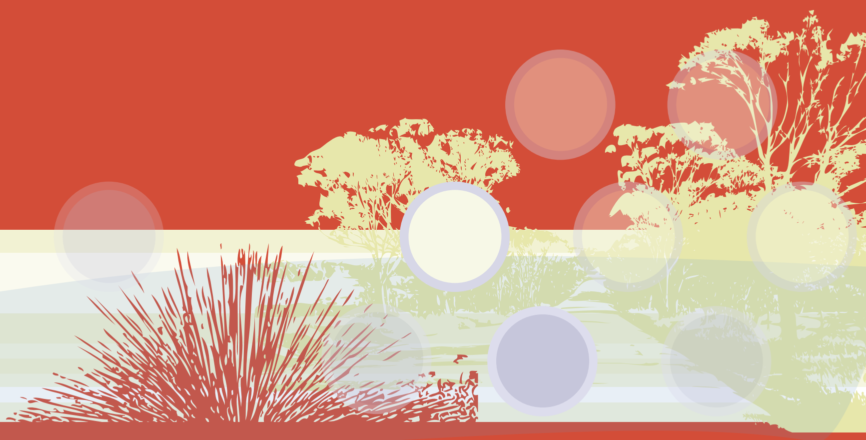
Department of
Environment and Conservation

Acid sulfate soil survey in **Perth metropolitan region, Swan Coastal Plain, Western Australia**

March 2012

Prepared by Contaminated Sites Branch Environmental Regulation Division
Department of Environment and Conservation



ACID SULFATE SOILS
information and awareness

Acid sulfate soil survey

in Perth Metropolitan Region

Swan Coastal Plain, Western Australia

March 2012

Acknowledgments

The Australian and Western Australian governments funded this project. The Department of Environment and Conservation (DEC) would like to thank the following people and organisations for their contribution to this publication. The document was prepared by Balbir Singh, Yash Pal and Stephen Wong. Field work was undertaken by Balbir Singh, Yash Pal, Steve Clohessy and staff from the Contaminated Sites Branch. Steve Appleyard provided the technical input into the acid sulfate soil mapping program.

Mineralogical investigations using electron microscopy were conducted by Nattaporn Prakongkep and Bob Gilkes at The University of Western Australia.

Drilling services were provided by Strataprobe Pty Ltd and chemical analysis provided by ALS Laboratory Group.

Fugro Spatial Solutions Pty Ltd developed the ASO Database with spatial output.

We appreciate the support from John Dunn, Steve Rowlands, Steve Jones, Geoffrey Banks and Kate Ellis of the Geographic Information Services Branch.

Accessibility ASS risk map layers via Shared Land Information Platform was supported by Natasha Harris and Kevin Lee from Landgate.

For more information contact:

Acid Sulfate Soil Section
Contaminated Sites Branch
Department of Environment and Conservation
Locked Bag 104,
Bentley Delivery Centre
WA 6983
Email: acidsulfatesoils@dec.wa.gov.au

Recommended reference

The recommended reference for this publication is: *B. Singh, Y. Pal, S. Clohessy and S. Wong. Acid Sulfate Soil Survey in Perth Metropolitan Region, Swan Coastal Plain WA, Department of Environment and Conservation, Government of Western Australia.*

Contents

Summary

The Department of Environment and Conservation undertook a second stage of the acid sulfate soils (ASS) mapping program between 2008 and 2010. The purpose of the project is to validate the predictive ASS risk within the Perth metropolitan area, specific outcomes of the program included:

- evaluating the spatial extent of potential acid sulfate soil occurrence in the areas identified as being high to moderate risk
- determining the vulnerability of the Bassendean dune system (BDS) to acidification from increased urbanisation
- identifying the risk factors that cause soil and groundwater acidity
- enhancing the delivery of ASS risk maps using geographic information systems to display imagery of soil profiles and natural geochemical hazards.

A total of 200 sites were investigated, primarily in the estuarine and low-lying areas of the BDS. The groundwater depth is generally within three (3) metres (m) of the natural surface. Of the sites investigated 27 were located in the estuarine environment of the Spearwood dune system (SDS) and 46 were in the clay rich alluvium along the Swan and Canning rivers and Pinjarra Plain on the eastern margin of the BDS. The soil cores were recovered from between 6m–8m deep, logged and analysed in the field using the DEC's recommended ASS field pH (pH_F) and peroxide pH (pH_{FOX}) measurements at depth intervals of 0.25m. Laboratory based analysis was undertaken where soil samples recorded low pH_{FOX} less than 3.0. In addition selected soil profiles that previously recorded low inorganic sulfur content (<0.03%S) were recovered for further laboratory based oxidation trials to evaluate their potential to acidify on exposure to air.

Investigation revealed that the estuarine sediments contained variable amounts of sand, clay and highly decomposed organic matter. Topographic lows of the BDS host humus podzols with strongly cemented dark brown and organic B horizons (coffee rock). The depth and degree of induration of coffee rock material varied with watertable depth. In the topographic mid slopes iron-humus podzols were found while on the crests iron podzols were dominant. All these soils are sandy, highly leached and consequently have little or negligible acid buffering capacity.

Estuarine sediments on the fringes of lakes and rivers contained chromium reducible sulfur (S_{CR}) greater than the current action criterion for coarse textured soils (>0.03%S). Oxidisable inorganic sulfur in the form of pyrite often occurred in the top 2m of these soils. The median sulfur content was 0.47%S, while median pH_{FOX} was 1.8. Some estuarine peat materials showed a sulfur content as high 1.8%S and pH_{FOX} value as low as 1.2. The observed inorganic sulfur content and pH_{FOX} within the estuarine environment is consistent with the high to moderate risk class assigned to these areas in the predictive ASS risk maps. A few estuarine clay-rich locations with high S_{CR} values recorded pH_{FOX} >4. Clays in these materials provide a large acid buffering capacity which helps maintain the pH_{FOX} above 4 even at S_{CR} values as high as 0.5%S.

Areas outside the estuarine environment were dominated by sandy soils of the BDS that covers much of the Swan Coastal Plain within Perth metropolitan area. These sands comprised white, grey, brown or coffee rock sand. Coffee rock materials contained amorphous aluminosilicate as cementing materials and

were usually found at or near the watertable in the seasonal wetlands. The highest S_{CR} value found in these Bassendean materials was 0.5%S. The median S_{CR} content was 0.02% S while the median pH_{FOX} value was 2.0.

The majority of sandy soils on the BDS recorded low chromium reducible sulfur content of less than 0.03%S. However, the pH_{FOX} values of these soils are as low as 2, indicating their potential acidification on exposure to air. The incubation study recorded extreme soil acidification as low as pH 2.5 when these soils were exposed to natural oxidation at room temperature. It is likely that the low pH_{FOX} characteristics of these sandy soils with S_{CR} value <0.03% are attributed to their poor inherent acid buffering capacity.

Mineralogical analysis of these soils found that quartz sand is the dominant mineral, while acid buffering components such as clays or carbonates are negligible to resist soil acidification. Based on the current action criterion at 0.03%S to trigger responsive action to manage ASS, it is clear that the low pH_{FOX} values are of concern as these sandy soils of the BDS are geographically significant within the Perth metropolitan area.

The information captured in the field and laboratory investigation carried out during this study is stored in a custom-built ASS database. Improved ASS risk maps together with ASS summary of investigated sites are available via a web-based Shared Land Information Platform (SLIP) hosted by Landgate.

1. Introduction

1.1 General information

ASS are naturally occurring soils and sediments that are either acidic or have the potential to become acidic when exposed to air. These soils are commonly found in low-lying, water logged environments predominantly in coastal or estuarine areas including groundwater dependent wetlands. In this context, ASS (actual and potential ASS) have the capacity to generate acidity due to the presence of iron sulfides (mainly pyrite) found in permanently waterlogged, frequently anoxic and submerged soil layers (Dent, 1986; Sammut, 2000; Isbell, 1996).

