIVER (OFF FOWLER ROAD)	387445	6405278	0.1

Site Code	Database ref. code[a]	Sampling date	Location	Easting[b]	Northing	Elevation (mAHD)[c]
402j	ASS61400210	09/01/04	EAST YALBANBERUP POOL, SERPENTINE RIVER (OFF FOWLER ROAD)	387196	6405274	0.1
402k	ASS61400211	18/07/04	NORTH YALBANBERUP POOL, SERPENTINE RIVER (GULL ROAD TRACK)	388625	6406893	5.4
403a	ASS61400301	08/10/03	NORTH STAKEHILL BRIDGE, RESERVE, OFF WOODLAND PDE	386224	6402945	1.3
403b	ASS61400302	09/10/03	NORTH STAKEHILL BRIDGE, RESERVE, OFF WOODLAND PDE	386364	6402891	0.1
403c	ASS61400303	09/10/03	NORTH STAKEHILL BRIDGE, FOWLER ROAD	386535	6402630	2.8
403d	ASS61400304	09/10/03	NORTH STAKEHILL BRIDGE, FOWLER ROAD	386454	6402773	0.7
403e	ASS61400305	09/10/03	NORTH STAKEHILL BRIDGE, RESERVE, OFF WOODLAND PDE	386160	6403032	3.5
404a	ASS61400401	10/10/03	NAMBEELUP, OFF GULL ROAD	389518	6403699	8.6
404b	ASS61400402	05/11/03	LAKES ROAD	390097	6402193	9.8
405a	ASS61400501	07/11/03	NW BLACK LAKE, OFF HOUGHAM ROAD, BARRAGUP	386966	6399477	0.9
405b	ASS61400502	07/11/03	NW BLACK LAKE, OFF HOUGHAM ROAD, BARRAGUP	386828	6399543	1.1
405c	ASS61400503	23/01/04	WEST BLACK LAKE, HOUGHAM RD BARRAGUP	386736	6399551	0.9
406a	ASS61400601	07/11/03	COODANUP, LOWER SERPENTINE RIVER	383257	6397805	0.5
406b	ASS61400602	02/10/03	COODANUP, LOWER SERPENTINE RIVER	383068	6397926	4.2
406c	ASS61400603	03/10/03	RONLYN ROAD, FURNISSDALE	384990	6397590	2.8
406d	ASS61400604	03/10/03	WOODVIEW WAY, BARRAGUP	386009	6397605	1.5
406e	ASS61400605	04/10/03	BLACK LAKE SOUTH, RODGERS ROAD WEST	387308	6397885	0.0
406f	ASS61400606	10/10/03	BLACK LAKE SOUTH, RODGERS ROAD EAST, OFF FIEGERTS RD	387492	6397952	3.0

Site Code	Database ref. code[a]	Sampling date	Location	Easting[b]	Northing	Elevation (mAHD)[c]
406g	ASS61400607	08/11/03	BLACK LAKE SOUTH, RODGERS ROAD WEST	387108	6397922	2.2
406h	ASS61400608	13/11/03	BETWEEN RIVERSIDE DRIVE & RONLYN ROAD, FURNISSDALE	384170	6397510	2.3
406i	ASS61400609	13/11/03	COODANUP, LOWER SERPENTINE RIVER	382928	6397901	5.2
406j	ASS61400610	23/10/03	BLACK LAKE SOUTH, RODGERS ROAD EAST, OFF FIEGERTS RD	387448	6397905	1.5
406k	ASS61400611	24/10/03	BLACK LAKE SOUTH, RODGERS ROAD WEST	387213	6397900	1.7
406l	ASS61400612	31/10/03	COODANUP, LOWER SERPENTINE RIVER	383177	6397933	1.2
407a	ASS61400701	11/11/03	OFF RONLYN ROAD, FURNISSDALE	384156	6396626	0.6
407b	ASS61400702	11/11/03	OFF RONLYN ROAD, FURNISSDALE	384353	6396767	1.5
407c	ASS61400703	11/11/03	OFF RONLYN ROAD, FURNISSDALE	384030	6396541	0.9
407d	ASS61400704	11/11/03	OFF FURNISSDALE ROAD, FUNISSDALE	384581	6396421	0.1
407e	ASS61400705	03/10/03	SERPENTINE RIVER MOUTH, PEEL PARADE	383432	6396449	0.3
408a	ASS61400801	12/11/03	TONKIN DRIVE, NORTH YUNDERUP	385397	6395748	0.1
408b	ASS61400802	13/11/03	BARRAGUP WETLAND, JANNALI ROAD	385600	6396864	0.6
409a	ASS61400901	12/11/03	WILGIE CREEK, NORTH YUNDERUP	387214	6395304	1.0
409b	ASS61400902	12/11/03	WILGIE CREEK, CORREAS STREET, NORTH YUNDERUP	388022	6395102	0.9
409c	ASS61400903	12/11/03	WILGIE CREEK, NORTH YUNDERUP RD, NORTH YUNDERUP	386393	6395544	0.2
409d	ASS61400904	13/11/03	MURRAY RIVER BACKSWAMP, NORTH YUNERUP	386250	6394838	0.7
410a	ASS61401001	26/09/03	BANKSIA TCE EAST, SOUTH YUNDERUP	387485	6394746	0.9

Site Code	Database ref. code[a]	Sampling date	Location	Easting[b]	Northing	Elevation (mAHD)[c]
410b	ASS61401002	27/09/03	YUNDERUP ROAD, SOUTH YUNDERUP	386309	6394134	0.1
410c	ASS61401003	01/09/04	DELTA CRESCENT, SOUTH YUNDERUP	387755	6394231	2.2
411a	ASS61401101	25/09/03	SOUTH YUNDERUP FLOOD DRAIN GATES	385362	6392949	0.1
411b	ASS61401102	25/09/03	SOUTH YUNDERUP FLOOD DRAIN	386138	6393216	0.1
411c	ASS61401103	26/09/03	OFF STH YUNDERUP ROAD, SOUTH YUNDERUP	387999	6393701	1.2
411d	ASS61401104	26/09/03	OFF STH YUNDERUP ROAD, SOUTH YUNDERUP	386953	6393530	0.2
411e	ASS61401105	01/10/03	OFF STH YUNDERUP ROAD, SOUTH YUNDERUP	387508	6393510	0.8
411f	ASS61401106	23/01/04	MURRAY RIVER BACKSWAMP, MURRAY RIVER DRIVE, SOUTH YUNDERUP	388465	6393934	0.1
411g	ASS61401107	13/07/04	PINJARRAH RD AND SOUTH YUNDERUP RD INTERSECTION	389466	6393379	0.8
412a	ASS61401201	27/09/03	LEANDER WAY, RAVENSWOOD	389204	6394445	1.8
412b	ASS61401202	28/11/03	LEANDER WAY, RAVENSWOOD	389076	6394484	1.7
413a	ASS61401301	26/11/03	SOUTH OF RAVENSWOOD CARAVAN PARK	389894	6393486	2.5
413b	ASS61401302	26/11/03	SOUTH OF RAVENSWOOD CARAVAN PARK	390037	6393444	1.5
413c	ASS61401303	26/11/03	SOUTH OF RAVENSWOOD CARAVAN PARK	390206	6393555	1.2
413d	ASS61401304	26/11/03	SOUTH OF RAVENSWOOD CARAVAN PARK	390361	6393597	3.4
414a	ASS61401401	27/11/03	OLD SARUN LODGE, MURRAY RIVER	392637	6392787	1.7
414b	ASS61401402	27/11/03	OLD SARUN LODGE, MURRAY RIVER	392661	6392784	1.6
414c	ASS61401403	27/11/03	OLD SARUN LODGE, MURRAY RIVER	392986	6392699	2.0

Site Code	Database ref. code[a]	Sampling date	Location	Easting[b]	Northing	Elevation (mAHD)[c]
414d	ASS61401404	27/11/03	OLD SARUN LODGE, MURRAY RIVER	392837	6392725	1.3
415a	ASS61401501	28/11/03	BENS ROAD, SOUTH YUNDERUP	387561	6392515	0.6
415b	ASS61401502	28/11/03	OFF BENS ROAD, SOUTH YUNDERUP	387544	6392347	1.1
415c	ASS61401503	28/11/03	OFF BENS ROAD, SOUTH YUNDERUP	387652	6392054	0.7
415d	ASS61401504	28/11/03	BENS ROAD, SOUTH YUNDERUP	387549	6392697	0.4
416a	ASS61401601	19/09/03	AUSTIN BAY RESERVE NORTH, OFF BEECHAM ROAD	385126	6391352	3.2
416b	ASS61401602	19/09/03	AUSTIN BAY RESERVE NORTH, OFF BEECHAM ROAD	385572	6391406	2.9
416c	ASS61401603	20/09/03	AUSTIN BAY RESERVE NORTH, OFF BEECHAM ROAD	386161	6391138	0.2
416d	ASS61401604	20/09/03	CORNER BEECHAM RD AND PARKHILLS LANE	387716	6390732	1.7
417a	ASS61401701	09/12/03	OFF GREENLANDS ROAD, FAUNTLEROY DRAIN	384866	6388307	0.1
417b	ASS61401702	09/12/03	OFF GREENLANDS ROAD, FAUNTLEROY DRAIN	385197	6388127	2.2
419a	ASS61401901	29/10/03	BLACK LAKE, DUNKERTON ROAD, SOUTH BARRAGUP	386601	6398498	2.0
420a	ASS61402001	11/03/04	WETLAND, SOUTH YANGEDI ROAD, NAMBEELUP	394881	6402369	14.5
421a	ASS61402101	23/01/04	UPSTREAM NAMBEELUP POOL, NAMBEELUP BROOK, FIEGERTS ROAD NORTH	388335	6400983	2.7
421b	ASS61402102	11/03/04	LAKE GOEGERUP WEST, LAKES ROAD	384424	6401647	0.7
421c	ASS61402103	23/01/04	LAKE GOEGERUP EAST, DUNKERTON ROAD	386757	6401008	1.8
421d	ASS61402104	11/03/04	LAKE GOEGERUP WEST, BARDOC WAY	384141	6401570	0.4
422a	ASS61402201	11/03/04	SOUTH BLACK LAKE, PINJARRA ROAD	388359	6395738	3.0

Site Code	Database ref. code[a]	Sampling date	Location	Easting[b]	Northing	Elevation (mAHD)[c]
422b	ASS61402202	18/07/04	WETLAND, OFF FIEGERTS ROAD	388463	6397360	1.7
423a	ASS61402301	12/03/04	NORTH OF BEECHAM RD SOUTH OFF MURRAY FLOOD DRAIN, SOUTH YUNDERUP	386118	6392442	0.1
424a	ASS61402401	06/11/03	WEST LAKE AMARILLO, SERPENTINE RIVER	388414	6411608	2.1
425a	ASS61402501	09/01/04	WEST GUARNUP POOL, SERPENTINE RIVER	387281	6408273	0.7
426a	ASS61402601	09/01/04	WEST GUARNUP POOL, SERPENTINE RIVER	387596	6408812	0.1
426b	ASS61402602	08/01/04	WEST GUARNUP POOL, SERPENTINE RIVER	387474	6408841	0.8
427a	ASS61402701	12/07/04	MARY ST, HALLS HEAD	378471	6399998	1.9
427b	ASS61402702	12/07/04	CAMBRIA ISLAND RTT, HALLS HEAD	378746	6399832	1.8
427c	ASS61402703	12/07/04	APOLLO PLACE, PEEL ESTUARY MOUTH	379127	6399081	1.4
427d	ASS61402704	12/07/04	SHANNON RD, MANDURAH	380420	6401018	2.0
427e	ASS61402705	12/07/04	TINDALE ST, MANDURAH	381298	6401581	2.7
428a	ASS61402801	08/07/04	HILL TOP RISE, KARNUP, SERPENTINE FLOODPLAIN (DOWNSTREAM KERULUP POOL)	389542	6413734	2.1
428b	ASS61402802	08/07/04	HILL TOP RISE, KARNUP (DOWNSTREAM KERULUP POOL)	388927	6413388	2.0
430a	ASS61403001	18/07/04	PATTERSON RD, DANDALUP RIVER	395038	6394118	1.3
301a	ASS61300101	10/12/03	DRAIN, NATURE RESERVE OFF CARRABUNGUP RD, ROBERT BAY	379090	6385686	0.1
301b	ASS61300102	10/12/03	NATURE RESERVE OFF CARRABUNGUP RD, ROBERT BAY	378456	6386906	1.5
301c	ASS61300103	10/12/03	NATURE RESERVE OFF CARRABUNGUP RD, ROBERT BAY	378790	6386913	1.4
301d	ASS61300104	10/12/03	END CARRABUNGUP RD, ROBERT BAY	378067	6387590	1.7