In an anoxic state, these materials remain benign, and do not pose a significant risk to human health or the environment. However, disturbing ASS, exposing them to atmospheric oxygen, can cause extreme acidification in wetlands, waterways and groundwater. Detrimental environmental and economic impacts of acidification include widespread fish kills, loss of biodiversity and contamination of valuable groundwater resources by acid, arsenic, heavy metals and other contaminants. Loss of agricultural productivity and corrosion of concrete and steel infrastructure by acidic soil and water are also common economic impacts of ASS.

1.2 ASS exposure to oxidation

A number of anthropogenic activities and natural processes can expose ASS to oxidation causing localised or broad-scale acidification. Land developmental projects involving dewatering, dredging or excavation have the potential to expose ASS to oxidation locally, while groundwater abstraction coupled with low rainfall can impact groundwater quality on a wider scale. In the Perth metropolitan area the watertable in the sandy unconfined aquifer has declined by as much as 5m due to the combined effects of low rainfall events over the last decade, increased groundwater demand and rapid urbanisation. Consequently, water storage in the aquifer has declined by about 500GL over the last 20 years (Appleyard and Cook, 2008).

Groundwater acidity in Perth became a prominent issue in 2002 when a number of domestic garden bores in the City of Stirling were found to be contaminated with acid, arsenic and heavy metals. An investigation by DEC found pyritic peaty soils had been drained and disturbed by urban developments. The event triggered a need for DEC to assess the ASS risk on the Swan Coastal Plain so that appropriate management measures could be put in place to avoid adverse impact to water resources, infrastructures and groundwater dependent ecosystems.

A review of existing groundwater quality on the Swan Coastal Plain indicated that acidification of shallow groundwater was also common on the crests of the Gnangara and Jandakot Mounds. The review noted that the extent of acidification posed a threat to public health and biodiversity of groundwater dependent wetlands in those affected areas.

Activities that have the potential to disturb ASS, either directly by excavation or indirectly by changes in groundwater elevation, need to be managed appropriately. In Western Australia management of ASS risk is guided by the land use planning process for urban development projects (Western Australian Planning Commission, 2009) to avoid adverse impact to the receiving environment. Where ASS disturbance is unavoidable, an appropriate ASS investigation and management plan based on DEC guidelines is required.

1.3 Predictive ASS risk maps

Mapping of potential ASS in the eastern states of Australia primarily focuses on coastal landforms including estuarine floodplains, mangrove tidal flats, salt marshes and back-swamps as the possible hosts of sulfide minerals (Atkinson et al., 1996; Smith et al., 2000; Merry et al., 2003; Rampant et al., 2003). High priority for the low-lying coastal landforms was based on the hypothesis that potential ASS materials formed during the last recession of sea levels in the Holocene epoch and their occurrence was confined to superficial layers of landscapes within 5m of the current mean sea level (Graham and Larsen, 2000; Powell and Ahern, 2000).

In Western Australia the ASS risk maps were developed based on existing 1:50 000 urban and environmental geology map series published by the Geological Survey of WA (Degens 2006). Predictive maps for ASS occurrence on the Swan Coastal Plain were prepared by identifying those surficial landforms that are likely to host ASS in their natural environment. Targeted field investigations were carried out in the southwest coastal region between Mandurah and Dunsborough for landforms at elevations <10mAHD (Degens 2006; Degens and Wallace-Bell 2009) and the landscapes adjacent to Peel-Harvey estuary (Degens 2009). These investigations found considerable variations of sulfidic materials at depths and extent consistent with other ASS studies in other parts of the world (Dent, 1986; Naylor et al., 1998; Graham and Larsen, 2000).

The ASS risks are classified into two categories on the basis of ASS occurrence within the soil profiles:

- high to moderate risk of ASS occurrence within 3m from the surface elevation
- moderate to low risk of shallow ASS occurrence at depth beyond 3m from surface elevation.

Areas outside these two categories have not been assessed due to the absence of geological and geochemical information. However ASS may occur in these areas.

1.4 Aims of this study

Although the ASS risk maps serve as a predictive guide for land use planning, recent increases in urban development and the detection of landscape acidity in a number of areas within the Perth metropolitan area warrant an improved understanding of ASS risk. Apart from sporadic ASS investigations conducted by various urban land development industries, a comprehensive field assessment has not been carried out in the Perth metropolitan area to validate the geographic extent and intensity of ASS occurrence. This report presents the work undertaken by DEC to characterise the extent and distribution of ASS in the dominant landforms of Perth Metropolitan area. The outcomes of the investigation will assist DEC to develop remedial options for managing ASS on the Swan Coastal Plain.

2 Regional setting

2.1 Geomorphology

The Swan Coastal Plain forms the eastern onshore edge of the Perth Basin, extending from the coastline of the Indian Ocean to the Darling Scarp to the east of the Perth region. It is bounded by Geraldton in the north and Dunsborough in the south. The Perth metropolitan area extends about 25 kilometres (km) north, 20km south and 20km east from Perth Central Business District on the bank of Swan River, the major geomorphic feature of the Perth Region. This mapping study is limited to Perth metropolitan areas shown in Figure 1.

The Swan Coastal Plain comprises Tertiary to Quaternary superficial sediments in the Perth Basin with subdued topography shaped by aeolian and alluvial processes over the last two to three million years. Sea levels have fluctuated widely over this period so that the coastline sometimes extended to the Darling and Whicher Scarps to the east. Extensive leaching from topographic highs, weathering of the coastal materials, seawater invasion and deposition of fresh alluvium are the major contributors to the chemical nature of the soil materials in the area.

Prominent landforms in the Swan Coastal Plain are aligned roughly parallel to the Darling Scarp and the present coastline except where intersected by major rivers (McArthur and Bettenay, 1960; Semeniuk and Semenuik, 2005). The most easterly feature of the plain is a series of laterite covered spurs, known as the Ridge Hill Shelf, at the foot of the Darling Scarp (Figure 2).

To the west of and adjacent to this foot hill zone of the Darling Scarp lies the flat to gently undulating Pinjarra Plain consisting generally of alluvial deposits (McArthur and Bettenay, 1960). The Pinjarra plain is about 5km wide near the centre of the Perth metropolitan area and widens up to 15km around the Serpentine River on the southern end of the study area. Surface soils of the Pinjarra plain consist of unconsolidated alluvial fans of pale-grey and blue clays through to brown silty and sandy clays with lenses of conglomeritic and shelly sands (Davidson, 1995). This landform only occurs on the eastern margin of the current study area.

A series of coastal dunes systems occur along the western edge of the alluvial terrain. These dunes systems, younger in age from east to west (McArthur and Bettenay, 1960), have a distinct mineralogical and chemical composition. The most easterly dune system which covers most of the present study area is the Bassendean Dune System (BDS). Further towards the west respectively are the Spearwood Dune System (SDS) and the Quindalup Dune System (QDS) as shown in Figure 2.

The Bassendean sands are the surface expression of the Bassendean Dune System (BDS) which forms a landscape comprised of low hills and intervening swampy areas. The BDS is considered to have been deposited during the early to mid Pleistocene (Playford et al., 1976; Gozzard, 2007). It reaches its maximum thickness (over 20m) and width (up to 20km) in the northern part of the study area. The BDS in the central and southern part of the study area is covered by sediments associated with the Swan, Canning and Serpentine rivers.

The BDS hosts regionally-extensive fresh water aquifers which play an important role in maintaining a healthy aquatic and soil environment. The Perth metropolitan area relies heavily on these BDS hosted aquifers as a source of potable water. The two main sources of potable water are the Gnangara Mound to the north of Perth and the Jandakot mound, to the south. These supply about 40 to 45% of Perth's metropolitan drinking water.

The BDS has been highly leached over a geological timescale consequently it contains no limestone and has only negligible clays, the main natural buffers against soil acidity. The nature of surface soils (less than 2m deep) varies in response to elevation and drainage. In the lowest topographic parts of the formations, where the present day groundwater table is less than 2m deep, humus podzol soils with a strongly cemented dark brown, organic B horizon[1] (coffee rock) occur. In the topographic midslopes and crests, iron-humus podzol and iron podzol are found. All of these soils are largely sandy, highly leached and consequently poorly buffered against acidity. The variability of the coffee rock formation in the BDS is associated with watertable fluctuations, hence leaving imprints of recent pedological and hydrological processes on otherwise highly leached sandy materials.

The Spearwood Dune System consists of a core of Tamala Limestone capped by secondary calcite. The surface layers consists of varying depths of orange earthy sands produced by continued leaching of calcareous beach sand blown inland from the coastline (McArthur and Bettenay, 1960; McArthur, 1991). The western part of the SDS consists of yellow sandy soils, often occurring 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). Subsoils in this landform unit are generally rich in limestone and hence resistant to acidification.

The Quindalup Dune System consists of coastal calcareous dunes (McArthur and Battenay, 1960) that are 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).

2.2 Genesis of sulfides

The mechanism and time of sulfide formation on the Swan Coastal Plain is poorly understood. One school of thought believes that Pleistocene sediments are benign as any ASS materials in them would have oxidised during subsequent periods of low sea levels (Atkinson et al., 1996). However, evidence indicating ASS materials in Pleistocene sediments also exists (Malcolm et al., 2006). There is certainly ample evidence that ASS materials occur in sediments >5m above mean sea level in pre Holocene sediments (Appleyard et al., 2004). ASS materials in these sediments have presumably either remained unoxidised or have authigenically formed in subsequent periods of waterlogged conditions created by higher sea levels. Smaller areas of soils with significant ASS 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.

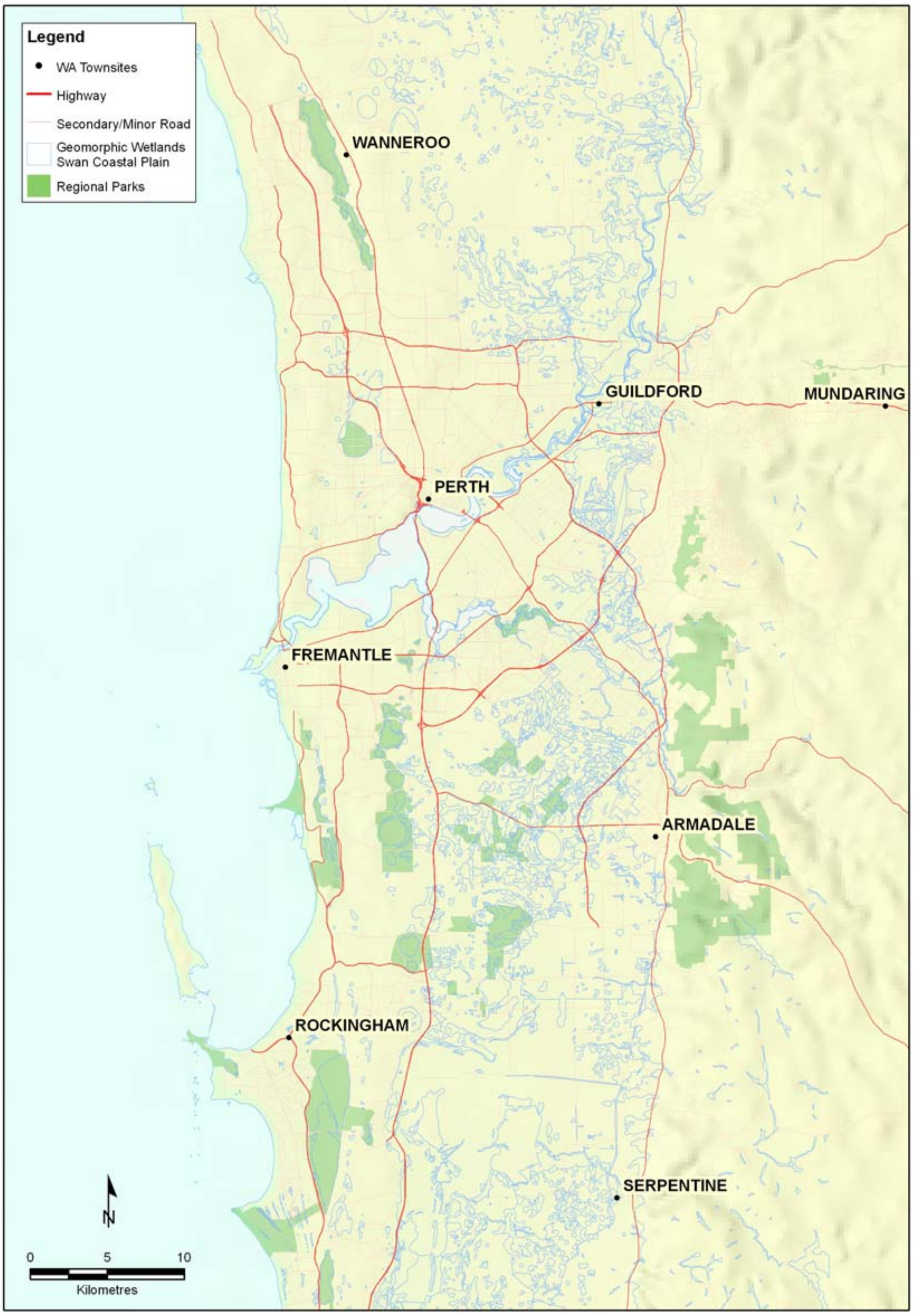


Figure 1: Overview f the Perth Metropolitan Region study area showing, towns, major roads and main wetlands.