Site Code	Database ref. code[a]	Sampling date	Location	Easting[b]	Northing	Elevation (mAHD)[c]
301e	ASS61300105	10/12/03	DRAIN CUTTING, NATURE RESERVE OFF CARRABUNGUP RD, ROBERT BAY	379650	6385901	1.0
301f	ASS61300106	10/12/03	DRAIN CUTTING, NATURE RESERVE OFF CARRABUNGUP RD, ROBERT BAY	379221	6385687	0.1
302a	ASS61300201	09/12/03	WETLAND, EAST ROBERT BAY, AUSTIN BAY CONSERVATION RESERVE	380354	6386981	4.0
302b	ASS61300202	24/02/04	EAST ROBERT BAY, AUSTIN BAY CONSERVATION RESERVE	380038	6388442	3.0
302c	ASS61300203	24/02/04	EAST ROBERT BAY, AUSTIN BAY CONSERVATION RESERVE	380032	6388179	3.2
302d	ASS61300204	24/02/04	EAST ROBERT BAY, AUSTIN BAY CONSERVATION RESERVE	380083	6387913	3.8
302e	ASS61300205	24/02/04	EAST ROBERT BAY, AUSTIN BAY CONSERVATION RESERVE	380124	6386958	3.1
302f	ASS61300206	25/02/04	EAST ROBERT BAY, AUSTIN BAY CONSERVATION RESERVE	380039	6386965	3.9
302g	ASS61300207	11/01/04	WETLAND, EAST ROBERT BAY, AUSTIN BAY CONSERVATION RESERVE	380138	6387373	4.1
302h	ASS61300208	10/05/04	WETLAND, CARRABUNGUP ROAD VERGE	381345	6386383	2.7
302i	ASS61300209	05/01/04	POINT GREY SOUTH	375260	6389130	2.9
303a	ASS61300301	11/12/03	CARRABUNGUP ROAD NEAR MEELUP ROAD	382209	6385101	4.0
304a	ASS61300401	11/12/03	SOUTH MUNGINUP SWAMP, LAKE MEELUP ROAD	382322	6383458	2.4
304b	ASS61300402	11/12/03	SOUTH MUNGINUP SWAMP, LAKE MEELUP ROAD	381700	6383260	3.7
305a	ASS61300501	12/12/03	WETLAND WEST OF LAKE MEELUP	378543	6383878	1.6
305b	ASS61300502	12/12/03	LAKE MEELUP WEST BANK	378856	6383611	3.6
305c	ASS61300503	23/02/04	LAKE MEELUP SOUTH	379184	6383054	2.7
305d	ASS61300504	23/02/04	EAST LAKE MEALUP	379427	6383790	1.7

Site Code	Database ref. code[a]	Sampling date	Location	Easting[b]	Northing	Elevation (mAHD)[c]
305e	ASS61300505	11/03/04	EAST LAKE MEALUP	379653	6383789	2.2
306a	ASS61300601	12/12/03	SOUTH MEALUP POINT, OFF LAKE MEELUP ROAD	377814	6382601	2.8
306b	ASS61300602	12/12/03	SOUTH MEALUP POINT, OFF LAKE MEELUP ROAD	377899	6382600	4.0
306c	ASS61300603	25/02/04	SOUTH MEALUP POINT, OFF LAKE MEELUP ROAD	377940	6382565	4.1
306d	ASS61300604	25/02/04	WETLAND WEST SIDE OF LAKE MEALUP	378707	6381897	2.0
306e	ASS61300605	25/02/04	SOUTH MEALUP POINT, OFF LAKE MEALUP ROAD	378103	6382562	5.0
307a	ASS61300701	26/02/04	OFF BIRCH GROVE, LAKE MCLARTY	378169	6381514	3.0
307b	ASS61300702	26/03/04	OFF BIRCH GROVE, LAKE MCLARTY	378236	6381494	3.9
307c	ASS61300703	26/02/04	OFF BIRCH GROVE, LAKE MCLARTY	378345	6381491	5.0
307d	ASS61300704	01/08/05	KANGAROO LOOP, OFF BIRCH GROVE, LAKE MCLARTY	378574	6381306	3.8
307e	ASS61300705	01/08/05	MCSWANN RD, LAKE MCLARTY	381079	6380674	6.2
308a	ASS61300801	26/02/04	PIONEER PLACE, SOUTH OF LAKE MCLARTY	379296	6379257	1.1
308b	ASS61300802	09/03/04	ESTUARY FORESHORE, SOUTH OF LAKE MCLARTY	378981	6379243	1.6
308c	ASS61300803	09/03/04	ESTUARY FORESHORE, SOUTH OF LAKE MCLARTY	378946	6379339	1.9
308d	ASS61300804	09/03/04	SOUTHERN EDGE OF LAKE MCLARTY, MILLS ROAD	379538	6379668	0.1
308e	ASS61300805	10/03/04	SOUTHERN EDGE OF LAKE MCLARTY, MILLS ROAD	379511	6379490	1.8
308f	ASS61300806	10/03/04	SOUTH OF LAKE MCLARTY, MILLS ROAD	379985	6379211	3.5
309a	ASS61300901	10/03/04	HERRON POINT SOUTH, HERRON POINT ROAD	380583	6375965	1.8

Site Code	Database ref. code[a]	Sampling date	Location	Easting[b]	Northing	Elevation (mAHD)[c]
309b	ASS61300902	10/03/04	HERRON POINT SOUTH, HERRON POINT ROAD	380720	6376057	3.2
310a	ASS61301001	17/03/04	WEST OF HILLS ROAD, KOOLJERRENUP RESERVE	380746	6372177	1.5
310b	ASS61301002	17/03/04	WEST OF HILLS ROAD, KOOLJERRENUP RESERVE	380901	6372152	2.7
310c	ASS61301003	17/03/04	WEST OF HILLS ROAD, KOOLJERRENUP RESERVE	381137	6372091	1.4
311a	ASS61301101	18/03/04	SOUTH OF HARVEY RIVER DELTA, OFF SOUTHERN ESTUARY ROAD	379657	6370169	1.3
311b	ASS61301102	18/03/04	SOUTH OF HARVEY RIVER DELTA, OFF SOUTHERN ESTUARY ROAD	379558	6369889	0.0
311c	ASS61301103	18/03/04	SOUTH OF HARVEY RIVER DELTA, OFF SOUTHERN ESTUARY ROAD	379504	6369826	0.1
311d	ASS61301104	16/08/04	SOUTH OF HARVEY RIVER DELTA, OFF SOUTHERN ESTUARY ROAD	379087	6369702	1.4
312a	ASS61301201	11/03/04	SOUTH OF MANDURAH ROAD BRIDGE, ERSKINE	379250	6397505	2.3
312b	ASS61301202	11/03/04	SOUTH OF MANDURAH ROAD BRIDGE, ERSKINE	379073	6397528	2.4
312c	ASS61301203	11/03/04	SOUTH OF MANDURAH ROAD BRIDGE, ERSKINE	378957	6397593	3.4
312d	ASS61301204	11/03/04	SOUTH OF MANDURAH ROAD BRIDGE, ERSKINE	378672	6397590	1.4
312e	ASS61301205	12/03/04	SOUTH OF MANDURAH ROAD BRIDGE, ERSKINE	378539	6397321	1.4
312f	ASS61301206	12/03/04	SOUTH OF MANDURAH ROAD BRIDGE, ERSKINE	378565	6397605	3.2
313a	ASS61301301	09/03/04	FALCON POINT FORESHORE, OFF PLEASANT GROVE CIRCLE	374851	6392798	0.5
313b	ASS61301302	09/03/04	FALCON POINT FOOTSLOPES, OFF PLEASANT GROVE CIRCLE	374979	6392641	0.9
313c	ASS61301303	16/03/04	FALCON POINT FOOTSLOPES, OFF PLEASANT GROVE CIRCLE	374594	6392904	1.3

Site Code	Database ref. code[a]	Sampling date	Location	Easting[b]	Northing	Elevation (mAHD)[c]
313d	ASS61301304	16/03/04	FALCON POINT FOOTSLOPES, OFF PLEASANT GROVE CIRCLE	373980	6392672	2.2
314a	ASS61301401	16/03/04	POINT MORFITT NORTH, ESTUARY ROAD	373419	6386149	0.5
314b	ASS61301402	16/04/04	POINT MORFITT NORTH, ESTUARY ROAD	373447	6386190	0.3
315a	ASS61301501	16/03/04	NORTH ISLAND POINT FORESHORE, SOUTH ESTUARY DRIVE	376481	6375902	0.9
315b	ASS61301502	16/03/04	NORTH ISLAND POINT FOOTSLOPES, SOUTH ESTUARY DRIVE	376343	6375894	1.8
316a	ASS61301601	18/03/04	SOUTH ISLAND POINT FORESHORE, SOUTH ESTUARY DRIVE	377479	6374530	1.5
316b	ASS61301602	19/03/04	SOUTH ISLAND POINT FOOTSLOPES, SOUTH ESTUARY DRIVE	377326	6374543	2.2
316c	ASS61301603	18/03/04	SOUTH ISLAND POINT FOOTSLOPES, SOUTH ESTUARY DRIVE	377177	6374594	2.4
317a	ASS61301701	18/03/04	BACKSWAMP, OFF SOUTHERN ESTUARY DRIVE	377734	6372558	0.1
317b	ASS61301702	07/04/04	NORTH HARVEY DELTA, OFF SOUTHERN ESTUARY DRIVE	377606	6373061	0.9
317c	ASS61301703	07/04/04	BACKSWAMP, OFF SOUTHERN ESTUARY DRIVE	377519	6372600	3.7
322a	ASS61302201	12/03/04	CARRABUNGUP ROAD, BOGGY BAY	382693	6386627	3.6
322b	ASS61302202	12/03/04	CARRABUNGUP ROAD, BOGGY BAY	382415	6386451	3.4
340a	ASS61304001	23/03/04	HARVEY RIVER, OLD BUNBURY ROAD	381601	6368282	4.6
340b	ASS61304002	13/12/04	HARVEY RIVER DELTA, EAST	381010	6370354	2.0
340c	ASS61304003	13/12/04	HARVEY RIVER, DOWNSTREAM OLD BUNBURY RD	381577	6368808	2.7

Site Code	Database ref. code[a]	Sampling date	Location	Easting[b]	Northing	Elevation (mAHD)[c]
341a	ASS61304101	23/03/04	LAKE MCLARTY, WEST BANK	379038	6380751	0.4
347a	ASS61304701	07/04/04	WETLAND MARGIN, OLD BUNBURY RD	380148	6368180	3.9
347b	ASS61304702	06/04/04	WETLAND MARGIN, OLD BUNBURY ROAD	380452	6368084	3.1
348a	ASS61304801	06/04/04	HARVEY RIVER, UPSTREAM OLD BUNBURY ROAD	381972	6367730	4.1
349a	ASS61304901	16/04/04	POINT MORPHITT SOUTH, ESTUARY ROAOAD	373965	6384062	2.2

[a] Water Information (WIN) database site number
[b] All co-ordinates are for MGA Zone 50 (with the GDA94 centroid)
[c] Elevation is an estimate obtained from a digital elevation model for the region (based on Department of Land Information, WA elevation data)

Appendix 3: Acid sulfate soil field methods (Department of Environment, 2003-2005)

OBJECTIVES

The objective of these sampling methods is to provide a standard that can be used state-wide, to enable a sampling and analysis regime that will provide an accurate assessment of environmental impact prior to disturbance of acid sulfate soils (ASS) and potential acid sulfate soils (PASS). The following general guidelines apply:

- All field personnel will ensure that investigation of all sites will be conducted with minimum disturbance to fauna and flora.
- Where material disturbance occurs, all consideration will be taken to leave the site as near as possible to its' original state. Cuttings from site hole augers will be replaced in the hole where investigation has been conducted.
- Communicate with all stakeholders during the field programme.