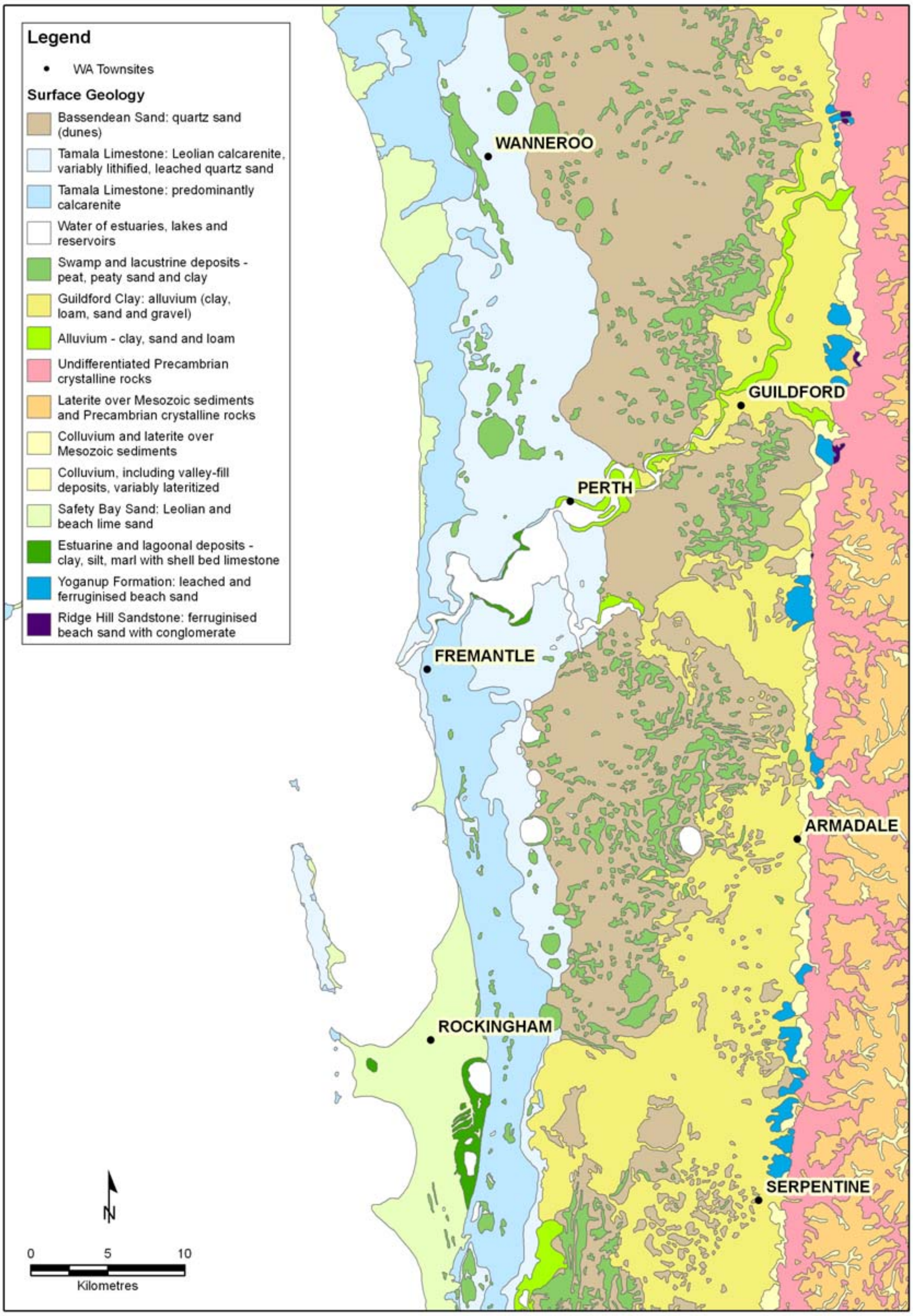


Figure 2: Surface geological formations in the Perth Region. Bassendean sands and associated swamp are the major focus this study.

3 Field and laboratory methods

Field investigations of ASS include soil cores recovered from strategic locations to identify broad relationships between shallow lithology, the occurrence of ASS, geomorphology and existing map units. Physical and chemical information derived from soil cores collected in this study were used to select soil cores for confirmatory laboratory analysis. Soil mineralogy and incubation experiments were also conducted to further characterise the sulfur species. Field measurements coupled with laboratory analysis were used to describe the general characteristics of ASS within the Perth metropolitan region.

3.1 Selection of field investigation sites

Aerial photos and wetland classification maps were used to identify the sumpland and dampland environments with likely past or present hydrological connection to estuarine waters and tidal flats. Identified targeted areas were based on the precept that ASS are likely to be present in areas with permanent waterlogged sediments (but not devoid of oxygen), an abundance of iron, organic matter and a source of sulfate (Dent, 1986). The sulfate found in the superficial formation could be sourced from oceanic (via present or former tidal influence), meteoric and the discharge of sulfate containing groundwater from deeper aquifers.

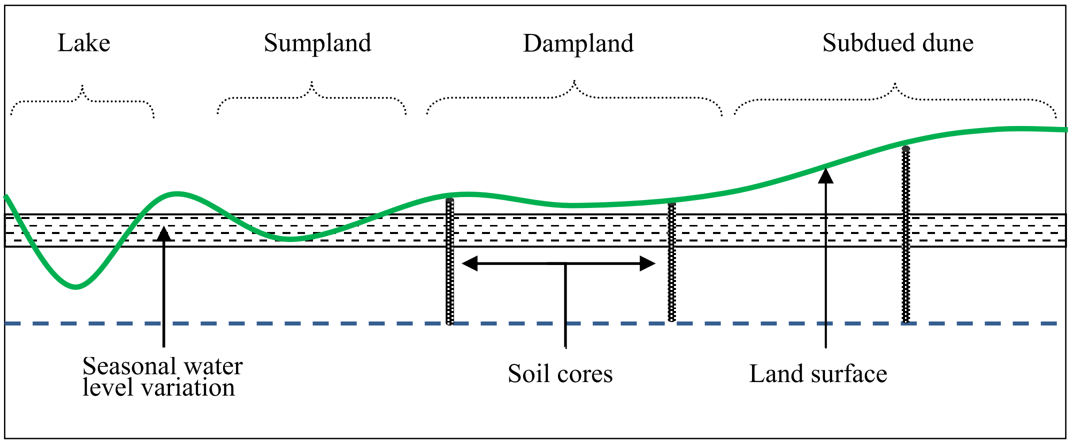


Figure 3: Schematic diagram showing the position of lakes, sumplands and damplands in relation to groundwater fluctuation (after Hill et al. 1996).

Selected sites were generally located on transects along the current rivers and paleodrainage marked by wetland chains. In open sumplands and damplands areas, sites were selected at about one km intervals in areas identified as high to moderate ASS risk (Figure 5). In areas of moderate to low ASS risk such as clay dominated Pinjarra Plain, sites were more sparsely located. Details of site locations are listed in Appendix 1.

Other considerations that impacted on the site selection were:

- land ownership and permission to access
- Aboriginal sites of significance
- underground utility services such as power, gas or telephone services

- physical access for tractor mounted drilling rig.

Road reserves, suburban parks and nature reserves near wetlands provided easy site access for soil coring.

In addition, existing ASS risk maps for the Perth metropolitan region were used to select sampling locations (Western Australian Planning Commission, 2003). These risk maps are principally based on an existing 1:50 000 urban (1977-1982) and environmental geology (1984-1991) map series published by the Geological Survey of WA (Degens 2006).

The majority of the sites were located on the BDS where urban development is most likely to occur. The highly leached, almost lime free nature of this landform unit is ideal for urban development. The study particularly focussed on the lower elevation of the BDS where depth to the groundwater table is usually less than 2 - 3m (Figure 6 and 7). These swampy areas are considered high risk of ASS occurrence due to:

(i) the presence of sulfidic materials in subsoils near surface layers

(ii) the potential for development to lower of the watertable during construction.

Figure 4: Photograph of the tractor-mounted sonic drill rig used for extracting soil cores.

3.2 Soil core retrieval and physical description

Soil samples were typically recovered by coring down to 6m–8m below the natural surface using sonic direct push soil coring equipment to obtain continuous 85 millimetre (mm) diameter soil cores (Figure 4). A hand augur was used where there was doubt about the absence of underground services. *Dial Before You Dig* clearance was sought from various utility providers. Soil cores were placed in one metre plastic core trays (Figure 5) and logged using standard ASS investigation methods described in Appendix 2. 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 if encountered.

Site characteristics such as dominant vegetation, local geomorphology, any surface indicators of ASS, and presence of natural or artificial drainage were recorded.

3.3 Field chemical analysis

Soil core materials were analysed in the field for pH in water (pH_F) and 30% hydrogen peroxide (pH_{FOX}) at a depth interval of 0.25m using methods described in Appendix 2. Results of the pH_F and pH_{FOX} were used to select soil zones for further laboratory analysis using both the Suspended Peroxide Oxidation Combined Acidity and Sulfur (SPOCAS) and Chromium Reducible Sulfur (S_{CR}) suites. Generally, a representative sample was taken from a zone where pH_{FOX} was below pH 3.0.

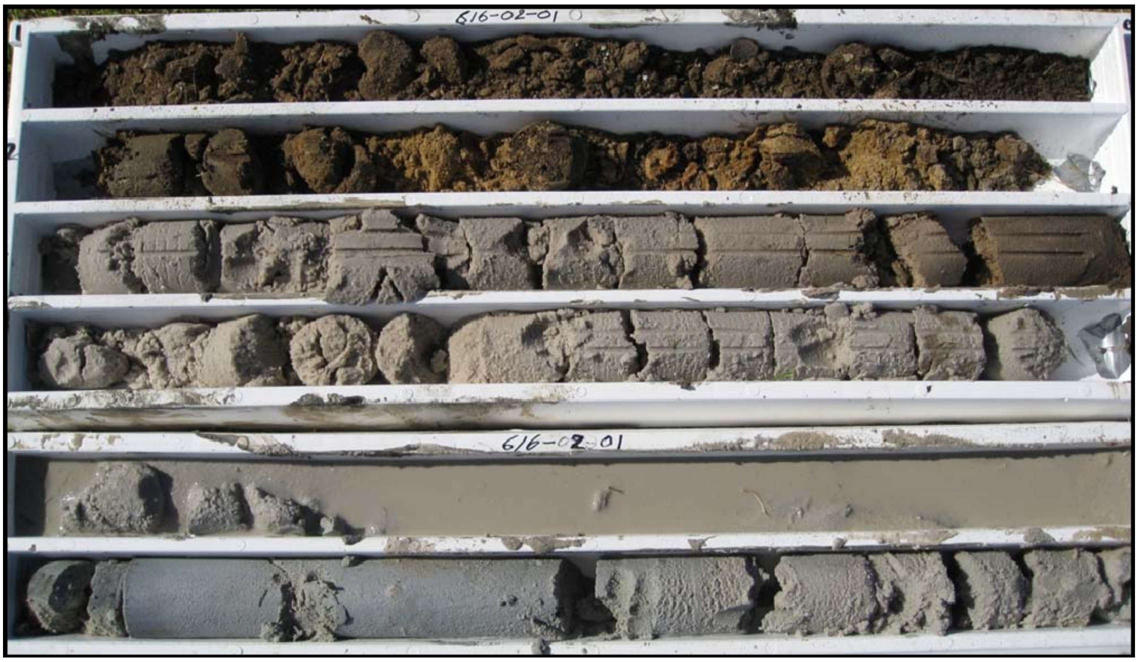


Figure 5: Photograph of a 6m soil core extracted from a site using sonic drilling.