SELECTION OF SITES

General selection of investigation sites (within 200m) is determined by the supervising scientist, with finer scale placement (<100m) determined by field technicians (involving on-site assessment of access and safety issues).

SITE INFORMATION

All information is recorded on standard Land and Water Quality ASS field record sheets.

INFORMATION OUTLINE

- The location of each borehole is determined using GPS using the Geocentric Datum Australia 1994 (GDA94) centroid and reported as Easting and Northing (Metric Grid of Australia).
- Map reference sheet name and number e.g. *Perth Environmental Geology 1:50 000 2034 II*
- Date/month/year (DD-MM-YYYY).
- Approximate surface elevation (AHD), taken from reference topography map.
- Landform e.g. *estuarine, lagoon, floodplain, dune.*
- Dominant vegetation
- Standing groundwater level

MATERIAL PROFILE DESCRIPTIONS

The following lithological observations and field measurements must be recorded:

- Material horizons and their depths.
- Material loss during extraction of sampling rod/tube (i.e. recovery of profile during coring run).
- Munsell colours (2000 edition), mottles (including approximate proportion of exposed core area mottled), iron monosulfides, jarosite mottling.
- Field texture and structure e.g. *clay, loam, silt – moist, hard, pliable, plastic, organic material.*
- Visible shell fragments, size and abundance must be recorded before removal for sampling. Test for presence of reactive carbonates using HCl-drop test.
- Measurement of field pH_F and field pH_{FOX} after oxidation with 30 per cent peroxide (H_2O_2) should be recorded at 0.25m or within each horizon.
- Depth of water table (mbgl).
- Profiling should continue to one to two metres below the water table.

FIELD pH TEST (pH_F)

PROCEDURE OUTLINE (adapted from Hey et al., 2000)

1) **Calibrate battery powered field pH meter (pH4 – pH7).**
2) **Test and record the pH value of the deionised water.**
3) **Prepare the test tubes in the test rack.** Make sure the rack is marked with the depths so there is no confusion about the top and bottom profile. Use of separate racks for the pH_F and the pH_{FOX} tests is recommended as contamination may occur when the pH_{FOX} reactions become violent.
4) **Conduct tests at intervals on the soil profile of 0.25 or at least one test per horizon whichever is lesser.**
5) **Remove approximately 1 teaspoon of soil from the profile. Place approximately half a teaspoon of the soil into the pH_F test tube** and place the other **half a teaspoon of the soil into the pH_{FOX} test tube** for the corresponding depth test. It is important that these 2 sub-samples are taken from the same depth and that they are similar in characteristics.
6) **Place enough deionised water (~pH 5.5) in the test tube** to make a paste similar to a 'grout mix' stirring with a skewer or similar to ensure all lumps are removed. Do not leave the sample in the test tube without water for longer than 10 minutes. This will reduce the risk of oxidation--the pH_F is designed to measure acidity, any oxidation subsequent to the soils removal from the ground will not reflect the true situation. In some instances, in less than 5 minutes, monosulfidic material may start to oxidise an substantially affect the pH_F results.
7) **Immediately place the spear point electrode (preferred method) into the test tube,** ensuring that the spear point is totally submerged in the soil/water paste. **Never stir** the paste with the electrode. This will damage the semi-permeable glass membrane.
8) **Measure the pH_F** using the pH meter with the spear point probe.
9) **Wait for the reading to stabilise and record the pH measurement.** All measurements should be recorded on a data sheet.

pH value	Result	Comments
$pH_F \leq 4$	Actual acid sulfate soils (AASS) indicating oxidation of sulfides	This is generally not conclusive but highly organic soils such as peat and occasionally heavily fertilised soils may also give $pH_F \leq 4$.
$pH_F \leq 3.7$	Expected if jarosite exists in the sample	This is indicative of an Actual ASS layer. Jarosite needs a pH of at least 3.7 to form. Horizons containing some jarosite and some other mottling (iron, grey) may have a pH >3.7 if the sample contains a mixture of jarosite and higher pH soil. This depends on the level of oxidation and the ability of the soil to retain any soluble acidity arising from oxidation of PASS materials.
$pH_F \geq 7$	Expected in waterlogged, unoxidised, or poorly drained soils.	Marine mud commonly have a pH>7 and reflects seawater (pH 8.2) influence, although carbonate rich profiles can also be at this pH. May contain PASS materials.
$pH_F > 4, \leq 5.5$	A strongly acid soil	Investigate further for possible ASS link. e.g. actual ASS materials with shells/carbonates present.

FIELD pH PEROXIDE TEST (pH_{FOX})

The pH and strength of peroxide used is important. The pH of the peroxide should be pH 4.5-5.5 (ideally pH 5.5). This ensures that the result measured is a reflection of the oxidation of the soil (if any) and not of the existing pH of the peroxide. When peroxide is purchased often the phosphoric acid stabilisers added by the chemical companies will result in a pH of approximately 2-3. The pH can be increased by adding small amounts of sodium hydroxide (NaOH) (refer to Health and Safety data sheet for 30 per cent peroxide). Failure to adjust the pH can lead to false field peroxide test results.

PROCEDURE OUTLINE

1) **Adjust the pH of the hydrogen peroxide before going into the field.** This can be achieved by adding a few drops of concentrated NaOH (general laboratory grade) at a time and checking the pH with the electrode regularly. Concentrated NaOH solution is highly caustic and safety precautions must be exercised. Also, NaOH will raise the pH quickly so the pH needs to be regularly checked during this process. DO NOT buffer a large quantity of hydrogen peroxide at one time since the acid preservative maintains the stability of the peroxide. Only buffer the amount to be used in the field storing the remaining in darkness at 5 degrees C in a well-labelled container with only small quantities to be taken into the field at one time. It is recommended that the pH-adjusted peroxide solutions used for field-testing is stored in a dark, shatter-proof container that prevents light penetration and stored in such a manner that does not submit the container to extreme temperature conditions. The pH of the peroxide that has already been buffered may change over time and must be measured (and corrected, if necessary) prior to use in the field as part of QA/QC requirements (only once at the beginning of each field work day is necessary). It is recommended that a small quantity of concentrated NaOH is kept with the field test kit so the peroxide can be buffered if needed.

2) **Calibrate battery powered field pH meter** record the measured calibration**.** Records of the probe calibration can give the field officer an indicator on the life of the probe. The peroxide can be particularly aggressive to semi-permeable glass membrane tipped spear point probes.

3) **Prepare the test tubes in the test rack as for pH_F** test. Make sure the rack is marked with the depths so there is no confusion about the top and bottom profile. Use of separate racks for the pH_F and the pH_{FOX} tests is recommended as contamination may occur when the pH_{FOX} reactions are violent.

4) **Conduct pH_F tests at intervals on the soil from the profile of 0.25m or at least one per horizon whichever is the lesser.**

5) **Remove approximately 1 teaspoon from the profile. Place approximately half a teaspoon of that soil into the pH_F test tube and place half a teaspoon of soil into the pH_{FOX} test tube.** It is important that these 2 sub-samples come from the same depth and that they are similar in characteristics. DO NOT TAKE SAMPLES FROM OBVIOUSLY DIFFERENT SOIL TYPES. These will give different results from the type of test conducted.

6) **<u>Remove any large shell and/or limestone fragments from the material before testing. If unsure about material buffering capacity, use a few drops of 10 per cent HCl to verify the presence of carbonates in material. If carbonates are present a fizzy bubbling reaction will occur. HCl should be carried in a glass bottle with eye dropper. It should be safely secured in the vehicle, clearly identified of its harmful potential.</u>**

7) **Add a few drops of 30 per cent H_2O_2 adjusted to pH 4.5-5.5 to the soil in a heat resistant test tube and stir the mixture.** For soil horizons that have a substantial amount of organic material DO NOT add more than a few drops at a time. This will prevent overflow and wastage of peroxide. A day's supply of peroxide should be allowed to reach ambient temperature prior to use.

8) **Ideally allow no less than 15 minutes for any reactions to occur.** If substantial PASS materials are present, the reaction will be vigorous and may occur almost instantly. Careful watch will be needed in the early stage to ensure that there is no cross contamination of the sample in the test rack. If the reaction is violent and the soil/peroxide mixture is escaping from the test tube, a small amount of deionised water can be added to cool and calm the reaction. DO NOT add too much deionised water as this may dilute the mixture and affect the pH value.

9) Steps 6 and 7 may be repeated until the soil/peroxide mixture reaction has slowed. This will ensure that most of the sulfides have reacted.

10) **If there is no initial reaction**, individual test tubes containing the soil/peroxide mixture can be placed into a cup of hot water (especially in cooler weather) or in direct sunlight. This will encourage the initial reaction to occur. When the sample starts to 'bubble' remove the test tube immediately from the cup and replace into test tube rack.

11) **Rate the reaction using the scale:**

L	Slight effervescence (generally small bubbles, reaction jar warmer than equivalent pH_F test jar)
M	Moderate reaction (large bubbles, contained within reaction jar for duration of test, reaction jar is warm to hot)
H	High reaction (large bubbles, foaming over the top of reaction jars often in continuous stream, reaction jar is warm to hot)

X	Volcanic (very vigorous, violent, spitting, with a gas given off, reaction jar is hot).

12) **Wait for the soil/peroxide mixture to cool** (may take up to 10 minutes). The reactions often exceed 90ºC. Placing an electrode into these high temperature situations may result in physical damage and inaccurate readings as most pH meters are calibrated to record a result for an ambient temperature of approximately 25ºC.

13) **Measure the pH_{FOX} with an electronic meter.** Place the spear point probe electrode into the test tube, ensuring that the spear point is totally submerged in the soil/peroxide mixture. NEVER STIR the mixture with the electrode. This will damage the semi-permeable glass membrane.

14) **Wait for pH reading to stabilise and record the pH_{FOX} measurement.**

15) **Record all measurements on a field data sheet.**

MATERIAL SAMPLING

- Samples should be taken every 0.5m, or every material horizon whichever is greater or lesser.
- Each sample should be greater than 200 grams (more than half the sample bag supplied).
- Any visible shell fragments should be removed from the sample in the field. If shell is not removed, it will bias laboratory results by overestimating the buffering capacity of the soil.
- Sample bags should be labelled externally detailing site name and sample depth. Waterproof labels can be inserted in the bag detailing the site name and depth, although the laboratory will need to be made aware of these prior to sample processing.
- Samples should be placed in a plastic snap-lock bag, as much air as possible should be evacuated from the sample bag before sealing.
- Immediately freeze sample bags in a portable fridge (e.g. 12V ENGEL Fridge).
- A register of all samples should be kept.
- Duplicate samples should be taken every 20 samples. Labelling and numbering of duplicates should continue as the convention set for the labelling of all other samples.
- The cleaning of sampling equipment is essential between each sampling horizon to avoid cross-contamination of samples.
- DO NOT LEAVE ANY POTENTIAL ACID SULFATE SOILS EXPOSED AT A SAMPLING SITE.
- All samples are returned to deep frozen storage in Perth. Samples assessed for laboratory analysis are submitted in bulk batches to laboratory.
- If several sampling horizons from one hole are to be sent they should be grouped and placed in a larger bag.

- All samples for analysis with analytical suite must be recorded on DoE chain-of-custody sheets to accompany sample to laboratory.

- Cuttings of all horizons to be collected in chip trays clearly identified with site name/number and depth of horizon.

QUALITY CONTROL AND QUALITY ASSURANCE

- Calibration of pH meter is checked (and adjusted if necessary) at the beginning and end of each day (further details below). Periodic rechecking of calibration is conducted when samples have sudden low or high pH readings in a soil profile compared with measurements for samples from adjoining depths or if the time before stable pH readings obtains increases.

- The pH of the peroxide solution is verified to be within an acceptable range (4.5-5.5) and adjusted if necessary at the beginning of each day of field-testing. Similarly, the pH of DI water solutions is also checked.

- Duplicate field pH_F and pH_{FOX} should be conducted every 15 sets of samples.

- Every sample taken for analysis should be given a WIN data generated number, site name/number and horizon depth clearly visible on the outside of bags and inside with waterproof labels.

- Duplicate soil samples should be submitted to a separate laboratory after every 1:20 of set samples.

- Chain-of-custody forms listing all samples and their details, (white and pink sheets) must be attached to the samples for transport to laboratory.

- Samples that go interstate must have a clear written request indicated on the chain-of-custody (C.o.C) for a faxed copy of all samples on C.o.C. with laboratory numbers allocated to each sample. These should be sent immediately on receival at laboratory.

- A sample of split be retained by laboratory after drying to be kept by laboratory or handed back to DoE until Land and Water Quality have validated results.

CALIBRATION AND USE OF pH ELECTRODES

pH electrodes	Calibration of pH meter	Soil conditions and electrode use
Use spear point probe without protective sleeve. Store electrode in aqueous solution and ensure protective cap on probe when not being used. NEVER LET PROBE DRY OUT. Check to see if electrode is scratched or damaged – if it is REPLACE IT.	Calibrate probe each day before use. Rinse probe with deionised water and dry with clean tissue. Ensure buffer solutions are fresh and clean by using small amounts in small tube. Never insert in bulk bottle. Replace protective wetting cap on probe.	**Saturated soil** if measuring directly into saturated soil – press spear point probe into soft wet soil and wait for stable reading. (Do not push into dry soil or sand – it will damage the glass point). **Unsaturated soil** insert a sharp implement into the soil core sample and then add a small amount of DI and insert probe.

Reference

Hey, K.M., Ahern, C.R. and Watling, K.M. (2000). Using chemical field tests to identify acid sulfate soils likelihood. In 'Acid Sulfate Soils: Environmental Issues, Assessment and Management, Technical Papers'. Ahern, C.R., Hey, KM, Watling, KM and Eldershaw, VJ (eds), Brisbane, 20-22 June 2000. Department of Natural Resources, Indooroopilly, Queensland, Australia.

Appendix 4: Classification of ASS disturbance risk

ASS disturbance risk is the combination of the probability of an ASS hazard occurring in soils/superficial sediments soils and the likelihood of these materials being disturbed (for example, by activities commonly occurring during land development). In simplified terms, ASS hazard occurs where soil materials contain sulfide concentrations that exceed environmental action limits (Department of Environment, 2004b) and are sufficiently close to the ground surface as to be at risk of being disturbed. In this investigation, sulfidic horizons (after Isbell, 1996) with levels of sulfides (generally termed PASS materials) exceeding 0.03% sulfide-S (w/w) or likely to contain such sulfide levels (based on assessment of ASS field test results and sample analysis for a soil profile) are considered to constitute an environment hazard. Evaluating the disturbance component of ASS disturbance risk involves considering the depth and extent of likely disturbance activities (including shallow or deep excavations, de-watering or drainage). The standard criteria for categorising ASS disturbance risk applied in WA are outlined in Table 1.

Table 1: Relationship between ASS disturbance risk categories, characteristics of soils/sediments within each category and activities that carry a significant risk of disturbing ASS within each category.

Class	Disturbance Risk Summary	Underlying ASS hazard	Activities that carry a risk of disturbing ASS
1a[1]	High to moderate ASS disturbance risk (within 2m of ground-surface)	PASS materials or disturbed ASS occur within 2m of ground surface, often above action criteria (0.03% sulfide-S)	Any works below natural ground surface carry a high to moderate risk of disturbing ASS.
1b[1]	High to moderate ASS disturbance risk (generally 1.5-3m below ground-surface)	PASS materials or disturbed ASS occurs generally at greater than 1.5m below ground-surface, often above action criteria (0.03% sulfide-S). Includes soils where substantial potential acidity occurs marginally below 3 m from ground surface.	Any works (including dewatering) to greater than 1.5m below natural ground surface carry a high to moderate risk of disturbing ASS.
2	Moderate to low ASS disturbance risk	PASS materials or disturbed ASS generally occurs at greater than 3 m below ground surface. Can include soils where there thin lenses (<0.25m) of PASS materials within 3m of ground surface.	Any works (including dewatering) to greater than 2.5m below natural ground surface carry a high to moderate risk of disturbing ASS. Moderate to low risk of most works within 2.5m of soil surface disturbing ASS.
3	Low to nil ASS disturbance risk	No known occurrence of PASS in profiles, or very patchy distribution with no PASS found at investigation sites	No known risk of any works disturbing ASS, except where dewatering occurs within 500m of high or moderate risk areas

[1] Note: Distinction of high to moderate ASS disturbance risk subcategories 1a and 1b mapping units has not been carried out due to the limited availability of land elevation data to enable delineation of these areas within in areas of high to moderate ASS disturbance risk (generally occurring 0-5mAHD).

It is important to note that assessments of ASS **disturbance risk** differ from an assessment of **environmental risk** posed by acid sulfate soils for different disturbance scenarios. While disturbance risk reflects elements of environmental risk (e.g. there would be negligible environmental risk if ASS disturbance risk was minimal), the exact nature of this risk is dependent on the activities carried out and local site conditions. Assessing environmental risk of ASS would involve determining the overall impact of acid released from disturbed acid sulfate soils, including dynamics of acid and trace metal generation, neutralisation processes, transport pathways and reactions, and evaluation of impacts on receiving water ecosystems (surface and groundwater) and infrastructure. Individual characteristics of sites, the differences in the how the disturbance is carried out and climactic conditions prevent generalised assessment of environmental risk of acid sulfate soil disturbance. This is level of evaluation, achieved through statutory requirements for proponents managing areas with acid sulfate soils to carry out site specific investigations of acid sulfate soils and prepare management plans prior to disturbing ASS.

Appendix 5: Potential ASS characteristics of superficial formations investigation sites

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
401a	NORTH GUANANUP POOL, GULL ROAD NORTH, SERPENTINE RIVER	Sporadically distributed PASS detected in shallow peaty silt (0.25-0.5mbgl). Core depth limited to 1.3mbgl by iron cemented sand hard-pan. PASS materials suspected below iron cemented sand.	1a	0.25	
401b	NORTH GUANANUP POOL, GULL ROAD NORTH, SERPENTINE RIVER	PASS materials (ca. 0.04% sulfide-S) in yellowish-brown sands (5.0-6.0mbgl) in a deep sandy profile.	2	5.00	0.40
401c	NORTH GUANANUP POOL, GULL ROAD NORTH, SERPENTINE RIVER BACKSWAMP	PASS materials evident in black silty clays (with iron concretions) from c.a. 0.6 to 1.2mbgl, no PASS detected at 1.4mbgl	1a	0.60	0.50
402a	WEST YALBANBERUP POOL, SERPENTINE RIVER	Significant PASS materials (up to 2.2% sulfide-S) in silty clay (0.6-1.5mbgl), sand (1.5-2.1mgl) and clay (2.1-2.6mbgl) horizons and underlying sequences of clay, sandy clay and sand horizons (2.6-6.0mbgl)	1a	0.60	0.75
402b	WEST YALBANBERUP POOL, SERPENTINE RIVER	Significant PASS materials (up to 0.3% sulfide-S) in sand (1.2-3.0bgl) and silty sand (3.0-4.2mbgl) horizons	1a	1.20	0.75
402c	WEST YALBANBERUP POOL, SERPENTINE RIVER	PASS materials in greyish-brown sandy horizons (2.0 to >3.6mbgl). Increasing ferruginous sand layers with depth.	1a	2.00	0.85
402d	WEST YALBANBERUP POOL, SERPENTINE RIVER	PASS materials detected in sandy horizons with numerous ferruginous, weakly cemented sand lenses (2.5-3.0m).	1b	2.50	1.40
402e	EAST YALBANBERUP POOL, SERPENTINE RIVER (OFF FOWLER ROAD)	Sporadically distributed PASS materials (<0.25m lenses) occur in mottled sandy clay (1.2-1.8mbgl) and underlying mottled green clays (1.8-3.8m)	1b	1.20	1.10

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
402f	EAST YALBANBERUP POOL, SERPENTINE RIVER (OFF FOWLER ROAD)	Dark brown sands (2.0-3.0mbgl) contain PASS materials, but not underlying white sands (3.0-4.2mbgl) or clayey sands (4.2-6.0mbgl).	1b	2.50	0.50
402g	EAST YALBANBERUP POOL, SERPENTINE RIVER (OFF FOWLER ROAD)	Sporadically distributed PASS materials in clayey sand (2.5-3.0mbgl), <0.03% sulfide-S at 3m.	2	2.50	0.27
402h	EAST YALBANBERUP POOL, SERPENTINE RIVER (OFF FOWLER ROAD)	No PASS or actual ASS evident in predominantly mottled olive-brown and greyish-green sandy clay profile (likely sporadic distribution in profile)	1b	2.50	1.80
402i	EAST YALBANBERUP POOL, SERPENTINE RIVER (OFF FOWLER ROAD)	No PASS or actual ASS evident in sandy profile, possibly sporadic PASS materials, core limited to 1.8m	2		0.55
402j	EAST YALBANBERUP POOL, SERPENTINE RIVER (OFF FOWLER ROAD)	Significant PASS materials up to 0.5% sulfide-S in olive and grey sand horizons (0.8 to >1.5mbgl)	1a	0.80	0.30
402k	NORTH YALBANBERUP POOL, SERPENTINE RIVER (GULL ROAD TRACK)	Evidence of PASS materials (1.5-1.8mbgl) in soil inspection and field testing of soil profile. Coring limited to 1.8mbgl	1b	1.50	
403a	NORTH STAKEHILL BRIDGE, RESERVE, OFF WOODLAND PDE	PASS materials occur below 2.4m in sandy horizons (0.04% sulfide-S at 2.8m, increasing to 0.28% at 5mbgl)	1b	2.40	1.90
403b	NORTH STAKEHILL BRIDGE, RESERVE, OFF WOODLAND PDE	PASS materials (up to 0.1% sulfide-S) in shallow sandy horizons (2.4-4.8mbgl) and underlying silt horizons (>4.8mbgl). PASS is <1m in surrounding dune swales.	1a	2.40	1.20
403c	NORTH STAKEHILL BRIDGE, FOWLER ROAD	No PASS or actual ASS materials evident. White and yellow sands (0.1-1.2mbgl) over mainly mottled yellow-brown sand horizons (1.2-3.6mbgl) with white sands at depth.	3		2.01