3.4 Sample collection, transport and laboratory analysis

Soil samples for laboratory analysis were collected in the field and placed in air-tight zip lock bags. Air was excluded from bags to the maximum possible extent before closing the zip locks prior to storing in portable refrigerators for transportation to the laboratory.

Potential acidity present in un-oxidised sulfides was estimated by the S_{CR} method (Australian Standard AS 4969.7). ASS materials measured by S_{CR} analyses were unlikely to include mono-sulfidic materials as these are likely to have oxidised during sample handling and preparation.

Actual acidity was determined from measurements of pH (pH_{KCl} determined in one molar KCl extracts) and actual acidity (total actual acidity or TAA based on Australian Standard AS 4969.2). This method takes account of acidity contributed by cation exchange sites, organic matter and soluble acidity. These are obviously not accounted for by pH measurement which only measures H^+ in solution.

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 S_{CR}) or as oxidised S in acid soluble sulfate minerals. 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 (Australian Standard AS 4969.7).

Detailed mineralogy and chemical analysis of selected soil samples was conducted at The University of Western Australia to characterise the forms of sulfidic materials and acid neutraling materials in the major soil types within the Perth metropolitan region. Findings of this project are published in a separate technical report (Prakonkep et al. 2011). Some of the most relevant results are discussed in this report.

3.5 Incubation and column leaching experiments

The aim of the incubation and column studies was to determine if soils with a low sulfur content <0.03%S could acidify under natural drying conditions. The field investigation identified a number of sites that recorded low sulfur content <0.03%S as well as low pH_{FOX} values. These sites were generally located in damplands of the BDS where the groundwater table is within 3m below the natural surface. Measuring pH_F and pH_{FOX} provides useful field screening to identify the presence or absence of ASS prior to laboratory analysis.

Incubation studies

Plastic chip trays measuring 50.5 centimetres (cm) long, 5.5cm wide and 3.5cm deep were used for the incubation study. The trays have 20 compartments that can be closed with a snaplock lid. Fitzpatrick et al (2010) demonstrated the tray's suitability for holding small quantities of soils for allowing natural soil oxidation to occur. Each compartment was filled with soils corresponding to the core depth at 0.25m intervals. Field pH of all soil segments was measured to represent field condition. The soils in the chip trays were kept moist at room temperature. The lids were partially closed to control evaporation. When necessary, the trays were sprayed with deionised water to keep the soil moist but not saturated.

A soil slurry was made within the chip tray compartment before pH measurement by adding sufficient deionised water to bring the moisture content near saturation. Soil slurry pH was measured fortnightly over a 10 week period.

Column leaching studies

The column leaching experiment was conducted in plastic tubing (85mm diameter and 900mm long). One end of the tubing was fitted with a closable outlet. The columns were filled with selected soil cores (near field capacity) by gently tapping the tube while adding the core material from the top. The soil columns were held upright by a custom made stand and incubated in a glass house with a room temperature ranging between 20°C and 25°C.

The columns were allowed to drain and oxidise naturally over several weeks. After each oxidation cycle, the columns were gradually recharged from the bottom outlet with deionised water. After resaturation, the columns were drained under gravity. The recovered leachate volume was measured including pH and titratable acidity. This cycle of column leaching, oxidation and recharge was repeated for several months.

3.6 Data storage, quality assurance and quality control

Sites were identified by a unique site number with the general code: XXXYYZZZ where XXX denoted the AWRC hydrographic basin number (616 in this context), YY denote the transect number and ZZZ denoted the site number within each transect.

The transport of sample and analytical data between DEC and the analytical laboratory was tracked using chain of custody forms. The quality of analytical data received from the laboratory was assured by comparing with blind duplicates, and cross-checking with field pH data and lithology descriptions.

All field and laboratory data sites are stored in the custom built SQL database. All field data were validated by the database input module against preset data values. Details for quality assurance and control standards applied in the field are outlined in Appendix 2.

3.7 Analysis of ASS risk

Field measurements (pH and pH_{FOX}) were used as screening tools to determine the likelihood of ASS occurrence. Soil profile that recorded $pH_{FOX}<3.0$ were sampled for further laboratory analysis. Soil profiles that recorded S_{CR}, values exceeding 0.03%S were considered to pose an environmental hazard based on ASS guidelines.

Results of pH_F, pH_{FOX} and laboratory analyses from each soil profile were evaluated together with the soil core information (texture, colour, mottling and water table depth) to determine and characterise the presence or absence of ASS within each profile.

It is noted that pH_{FOX} values <3 without accompanying high S_{CR} or TPA (>0.03%S) were still considered moderate risk due to the poor buffering capacity of Bassendean sands.

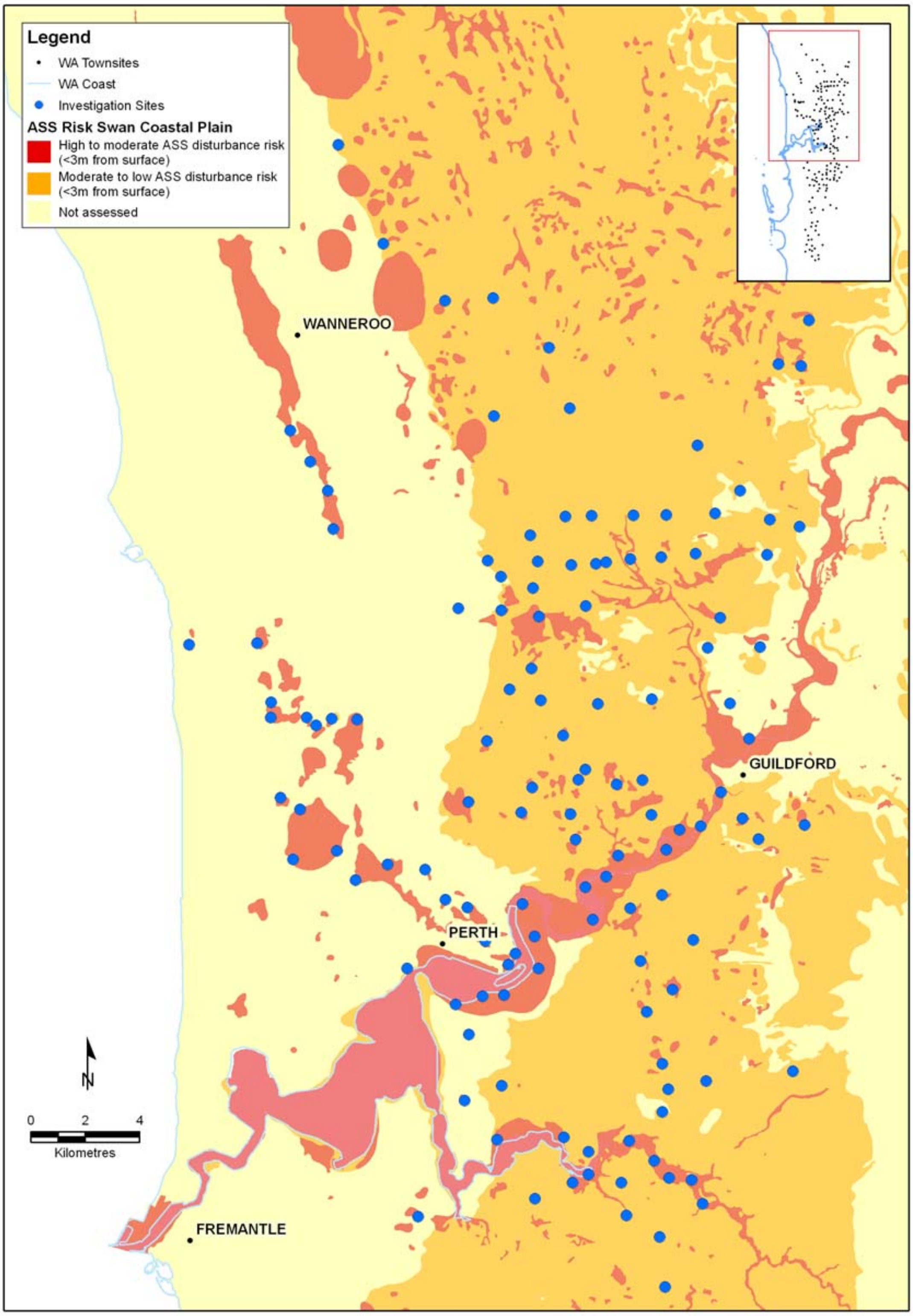


Figure 6: Investigation sites in the northern half of study area in relation to ASS disturbance risk.

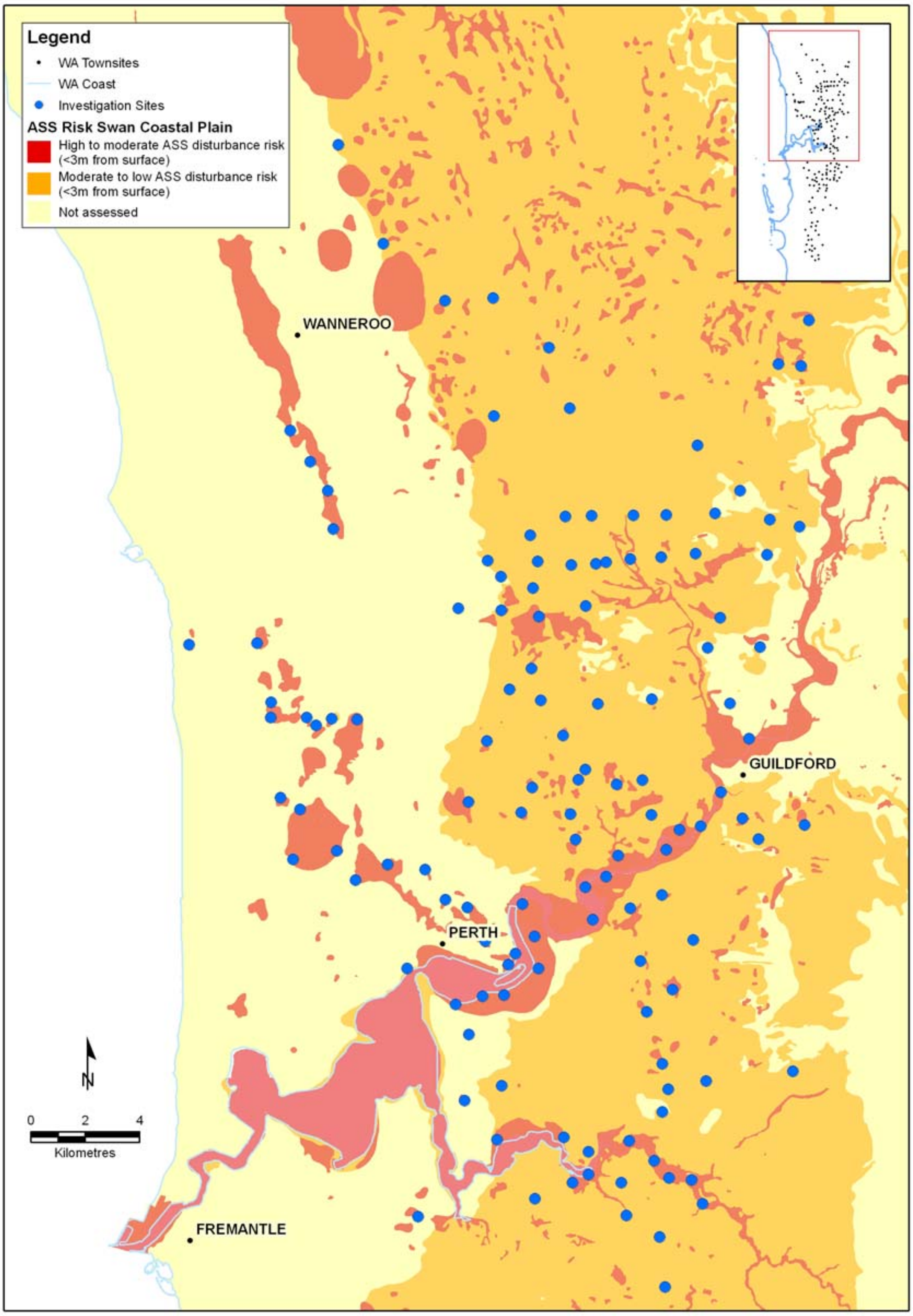


Figure 7: Investigation sites in the northern half of study area in relation to ASS disturbance risk.

4 Characteristics of soil materials

The acid sulfate soil survey covers about 1,000km^2 of the Perth metropolitan area The dominant surficial geological formations are the Bassendean Dune System (BDS), Spearwood Dune System (SDS) and Pinjarra Plain. These formations are sporadically modified by the occurrence of rivers, lakes and wetlands associated with topographic lows of these geomorphic units.

The highly leached, siliceous and porous soils of the BDS were the main focus of this study. Soils associated with the SDS and Pinjarra Plain contain calcareous materials and clay respectively. Only the estuarine sediments of these formations were targeted in the sampling program. Another consideration for site selection was the detection of groundwater acidity in housing development areas, in particular the southern areas of the Kwinana freeway.

A total of 200 sites were selected and investigated. Most of these sites were located on sumpland and damplands on the BDS. The groundwater table in these areas is usually within 3m of the natural surface and soils are extremely sandy with minimum capacity to resist changes in soil acidity.

While 27 sites were located in an estuarine environment within the SDS, 46 were located in the clay rich alluvium along the Swan and Canning rivers and Pinjarra Plain on the eastern margin of the BDS. These areas within the Pinjarra Plain are under immense housing development pressure as a consequence of the Kwinana freeway extension.

4.1 Soil profile characteristics of dominant materials

The physical aspect of soil characteristics includes mineralogy, organic matter content and particle size distributions. In this mapping study, particular attention was given to recording the soil physical characteristics which include colour, mottles and soil texture such as clays, organic matter, calcareous materials, etc. A selected number of soil samples representing typical profiles were also investigated at The University of Western Australia to characterise the highly reactive components of soil materials such as clay, sulfides and fine grained minerals. Typical soil profiles in each of the surficial geological formations are described below in order to provide a mineralogical background to the discussion of chemical data in the subsequent sections.

Bassendean dune system (BDS)

A typical soil profile of dampland in the BDS is described in Figure 8. The soil profile can be divided into a number of distinct horizons formed by pedological processes active at the surface. Near the surface, horizon A[2] is characterised by dark grey to black colour attributed to organic matter deposition from the surface. Generally the horizon extends a metre deep with decreasing amounts of organic matter and consequently colour grading from dark to light grey with depth.