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
403d	NORTH STAKEHILL BRIDGE, FOWLER ROAD	PASS materials detected in light grey sand horizons (2.5 to 4.2mbgl) and underlying mainly light bluish-grey silty sands (4.2-5.4mbgl).	1b	2.50	1.10
403e	NORTH STAKEHILL BRIDGE, RESERVE, OFF WOODLAND PDE	No PASS or actual ASS materials evident. Core depth limited to 3m. PASS materials occur in olive sand horizon at c.a. 4-4.5mbgl in adjacent excavation.	2	3.00	
404a	NAMBEELUP, OFF GULL ROAD	PASS materials in ferruginous sandy layer (1.5-3.3mbgl), coring limited to 3.3m by iron cemented sands	1a	1.50	0.20
404b	LAKES ROAD	No PASS or actual ASS evident; coring limited to 2.4m (+ limited core recovery); Uncertainty regarding PASS at >2.4mbgl	2		1.00
405a	NW BLACK LAKE, OFF HOUGHAM ROAD, BARRAGUP	Significant PASS materials (up to 0.31% sulfide-S) in sand horizons (1.3-3.2mbgl) grading to clayey sand horizons (3.2-6mbgl)	1a	1.30	1.04
405b	NW BLACK LAKE, OFF HOUGHAM ROAD, BARRAGUP	PASS materials (0.14 to <0.03% sulfide-S) in sand and underlying clayey sand horizons from 2.0 to >4.8mbgl	1b	2.00	1.30
405c	WEST BLACK LAKE, HOUGHAM ROAD BARRAGUP	Significant PASS materials in sand horizons from 1.3 to >2.5mbgl (0.03-0.6% sulfide-S) in deep sandy profile	1a	1.30	1.30
406a	COODANUP, LOWER SERPENTINE RIVER	Significant PASS materials in sand and silty sand horizons 0.75mbgl to >6mbgl (0.5-2% sulfide-S), in situ neutralising materials present	1a	0.75	0.10
406b	COODANUP, LOWER SERPENTINE RIVER	PASS materials detected sporadically in sand horizons at >3.2mbgl (to 4.5m) of a deep sandy profile	2	3.20	2.60
406c	RONLYN ROAD, FURNISSDALE	Sandy PASS materials detected 2.8-4.0m (up to 0.05% sulfide-S) becoming increasingly sporadic in clayey sands horizons below 3.0m	2	2.80	1.98
406d	WOODVIEW WAY, BARRAGUP	PASS materials in sand horizons grading to silty sand 2.4 to >5.8m, increasing potential acidity with depth	1b	2.40	0.80

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
406e	BLACK LAKE SOUTH, RODGERS ROAD WEST	Significant PASS materials (0.35-3.7% sulfide-S) in predominantly bluish grey clay (1.0-4.0m) and sand (4.0-5.6mbgl) horizons. Shell fragments occur throughout clay PASS horizons.	1a	1.00	0.50
406f	BLACK LAKE SOUTH, RODGERS ROAD EAST, OFF FIEGERTS ROAD	PASS materials evident in sand layer (3.0-3.5mbgl) overlying sandy clay with minor PASS materials	2	3.00	1.90
406g	BLACK LAKE SOUTH, RODGERS ROAD WEST	Sporadically distributed PASS materials in white sandy horizon 3.5-4.5m	2	3.50	2.20
406h	BETWEEN RIVERSIDE DRIVE & RONLYN ROAD, FURNISSDALE	PASS materials (up to 0.06% sulfide-S) in brown ferruginous sand (2.0-2.8mbgl) and light-bluish grey clayey sand (2.8-3.3mbgl) with minor PASS materials in underlying greenish-grey clay (3.3-5.8mbgl).	1b	2.00	1.44
406i	COODANUP, LOWER SERPENTINE RIVER	No PASS or actual ASS evident	3		4.20
406j	BLACK LAKE SOUTH, RODGERS ROAD EAST, OFF FIEGERTS ROAD	Actual ASS materials (including jarosite) in mottled clayey sand (1-1.7mbgl) overlying silt (1.5 to >1.7bgl), no evidence of PASS materials to 1.7mbgl (limit of coring)	1a	1.70	0.90
406k	BLACK LAKE SOUTH, RODGERS ROAD WEST	PASS materials in olive-grey sand from 0.95 to >1.8mbgl. Evidence of PASS oxidation in mottled sand horizons (0.95-1.4mbgl)	1a	0.95	0.50
406l	COODANUP, LOWER SERPENTINE RIVER	Significant PASS materials (0.3-0.5% sulfide-S) in dark olive-green sand horizon (1.0 to >2.4mbgl) of deep sandy profile.	1a	1.00	1.20
407a	OFF RONLYN ROAD, FURNISSDALE	Significant PASS materials (0.2% sulfide-S decreasing to <0.05% sulfide-S at 3m) 1.3mbgl to >6mbgl in grey sand horizons	1a	1.30	1.26
407b	OFF RONLYN ROAD, FURNISSDALE	Mainly grey sandy PASS materials (<0.03% up to 0.12% sulfide-S) from 0.9m to >6mbgl in deep sandy profile	1a	0.90	0.94

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
407c	OFF RONLYN ROAD, FURNISSDALE	Minor PASS materials (<0.03% sulfide-S) in ferruginous sands (1.2-1.8m) overlying mainly grey sandy PASS materials (up to 0.09% sulfide-S) 1.8 to >6mbgl. Clay PASS materials at 3.2-4.0mbgl	1b	1.20	1.30
407d	OFF FURNISSDALE ROAD, FUNISSDALE	Sporadically distributed PASS materials (averaging 0.03% sulfide-S) in calcareous mottled blue-grey clays (1.0 to >3mbgl) beneath white and brown sands.	3		0.60
407e	SERPENTINE RIVER MOUTH, PEEL PARADE	Significant PASS materials (up to 0.42% sulfide-S) in sandy horizons (0.6-1.6mbgl). Core depth limited to 1.6mbgl	1a	0.60	0.50
408a	TONKIN DRIVE, NORTH YUNDERUP	PASS materials (0.05 to <0.03% sulfide-S) in grey sand horizons 1.5m to >6mbgl overlaid by ferruginous sand (0.8-1.5mbgl) with minor PASS materials at 1.4m	1a	1.50	0.48
408b	BARRAGUP WETLAND, JANNALI ROAD	Significant PASS materials in mainly grey sand (0.9-2.6mbgl) overlying light grey clayey sand (2.6-4.2mbgl) and white sand (4.2- > 6mbgl). 0.32% sulfide-S at 1m decreasing to <0.05% sulfide-S at >4mbgl.	1a	0.90	0.24
409a	WILGIE CREEK, NORTH YUNDERUP	Thin sandy PASS materials at 2.0-2.5m overlying significant PASS materials (1-2.2% sulfide-S) in silt between 2.5 to >6mbgl	1b	2.50	2.00
409b	WILGIE CREEK, CORREAS STREET, NORTH YUNDERUP	Partially oxidised PASS materials (but no actual ASS) evident in mottled clay (0.8-2.0mbgl) overlying clayey sand and sand PASS materials (up to 0.08% sulfide-S) from 2.0 to 5.3mbgl	1b	0.80	2.28
409c	WILGIE CREEK, NORTH YUNDERUP RD, NORTH YUNDERUP	Sandy PASS materials (2.0-2.9mbgl) overlying significant PASS materials in black silt (2.9 to >6mbgl) in situ neutralising materials present	1b	2.00	1.00
409d	MURRAY RIVER BACKSWAMP, NORTH YUNERUP	Actual ASS and PASS materials in peaty sand and silty sand horizons from 0-1mbgl. Significant PASS materials (1.4-2.1% sulfide-S) in black silt from 1.0-2.6mbgl. Underlying mottled olive green clay contains minor PASS materials	1a	0.10	0.40
410a	BANKSIA TCE EAST, SOUTH YUNDERUP	Actual ASS from 0.75-1.75mbgl in mottled silty sand horizons overlying mottled clay horizons with sporadic PASS materials (1.75-4.2mbgl)	1a	1.75	0.77

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
410b	YUNDERUP ROAD, SOUTH YUNDERUP	Significant PASS materials (up to 0.16% sulfide-S) in silty sand horizons from 1.2-2.3mbgl overlying PASS materials (0.07%- 3.1% sulfide-S) in silt, silty sand and sandy horizons to 6mbgl.	1a	1.20	0.15
410c	DELTA CRESCENT, SOUTH YUNDERUP	Actual ASS (including jarosite mottling) in mixed clay and sand fill (0-1.0mbgl) overlying buried soil with PASS materials in mottled clay (1.0-1.4mbgl), predominantly silty sand and sand horizons (1.4-3.1mbgl) and black silt (>3.1mbgl).	1a	1.00	1.40
411a	SOUTH YUNDERUP FLOOD DRAIN GATES	PASS materials detected in surface sand horizons (0.2-0.4mbgl) with sporadic or minor PASS materials in various underlying sandy clay and clayey sand horizons (1.5-5.3mbgl).	1a	0.20	0.20
411b	SOUTH YUNDERUP FLOOD DRAIN	Actual ASS and significant PASS materials (with up to 2.4% sulfide-S) in mottled silty sand (1.1-1.4mbgl) and underlying silt (1.4-1.6mgl) overlying non-PASS mottled clays	1a	1.10	0.40
411c	OFF STH YUNDERUP RD, SOUTH YUNDERUP	No PASS or actual ASS materials evident in deep sand profile	3		0.65
411d	OFF STH YUNDERUP RD, SOUTH YUNDERUP	Significant PASS materials in silty sand horizon from 1.8-2.7mbgl and clay (up to 1.2% sulfide-S) with sporadic mottled bands from 2.7-3.2mbgl.	1a	1.80	0.90
411e	OFF STH YUNDERUP RD, SOUTH YUNDERUP	Significant PASS materials (up to 0.63% sulfide-S) in silty sand and clayey sand (2.0-2.6mbgl) and sporadic lenses in sandy clay horizons below 2.6m.	1b	2.00	0.90
411f	MURRAY RIVER BACKSWAMP, MURRAY RIVER DRIVE, SOUTH YUNDERUP	Actual ASS (with jarosite mottling) in variously mottled silty clay horizons (0.3-0.8mbgl) also concurrent with PASS materials in silty clays and sandy clays from 0.4-1.2mbgl (<0.03-0.26% sulfide-S).	1a	0.40	1.80
411g	PINJARRAH RD AND SOUTH YUNDERUP RD INTERSECTION	Significant PASS materials (up to 2.8% sulfide-S) in dark grey silty clay from approx. 0.8 to >1.9mbgl (limit of coring). Evidence of actual ASS formation (but no mottling) in upper layers of silty clay horizon (0.8-1.6mbgl).	1a	1.60	0.20