Below the horizon A is the zone of elluviation[3] with little to no organic matter, clay or iron oxides. These soil components have been removed from this zone by continued leaching of the sandy soil column. This zone, marked as horizon E[4], therefore has a light grey to grey colour. The thickness of this horizon varies from half to several metres depending on the depth of the groundwater table and topographic position. The soil profile from the top of horizon A to the bottom of horizon E can be visualised as a highly leached soil column with some organic matter associated with dark coloration grading downwards from the surface to the boundary between horizon A and horizon E.

The next soil horizon below the E horizon is the zone of iluviation where the finer soil components accumulate either by downward movement from the top or precipitation from the solution. This zone, marked as horizon B, has a light yellow brown to very dark brown colour. The dark brown colour (coffee colour) is often provided by organic complexes that are considered to have precipitated from a fluctuating groundwater table. The physical strength of this coffee coloured horizon may vary from friable loose sand to massive, highly indurated sand called ‘coffee rock’ by the drilling industry. In this report, the friable coffee coloured zone is considered as incipient coffee rock material as it only differs in the intensity of precipitation and resulting strength of the material.

The depth of coffee rock horizon varies generally with the depth to the groundwater table. In the current mapping program, the depth of coffee rock varies from 1m to 3m, and is generally more prevalent in the southern part of the metropolitan area. The processes that lead to coffee rock formation are poorly understood.

Below the coffee rock lies sand with colour varying from light grey to light brownish grey. This zone is marked as horizon C representing the parent material of the soil profile above. In other words, it represents the original materials least altered by the pedological processes originating from the surface.

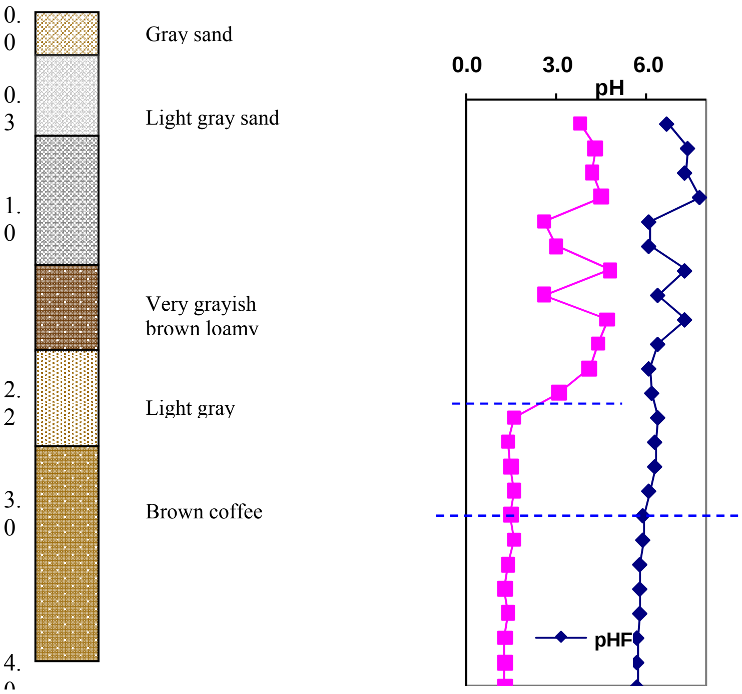


Figure 8: Field log and soil pH for a typical soil profile on Bassendean sand (616-01-179).

Spearwood dune system (SDS)

Only 27 sites are located in the SDS. However, all these sites are located within the estuarine environments and soil profile characteristics are dominated by the characteristic of the sediments rather than that of the host geological materials underneath (Figure 9). Soil profiles were similar to those developed in the estuarine environments within the BD.

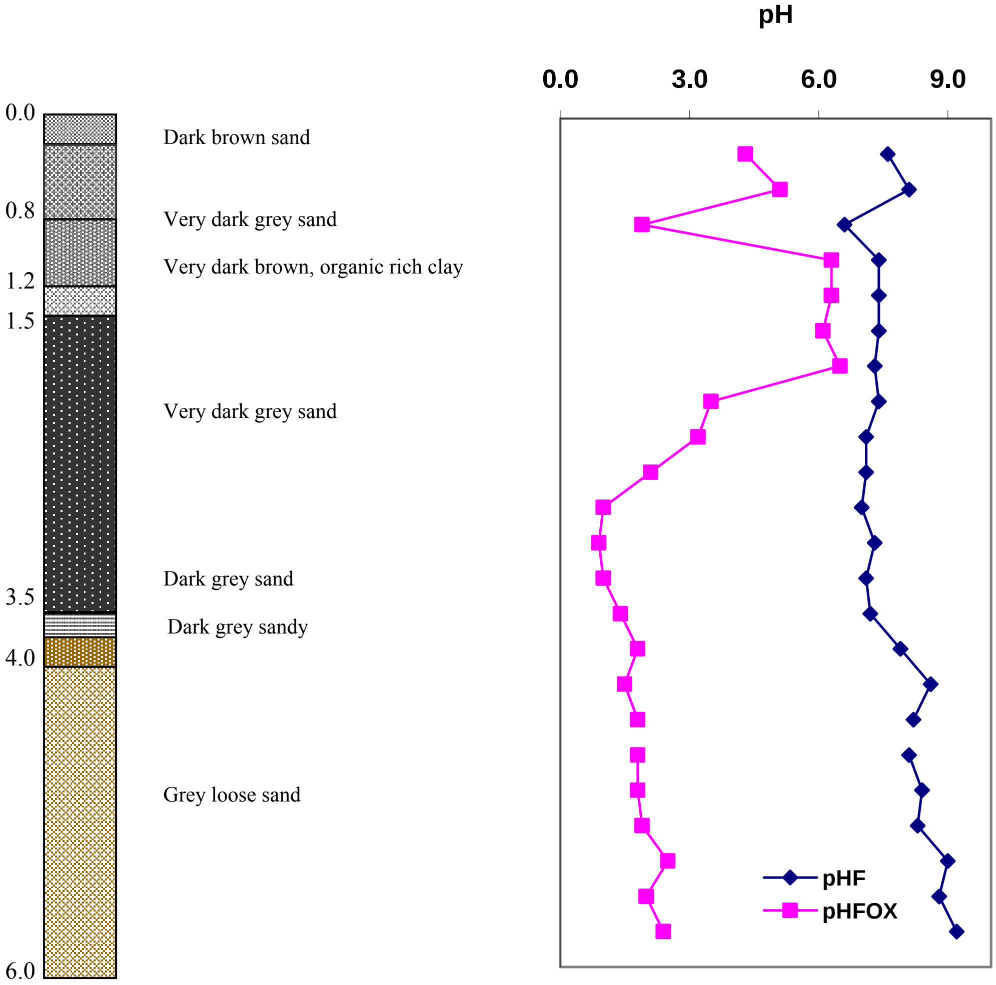


Figure 9: Field log and soil pH for a typical soil profile on estuarine sediments (616-02-101).

Pinjarra Plain

Soils of the Pinjarra Plain are derived from river alluvium of various ages. The clay rich soil profiles of this geological formation can be readily distinguished from estuarine sediments by their light yellowish-brown colour in contrast to the very dark grey to black surface horizons of estuarine sediments. Profile differentiation varies with the age of the sediment. Sandy materials of the underlying BDS characterised by its light grey colour were often intersected where thickness of the Pinjarra Plain alluvium was less than six metres (Figure 10).