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
412a	LEANDER WAY, RAVENSWOOD	PASS materials detected in white sand horizon (2.0-2.6m) overlying grey silty sand (2.6-4.4mbgl). Significant PASS materials (>3.5% sulfide-S) in underlying bluish-black clay horizon (4.4 to >6.0mbgl)	1b	2.00	1.90
412b	LEANDER WAY, RAVENSWOOD	Sporadically distributed PASS materials in silty sand horizons (>3.0mbgl) underlying mottled clays.	2	3.00	2.30
413a	SOUTH OF RAVENSWOOD CARAVAN PARK	Thin actual ASS in silty sand at 1.5mbgl overlying significant PASS materials in silty sand (1.5-2.8mbgl; up to 0.7% sulfide-S) and sand (2.8-6mbgl) horizons (0.17-0.6% sulfide-S).	1a	1.50	1.61
413b	SOUTH OF RAVENSWOOD CARAVAN PARK	Significant PASS materials in silty sand (2.0-3.0mbgl; 0.03-0.54% sulfide-S), sandy silt (3.0-4.4mbgl, up to 0.6% sulfide-S) and silt (4.4-6.0mbgl) horizons.	1b	2.00	1.52
413c	SOUTH OF RAVENSWOOD CARAVAN PARK	Significant PASS materials in mottled silty clay (1.0-2.2mbgl; 0.06-0.4% sulfide-S) overlying silty sand (2.2-5.4mbgl) with sporadic PASS materials.	1a	1.00	2.20
413d	SOUTH OF RAVENSWOOD CARAVAN PARK	No PASS or actual ASS evident to 5mbgl in deep sandy profile	3		3.50
414a	OLD SARUN LODGE, MURRAY RIVER	Actual ASS materials in mottled clayey sand and sand horizons (1.7-2.8mbgl) with significant PASS materials (0.8-1.4% sulfide-S) below 3.0m in black silt horizon (3-5.5mbgl) and minor sand (5.5-6.0mbgl).	1b	1.70	2.22
414b	OLD SARUN LODGE, MURRAY RIVER	Thin actual ASS in ferruginous sand at 2.5-2.8mbgl (overlaid by silt clays) overlying significant PASS materials (0.5-0.7% sulfide-S) in silty sand and sand horizons below 2.8m.	1b	2.50	2.50
414c	OLD SARUN LODGE, MURRAY RIVER	Actual ASS layer in mottled clay (2.2-3.4mbgl) and significant PASS materials in sandy horizons below 3.4m (up to 0.8% sulfide-S).	1b	2.20	3.42
414d	OLD SARUN LODGE, MURRAY RIVER	Significant PASS materials (up to 0.6% sulfide-S) below 3.3m in black silt (3.3-4.4mbgl) and sand horizons (4.4-6.0mbgl).	1b	3.30	3.03

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
415a	BENS ROAD, SOUTH YUNDERUP	PASS materials sporadically distributed in bluish-grey sandy clays below 3.0mbgl (duplex profile of 1.4m sandy overlying sandy clay and clay horizons)	2	3.00	1.23
415b	OFF BENS ROAD, SOUTH YUNDERUP	Sporadically distributed PASS materials in bluish-grey sandy clay horizons from 2.5-3.0m (duplex profile of 1.2m sandy overlying sandy clay and clay horizons)	1b	2.50	1.16
415c	OFF BENS ROAD, SOUTH YUNDERUP	No PASS or actual ASS materials evident, core depth limited to 3m, predominantly mottled sandy clay overlying clay profile	2		1.45
415d	BENS ROAD, SOUTH YUNDERUP	Actual ASS materials (jarosite formation) in clayey sand (0.5-1.0mbgl) of exposed drain walls, inspection only	1a		
416a	AUSTIN BAY RESERVE NORTH, OFF BEECHAM RD	Significant PASS materials at 0.5-3.1mbgl in sand overlying mottled clayey sand horizons (0.77% sulfide-S at 2mbgl decreasing to <0.03% at 2.5mbgl)	1b	0.50	0.10
416b	AUSTIN BAY RESERVE NORTH, OFF BEECHAM RD	PASS materials in white sand (2.0-2.2mbgl) grading to mottled sandy clay horizons (2.2-4.2mbgl) increasingly sporadic with depth (0.03%-0.09% sulfide-S). Mottled clayey sands at depth with minor PASS materials	1b	2.00	1.46
416c	AUSTIN BAY RESERVE NORTH, OFF BEECHAM RD	Thin layer PASS materials in mottled clay horizon (0.6-1.1m) overlying calcareous clays (intermittent mottled layers).	1a	0.60	0.00
416d	CORNER BEECHAM RD AND PARKHILLS LANE	No PASS or Actual ASS materials evident in predominantly deep mottled clay profile	3		0.62
417a	OFF GREENLANDS RD, FAUNTLEROY DRAIN	Minor PASS materials (ca. 0.02% sulfide-S) throughout olive clay and sandy clay (with minor lenses of sand and iron mottling) from 0.5-3.0mbgl. No significant PASS materials in calcareous sand and cemented sandy clay horizons >4.4mbgl.	2	ID	1.44
417b	OFF GREENLANDS RD, FAUNTLEROY DRAIN	Minor PASS materials in clay (with silicate cementations and lenses of iron mottling) from 0.8 to c.a.1.5mbgl. Sporadic No detectable PASS materials in mottled sandy clay horizons >2.9mbgl.	2	ID	1.87

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
419a	BLACK LAKE, DUNKERTON ROAD, SOUTH BARRAGUP	PASS materials in thin clayey sand horizon (0.6-0.7mbgl) and grey sand horizons (1.25 to >1.6mbgl) of a predominantly sandy profile	1a	0.60	0.20
420a	WETLAND, SOUTH YANGEDI ROAD, NAMBEELUP	Thin PASS materials in sands at 1.6mbgl with only minor PASS materials detected at 2mbgl	1b	1.60	1.80
421a	UPSTREAM NAMBEELUP POOL, NAMBEELUP BROOK, FIEGERTS ROAD NORTH	Significant PASS materials (up to 1.6% sulfide-S) in dark grey sand horizon 1.2 to >1.4mgl (limit of coring).	1a	1.20	0.45
421b	LAKE GOEGERUP WEST, LAKES ROAD,	Significant PASS materials (0.25-0.45% sulfide-S) in grey sandy strata from 1.2 to >2.1mbgl (limit of coring)	1a	1.20	1.18
421c	LAKE GOEGERUP EAST, DUNKERTON ROAD	Brown sandy PASS materials from 1.9 to >2.8mbgl in deep sandy profile	1b	1.90	1.55
421d	LAKE GOEGERUP WEST, BARDOC WAY	Some PASS materials detected in a thin sand layer at 2.8mbgl (site inspection and field testing in excavation)	2	2.80	2.20
422a	SOUTH BLACK LAKE, PINJARRA ROAD	Evidence of sporadically distributed PASS materials in grey sand horizons from 2.3 to >2.7mbgl (in deep sandy profile)	2	2.30	1.85
422b	WETLAND, OFF FIEGERTS RD	Evidence of PASS materials (1.0-1.3mbgl) in soil inspection and field testing of soil profile. Coring limited to 1.3mbgl	1b	1.00	
423a	NORTH OF BEECHAM RD SOUTH OF MURRAY FLOOD DRAIN, SOUTH YUNDERUP	Actual ASS and minor PASS materials from 0.25-1.4mbgl in mottled clayey sand and clay (with jarosite mottles); PASS materials sporadically distributed in sandy clay horizon (2.3 to >2.8mbgl)	1a	0.25	2.02
424a	WEST LAKE AMARILLO, SERPENTINE RIVER	PASS materials evident in mottled black silty clay (0.8 to >1.4mbgl)	1a	0.80	0.15

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
425a	WEST GUARNUP POOL, SERPENTINE RIVER	Significant PASS materials at in mainly peaty clayey silt (0.3-0.85mbgl) and underlying bluish-grey sandy clay (>0.9mbgl). 0.1% sulfide-S at 0.5mbgl to 0.3-0.6% sulfide-S at depth.	1a	0.30	0.55
426a	WEST GUARNUP POOL, SERPENTINE RIVER	Thin actual ASS materials (including jarosite) in peaty silty clay and clayey silt horizons (0.1-0.5mbgl) with PASS materials occurring in clayey horizon >1.2mbgl (limited depth of coring)	1a	0.10	0.83
426b	WEST GUARNUP POOL, SERPENTINE RIVER	Significant PASS materials in sand horizons 0.9 to c.a.1.8mbgl. Up to 1.3% sulfide-S at 1mbgl.	1a	0.90	0.83
427a	MARY ST, HALLS HEAD	No PASS or actual ASS evident in 2.9m sand overlying calcarenite	3		2.25
427b	CAMBRIA ISLAND RTT, HALLS HEAD	No PASS evident, sand fill (0-1.7mbgl) overlying buried profile with minor PASS materials in shelly marl (2.2-2.5mbgl). Calcarenite base at >2.5mbgl. Nearby excavation contained evidence of oxidised PASS materials in mottled grey silty sands	2	2.20	2.10
427c	APOLLO PLACE, PEEL ESTUARY MOUTH	PASS materials (up to 0.1% sulfide-S) in grey silty sands (1.75-2.2mbgl) overlying calcarenite	1a	1.75	1.30
427d	SHANNON RD, MANDURAH	PASS materials (up to 0.13% sulfide-S) in calcareous silt and peat (2.6 to>3.0mbgl), core depth limited to 3m, in situ neutralising materials present	1b	2.60	0.60
427e	TINDALE ST, MANDURAH	PASS materials (up to 0.2% sulfide-S) occur in dark grey, shelly calcareous sand horizon (0.9-1.4mbgl) and underlying olive grey, shelly sand with peat lenses (1.4-1.8 mbgl).	1a	0.90	1.00
428a	HILL TOP RISE, KARNUP, SERPENTINE FLOODPLAIN (DOWNSTREAM KERULUP POOL)	PASS materials (0.1-0.07% sulfide-S) in clay overlying predominantly sandy clay horizons (0.45-1.4mbgl). Minor PASS materials (<0.03% sulfide-S) in sandy clays below 1.5mbgl. Evidence of actual ASS formation (extensive iron mottling and actual acidity)	1a	0.45	0.80
428b	HILL TOP RISE, KARNUP (DOWNSTREAM KERULUP POOL)	Deep sandy profile with PASS materials (up to 0.08% sulfide-S) in brown sand (1.65-1.8mbgl) and bluish-grey sand (1.8 to >2.7mbgl) horizons.	1b	1.65	1.35

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
430a	PATTERSON RD, DANDALUP RIVER	Soil inspection identified PASS materials in <0.5m layer of fine-medium grained sand within river channel (1.5-1.8m below surrounding land surface); minor PASS materials also occur in clay horizons >3.5m below surrounding land surface	1b	1.50	
301a	DRAIN, NATURE RESERVE OFF CARRABUNGUP RD, ROBERT BAY	Minor PASS materials in mottled clays (1.75-2.0mbgl) and sporadically at depth in clayey sand horizons (>4.0mbgl).	2	4.00	1.10
301b	NATURE RESERVE OFF CARRABUNGUP RD, ROBERT BAY	Actual ASS in mottled sand and silt strata (0.4-1.4mbgl). PASS materials (<0.06% to >0.14% sulfide-S) in silt horizons (0.5-1.4mbgl) and underlying grey clayey sands (1.4-2.7mbgl).	1a	0.40	1.13
301c	NATURE RESERVE OFF CARRABUNGUP RD, ROBERT BAY	PASS materials sporadically distributed in sandy clay and sand horizons (2.75-3.3mbgl), minor PASS materials in sandy horizons (>5mbgl) below green and blue-grey clays	1b	2.75	0.90
301d	END CARRABUNGUP RD, ROBERT BAY	Significant PASS materials (up to 0.34% sulfide-S) in brown and white sand (0.6-2.1m) and clayey sand (2.1-2.5mbgl) horizons with sporadic PASS materials occurring in deeper clayey sands (>2.5mbgl)	1a	0.60	0.57
301e	DRAIN CUTTING, NATURE RESERVE OFF CARRABUNGUP RD, ROBERT BAY	Actual ASS materials (jarosite formation) identified on exposed clayey sand (0.5-0.75mbgl) of drain walls, inspection only	1a	0.50	
301f	DRAIN CUTTING, NATURE RESERVE OFF CARRABUNGUP RD, ROBERT BAY	Actual ASS materials (jarosite formation) identified on exposed clayey sand (0.25-0.5mbgl) of drain walls, inspection only	1a	0.25	
302a	WETLAND, EAST ROBERT BAY, AUSTIN BAY CONSERVATION RESERVE	PASS materials (up to 0.13% sulfide-S decreasing with depth) in grey and deeper white sand horizons (1.0-4.4mbgl) becoming increasingly sporadic with depth. Minor PASS materials (<0.02% sulfide-S) in clayey sands below 4.4mbgl.	1a	1.00	0.35
302b	EAST ROBERT BAY, AUSTIN BAY CONSERVATION RESERVE	Significant PASS materials (0.9-0.7% sulfide-S) in olive silty sand horizon (1.1-2.7mbgl) with minor PASS materials in underlying light olive silty sand (2.7-3.3mbgl). Deep sandy profile	1a	1.10	0.70

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
302c	EAST ROBERT BAY, AUSTIN BAY CONSERVATION RESERVE	PASS materials (0.2-0.4% sulfide-S) in grey, greenish-grey and pale olive silty sand horizons (0.7-2.7mbgl) of a deep sandy profile	1a	0.70	0.80
302d	EAST ROBERT BAY, AUSTIN BAY CONSERVATION RESERVE	PASS materials (0.1-0.16% sulfide-S) occurring in brown (1.5-1.9mbgl), greenish grey (1.9-2.9mbgl) and white sand (3-3.6mbgl) horizons. Sporadic PASS materials in underlying sandy clay, clayey sand and silty sand horizons (>3.6mbgl).	1a	1.50	1.50
302e	EAST ROBERT BAY, AUSTIN BAY CONSERVATION RESERVE	PASS materials throughout various brown, grey and white sandy horizons (1.5 to >6mbgl) in a deep sandy profile, generally low sulfide-S concentrations (0.01-0.03%)	1a	1.50	2.00
302f	EAST ROBERT BAY, AUSTIN BAY CONSERVATION RESERVE	Deep sandy profile with sporadic PASS materials in grey silty sand horizons (3.1 to >6.0mbgl)	2	3.10	1.80
302g	WETLAND, EAST ROBERT BAY, AUSTIN BAY CONSERVATION RESERVE	Significant PASS materials (up to 1% sulfide-S) in bluish grey (0.7-1.15mbgl) and bluish black silt horizon (1.15 to >1.5mbgl), in situ neutralising materials present	1a	0.70	0.80
302h	WETLAND, CARRABUNGUP RD VERGE	Shallow soil inspection PASS materials detected in grey sandy materials at 1.9-2.1mbgl	1b	1.90	1.10
302i	POINT GREY SOUTH	Soil inspection identified thin PASS materials (<0.25m) in sands at 2.5mbgl	1b	2.50	1.80
303a	CARRABUNGUP RD NEAR MEELUP RD	Field testing did not conclusively detect PASS materials, but possible low concentrations of PASS materials in upper layer of mottled clay (0.6-0.8mbgl) and in greenish-grey clayey sands (2.6-4.9mbgl)	2	3.10	1.20
304a	SOUTH MUNGINUP SWAMP, LAKE MEELUP ROAD	No PASS or actual ASS materials evident	3		2.80
304b	SOUTH MUNGINUP SWAMP, LAKE MEELUP ROAD	PASS materials detected in sporadic lenses in greenish-grey clayey sand horizons (3.25-5.25mbgl), overlaid by predominantly clay and clayey sand horizons (with no indications of PASS materials)	2	3.25	1.60

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
305a	WETLAND WEST OF LAKE MEELUP	PASS materials throughout brown, olive and greenish-grey sand horizons from 1.5 to >6mbgl (0.03-0.06% sulfide-S)	1a	1.50	1.20
305b	LAKE MEELUP WEST BANK	PASS materials throughout shallow white sand horizons (1.5-2.5mbgl; up to 0.06% sulfide-S) and underlying brown sand (2.5-4.5mbgl; 0.03-0.04% sulfide-S) and bluish grey silt and sandy clay (4.5-6.0mbgl) horizons (<0.06% sulfide-S).	1a	1.50	0.76
305c	LAKE MEELUP SOUTH	PASS materials throughout various sandy horizons from 1.5m to >6mbgl. Sulfide content declines with depth from >0.03% at 2.5mbgl to <0.01% sulfide-S at >4.2mbgl	1a	1.50	1.00
305d	EAST LAKE MEALUP	Actual ASS in surface sand horizons (0.6-1.0mbgl) with significant shallow PASS materials (up to 0.54% sulfide-S) in mottled sandy clay layer (0.8-1.2mbgl). Sandy clay layers (>1mbgl) contain PASS materials diminishing with depth.	1a	0.60	0.70
305e	EAST LAKE MEALUP	No PASS or actual ASS evident to 1.6mbgl (limited investigation depth)	2		1.40
306a	SOUTH MEALUP POINT, OFF LAKE MEELUP ROAD	Deep sandy profile with PASS materials (0.14% sulfide-S decreasing to <0.02% sulfide-S at 5.5mbgl) throughout dark brown and white sand horizons (1.75-6mbgl)	1a	1.75	1.30
306b	SOUTH MEALUP POINT, OFF LAKE MEELUP ROAD	Deep sandy profile with PASS materials (0.07-0.2% sulfide-S) in dark brown sand (2.0-2.1mbgl) overlying greenish-grey, grey and olive brown sands (2.1-6.0mbgl)	1a	2.00	1.42
306c	SOUTH MEALUP POINT, OFF LAKE MEELUP ROAD	Substantial PASS materials (up to 0.33% sulfide-S) throughout sand and silty sand horizons (1.9-5.0mbgl)	1b	1.95	1.80
306d	WETLAND WEST SIDE OF LAKE MEALUP	PASS materials (0.03-0.08% sulfide-S) in a greenish-grey silty sand horizon (1.3-2.6mbgl) overlying bluish-grey clayey sand (2.6-3.9mbgl) and grey silty sand horizons (3.9-5.0mbgl)	1a	1.30	1.10

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
306e	SOUTH MEALUP POINT, OFF LAKE MEALUP ROAD	PASS materials (0.05-0.07% sulfide-S) in brown and dark greyish brown sand horizons (2.5 to >3mbgl), core depth limited to 3mbgl	1b	2.50	2.50
307a	OFF BIRCH GROVE, LAKE MCLARTY	Shallow PASS materials (0.02-0.17% sulfide-S) in pale brown sand horizon (0.3-1.2mbgl) and underlying overlying olive grey and grey sand horizons (1.2-3.9mbgl; 0.08 to <0.02% sulfide-S)	1a	0.30	0.90
307b	OFF BIRCH GROVE, LAKE MCLARTY	PASS materials throughout sandy horizons (1.75 to >4.7mbgl) increasingly sporadic with depth (0.18% sulfide-S decreasing to <0.02% sulfide-S at depth)	1a	1.75	1.00
307c	OFF BIRCH GROVE, LAKE MCLARTY	PASS materials (0.08-0.13% sulfide-S) throughout various olive brown, greenish-grey and white sand horizons (2.5 to >6mbgl) in a deep sandy profile	1b	2.50	1.90
307d	KANGAROO LOOP, OFF BIRCH GROVE, LAKE MCLARTY	PASS materials (0.04-0.05% sulfide-S) throughout deep brown sand, mottled olive-grey clayey sand and grey and olive sand horizons (3.0-6.0 mbgl) of a deep sandy profile	2	3.00	2.00
307e	MCSWANN RD, LAKE MCLARTY	Sporadically distributed PASS materials in shallow ferruginous sand and clayey sand horizons (1.4-2.3mbgl) and intermittently in underlying clay and clayey sand horizons (>2.3mbgl)	2	1.40	0.20
308a	PIONEER PLACE, SOUTH OF LAKE MCLARTY	PASS materials (up to 0.22% sulfide-S at 3mbgl) in dark grey silty sand horizon (2.5-3.55mbgl) overlying limestone, in situ neutralising materials present	1b	2.50	2.20
308b	ESTUARY FORESHORE, SOUTH OF LAKE MCLARTY	Deep sandy profile with PASS materials (0.02-0.06% sulfide-S) in olive sand overlying light grey sand horizons (0.9-3.1mgbl) with minor PASS materials in underlying white sand and clayey sand horizons (3.1-6mbgl)	1a	0.90	1.00
308c	ESTUARY FORESHORE, SOUTH OF LAKE MCLARTY	Deep sand profile with PASS materials (0.06% sulfide-S at 2.5mbgl) in olive and light grey sand horizons (1.25-3.2mbgl) grading to sporadic PASS materials in deeper sand horizons.	1a	1.25	0.60
308d	SOUTHERN EDGE OF LAKE MCLARTY, MILLS RD	PASS materials (>0.03% sulfide-S) in grey sandy silt and silt horizons (1.0-3.0mbgl) overlaid by grey and light brown silty sand horizons	1a	1.00	0.90

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
308e	SOUTHERN EDGE OF LAKE MCLARTY, MILLS RD	PASS materials (average 0.07% sulfide-S) in lower part of olive-grey sand horizon (2.0-2.6mbgl) and underlying sand (2.6-2.8mbgl) and greenish-grey clayey sand horizon (2.8-3.8mbgl). Deep sandy profile.	1b	2.00	1.90
308f	SOUTH OF LAKE MCLARTY, MILLS RD	No PASS or actual ASS evident. Core depth limited to 2mbgl	3		
309a	HERRON POINT SOUTH, HERRON POINT ROAD	Thin layer of PASS materials (up to 0.15% sulfide-S) in ferruginous sand, grey sand and sandy clay horizons (1.25-2.0mbgl) overlying sand and sandy clay horizons with minor PASS materials (<0.02% sulfide-S)	1a	1.25	0.40
309b	HERRON POINT SOUTH, HERRON POINT ROAD	PASS materials (0.05-0.07% sulfide-S) throughout ferruginous, partially cemented sand horizons (1.1-2.5mbgl) and underlying grey sand and silt sand horizons (>2.5mbgl). Limited core depth.	1a	1.10	1.00
310a	WEST OF HILLS RD, KOOLJERRENUP RESERVE	Sporadic PASS materials occur sporadically in grey clayey sand horizons (1.1-3.0mbgl) and in deeper silty sand and sand horizons (>4mbgl; up to 0.05% sulfide-S)	1b	1.10	1.00
310b	WEST OF HILLS RD, KOOLJERRENUP RESERVE	Sporadic PASS materials (up to 0.07% sulfide-S in localised concentrations) throughout yellowish-brown, olive-brown and grey sands (2.2-5.0mbgl). Minor PASS materials at >5mbgl in grey sands.	2	2.20	2.00
310c	WEST OF HILLS RD, KOOLJERRENUP RESERVE	No PASS or actual ASS evident.	3		
311a	SOUTH OF HARVEY RIVER DELTA, OFF SOUTHERN ESTUARY ROAD	Actual ASS materials in brownish grey silty sand (1.0-1.3mbgl), greyish brown silt (1.3-1.8mbgl) and upper layer of dark grey clay (1.8-2.5mbgl) overlying grey/black clays and sandy clays (2.5-6.0mbgl) with PASS materials (0.1-0.23% sulfide-S)	1a	1.00	1.00
311b	SOUTH OF HARVEY RIVER DELTA, OFF SOUTHERN ESTUARY ROAD	Actual ASS materials in black and greyish brown clay horizons (1.1-2.3mbgl) overlying black and greenish grey clays (2.3-4.0mbgl) with PASS materials (0.06% to >0.12% sulfide-S)	1a	1.10	1.00

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
311c	SOUTH OF HARVEY RIVER DELTA, OFF SOUTHERN ESTUARY ROAD	Actual ASS materials in yellowish-grey and mottled yellowish-grey clay horizons (1.0-2.3mbgl) overlying mainly black clay horizons (minor sand lenses) with occassional PASS materials (2.3-3.0mbgl). Core depth limited to 3.0mbgl	1a	1.00	
311d	SOUTH OF HARVEY RIVER DELTA, OFF SOUTHERN ESTUARY ROAD	Deep, sporadically distributed PASS materials (some only 0.025% sulfide-S) in light grey and olive yellow clayey sands (4.2 to >5.5mbgl) overlaid by mottled light grey sand and clayey sands (2.8-3.6mbgl) with minor PASS materials (<0.02% sulfide-S).	2	4.20	3.00
312a	SOUTH OF MANDURAH RD BRIDGE, ERSKINE	PASS materials (>0.03% sulfide-S) in yellowish-brown and olive silty sands (2.5 to >6mbgl)	1b	2.50	2.30
312b	SOUTH OF MANDURAH ROAD BRIDGE, ERSKINE	Very low concentration of PASS materials (<0.012% sulfide-S) throughout olive-grey and olive-yellow silty sand horizons (>3mbgl)	2	3.00	
312c	SOUTH OF MANDURAH ROAD BRIDGE, ERSKINE	Very low concentrations of PASS materials (<0.02% sulfide-S) in olive yellow sand horizons (4.6-6.0mbgl) in a deep sandy profile	2	4.60	3.90
312d	SOUTH OF MANDURAH ROAD BRIDGE, ERSKINE	Shallow PASS materials in peaty sand (0.9-1.1) and grey clayey sand (1.1-1.8mbgl) with increased PASS materials (0.13-0.18% sulfide-S) in underlying dark grey and black silty sand horizons (1.8-4.5mbgl). Limestone at >4.5mbgl	1a	0.90	1.80
312e	SOUTH OF MANDURAH ROAD BRIDGE, ERSKINE	Significant PASS materials (up to 0.45% sulfide-S) in pale brown sand horizons (2.4 to >3mbgl), in situ neutralising materials present in overlying sands	1b	2.25	1.70
312f	SOUTH OF MANDURAH ROAD BRIDGE, ERSKINE	Deep PASS materials (up to 0.05% sulfide-S) in upper layer of pale yellow sands (4.5-5.25mbgl) with minor PASS materials (<0.02% sulfide-S) in overlying yellow sand horizon (3.75-4.5mbgl)	2	4.75	2.80
313a	FALCON POINT FORESHORE, OFF PLEASANT GROVE CIRCLE	Extensive PASS materials in greyish-brown sands (1.7 to >4mbgl) ranging from 0.15% sulfide-S decreasing to 0.08% sulfide-S at depth, in situ neutralising materials below 3.8m	1a	1.70	1.40

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
313b	FALCON POINT FOOTSLOPES, OFF PLEASANT GROVE CIRCLE	Significant PASS materials (0.1-0.4% sulfide-S) occurring in olive green and olive-brown sand horizons (1.9-3.75mbgl) overlying olive-brown sands (3.75-5mbgl) with reduced concentrations of PASS materials (<0.04% sulfide-S).	1a	1.90	1.80
313c	FALCON POINT FOOTSLOPES, OFF PLEASANT GROVE CIRCLE	PASS materials in dark-grey silty sand horizon (2.5-2.8mbgl) and upper layer of calcarenite with silty sand lenses (2.8 to >3mbgl)	1b	2.50	2.00
313d	FALCON POINT FOOTSLOPES, OFF PLEASANT GROVE CIRCLE	PASS materials (0.04-0.05% sulfide-S) in light-olive-brown silty sands (3.0-4.7mbgl). Calcarenite at >4.7mbgl	2	3.00	2.50
314a	POINT MORFITT NORTH, ESTUARY ROAD	PASS materials (0.06% decreasing to <0.02% sulfide-S) in predominantly olive and olive yellow sand horizons (below 1.5-3.5mbgl)	1b	1.50	1.60
314b	POINT MORFITT NORTH, ESTUARY ROAD	Significant PASS materials (0.18-0.24% sulfide-S) in dark brown peaty silts (0.3-0.5) and greenish-grey silty sands (0.5-1.6mbgl).	1a	0.30	0.25
315a	NORTH ISLAND POINT FORESHORE, SOUTH ESTUARY DRIVE	PASS materials (c.a. 0.03% sulfide-S) in dark grey silty sands (1.1-1.7mbgl) overlying bluish black, soft silts with shells (1.7-3.2mggl) and bluish-black sandy silts (3.2-4.0mbgl) with large concentrations of PASS materials (0.81-0.91% sulfide-S).	1a	1.10	0.90
315b	NORTH ISLAND POINT FOOTSLOPES, SOUTH ESTUARY DRIVE	PASS materials (up to 0.04% sulfide-S) concentrated in upper part of dark greyish brown silty sands (1.8-3.8 mbgl) becoming sporadic in underlying olive-brown silty sands (3.8-5.0mbgl).	1a	1.80	1.80
316a	SOUTH ISLAND POINT FORESHORE, SOUTH ESTUARY DRIVE	PASS materials of 0.1-0.12% sulfide-S (decreasing to <0.012% at >5mbgl) in olive and light grey sand horizons (1.0-6.0mbgl), in situ neutralising materials present	1b	1.00	1.00
316b	SOUTH ISLAND POINT FOOTSLOPES, SOUTH ESTUARY DRIVE	PASS materials of 0.04-0.08% sulfide-S (decreasing with depth) in predominantly olive brown and grading to grey silty sand horizons (2.75 to >5.0mbgl)	1b	2.75	2.80
316c	SOUTH ISLAND POINT FOOTSLOPES, SOUTH ESTUARY DRIVE	PASS materials (up to 0.1% sulfide-S) occurring part way through (2.5-3.0mbgl) pale olive sand horizon. Calcarenite at base of profile	1b	2.50	

Site Code	Location	ASS materials characteristics	ASS Risk Class[a]	PASS depth[b] (mbgl)	SWL[c]
317a	BACKSWAMP, OFF SOUTHERN ESTUARY DRIVE	Significant PASS materials (0.1-0.45% decreasing to <0.05% sulfide-S with depth) in olive yellow and pale olive sands (0.9-2.9mbgl) and underlying mainly grey sands (2.9 to >6mbgl), in situ neutralising materials present at surface	1a	0.90	0.90
317b	NORTH HARVEY DELTA, OFF SOUTHERN ESTUARY DRIVE	Significant PASS materials (mainly 0.24-0.35% sulfide-S) in olive grey silty sand horizons (1.6m to >5mbgl), >3m sandy strata	1a	1.60	1.60
317c	BACKSWAMP, OFF SOUTHERN ESTUARY DRIVE	No PASS or actual ASS materials evident in predominantly pale brown sand profile (with calcarenite basement)	3		4.60
322a	CARRABUNGUP RD, BOGGY BAY	Actual ASS materials (with jarosite mottling) in sandy silt and silty clay horizons (0.8-1.3mbgl). PASS materials residual in the silty clay (1.0-1.3mbgl) and underlying silty sands (1.3-1.6mbgl; containing up to 0.25% sulfide-S)	1a	0.80	1.20
322b	CARRABUNGUP RD, BOGGY BAY	No PASS or actual ASS evident, core depth limited to 2.4mbgl	2		1.90
340a	HARVEY RIVER, OLD BUNBURY RD	PASS materials (0.05 to 0.2% sulfide-S) in sandy clay (1.1-1.5mbgl) and sand (1.5-2.3mbgl) horizons overlaid by mottled clay horizons	1a	1.10	1.22
340b	HARVEY RIVER DELTA, EAST	Actual ASS materials in clays (1.15-1.3mbgl) and iron cemented clay horizons (1.3-1.4mbgl). PASS materials also occur (0.07% sulfide-S at 1.0mbgl) in clay (c.a. 0.75-1.3mbgl). Depth of investigation limited to 1.4mbgl by iron cemented clays.	1a	0.75	
340c	HARVEY RIVER, DOWNSTREAM OLD BUNBURY RD	Deep sandy profile with residual PASS materials (<0.02% sulfide-S) in mottled sand (1.5-2.0mbgl) and silt horizons (2.0-2.3mbgl) overlying PASS materials (up to 0.12% sulfide-S) in silty sand and sand horizons (2.3 to >6mbgl)	1b	1.50	2.50
341a	LAKE MCLARTY, WEST BANK	Significant PASS materials (0.12-0.44% sulfide-S) in sand horizons (0.5-1.2mbgl) ranging from dark brown to and bluish grey, and underlying greenish grey sandy clay (1.2-1.5mbgl) and sandy (1.5 to >1.6mbgl)	1a	0.50	1.05

Site Code	**Location**	**ASS materials characteristics**	**ASS Risk Class**[a]	**PASS depth**[b] **(mbgl)**	**SWL**[c]
347a	WETLAND MARGIN, OLD BUNBURY RD	PASS materials (up to 0.33 % sulfide-S) in light grey silty sand horizons (2.4-4.5mbgl) decreasing to lesser PASS materials (<0.03% sulfide-S) in deeper grey silty sands and clayey sands (>4.5mbgl)	1b	2.40	2.20
347b	WETLAND MARGIN, OLD BUNBURY RD	Minor PASS materials (<0.02% sulfide-S) in white and dark greyish brown sand horizons (1.5-3.8mbgl) of a sand profile	1b	1.50	1.60
348a	HARVEY RIVER, UPSTREAM OLD BUNBURY RD	Minor PASS materials (<0.02% sulfide-S) in grey silty sand horizons (2.9-4.0mbgl) of a predominantly sand profile	2	3.00	3.60
349a	POINT MORPHITT SOUTH, ESTUARY ROAD	PASS materials (0.04-0.14% sulfide-S) in thin sandy clay horizon (0.25-0.55mbgl) and underlying mottled grey and greenish grey sand horizons (0.55 to >1.6mbgl)	1a	0.75	0.70

[a] ASS risk classification for each site as described on Appendix 4.

[b] PASS Depth = depth (mbgl) of shallowest PASS materials below natural ground surface at the time of soil coring (does not include thickness of layers with these chemical properties).

[c] SWL = standing water level encountered in soil profile during coring (mbgl), where evident.

ID = indeterminate. Shallowest surface of PASS horizons not readily distinguishable.