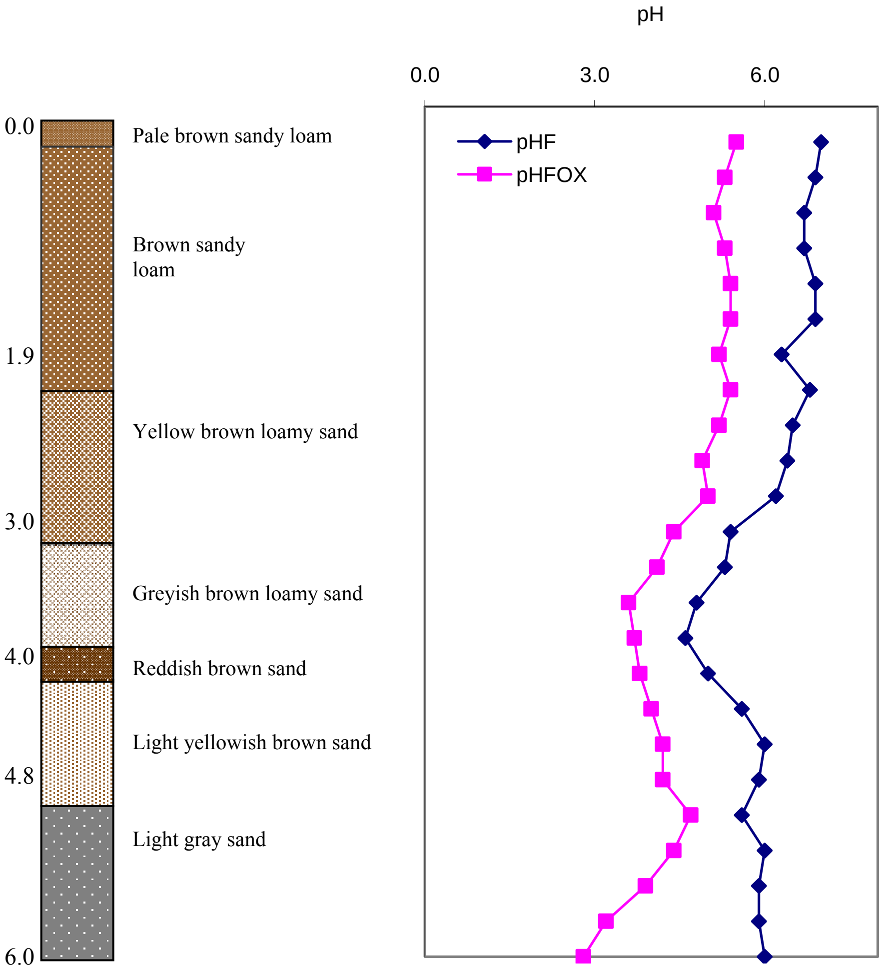


Figure 10: Field log and soil pH for a typical soil profile on Pinjarra Plain soils (616-02-151).

4.2 Field soil pH measurements

At each site soil pH_F and pH_{FOX} was measured at 0.25m intervals for the complete soil core. As a general rule, soil pH_{FOX} is expected to be lower than pH_F. The pH_{FOX} can be 3-6 units lower than pH_F depending on the amounts of sulfides and acid buffering materials such as carbonates and clays present in the tested soil sample. A pH_{FOX} value <3 is considered indicative of potential ASS in the form of sulfides.

Figure 11 represents a set of diverse soil pH profiles observed in this mapping program. About 80% of soil core pH profiles indicate that sulfides are likely to be present in some segments of the profile. Samples for laboratory analysis were taken from those soil profile segments that recorded low $pH_{FOX.}$ values.

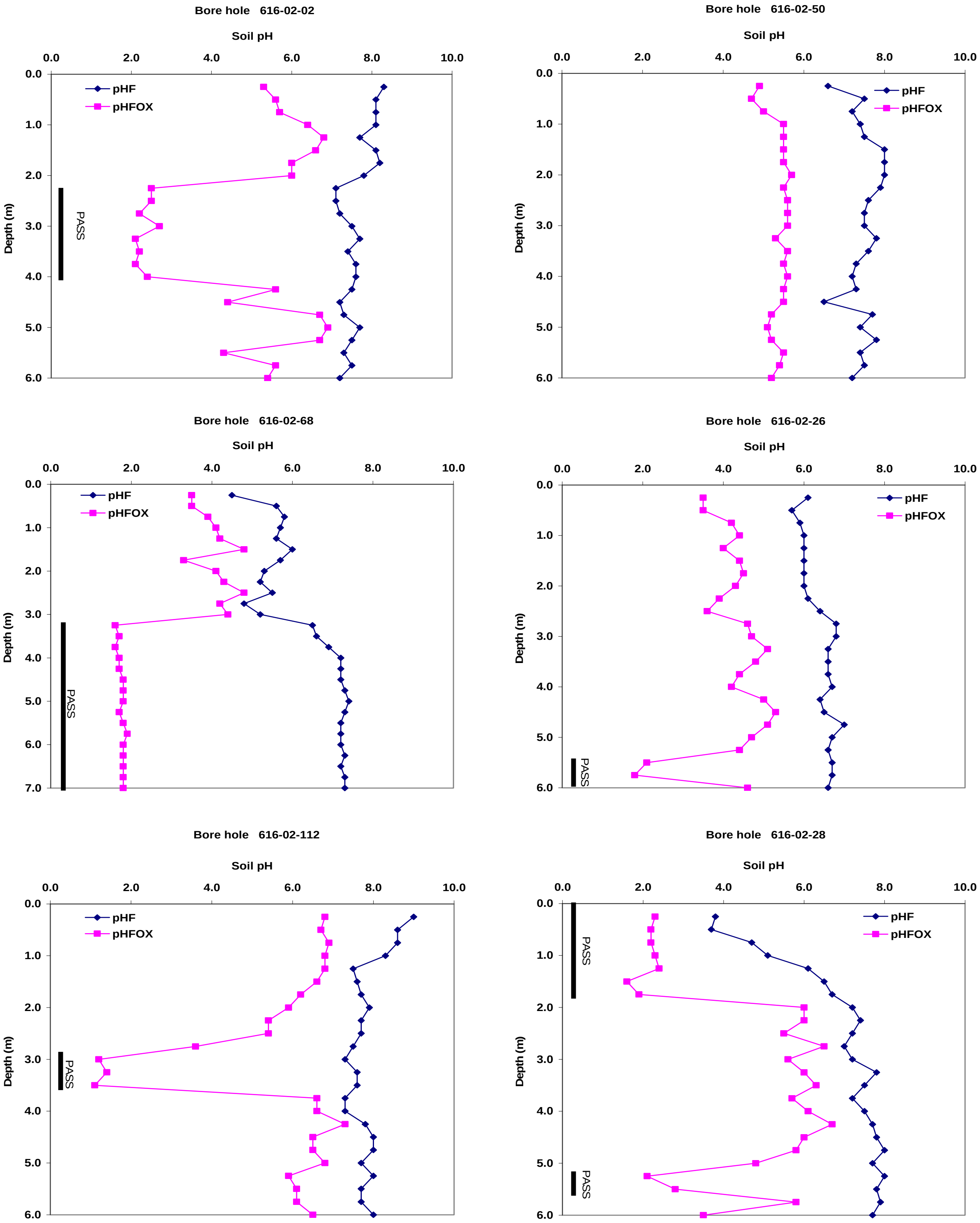


Figure 11: Representative set of soil pH profiles (pH_F and pH_{FOX}). Vertical black bars indicate the zones where the occurrence of ASS materials is suspected. These zones were sampled for SPOCAS analysis in the laboratory.

About 18 of the investigated sites showed no significant difference between pH_F and pH_{FOX}. No samples were taken from these sites for laboratory analysis.

In several instances, pH_{FOX} was significantly different to pH_F, even in the aerobic surface horizons where sulfides are not generally expected to persist. Lower pH_{FOX} values in these cases are partly attributed to oxidation of certain organic species.

Soil pH profiles showing pH_F <4 in surface horizons are indicative of occurrence of actual ASS. However this is generally inconclusive because highly organic soils such as peat, and occasionally coffee sands may also give pH_F <4. A typical organic matter rich soil profile is shown in Figure 9.

4.3 Bulk mineralogical properties

A set of representative ASS samples/profiles were further investigated at The University of Western Australia for detailed mineralogy and physico-chemical properties such as cation exchange capacity. The findings of this work are published in a separate report (Prakongkep et al. 2011). A summary of the relevant mineralogy data is provided in this report.

A particular focus of these detailed mineralogical investigations was to characterise the chemically active fraction of Bassendean sands that cover a larger area of the surface geology in the Perth metropolitan area. With the exception of significant coffee rock found in the subsoils, all samples were concentrated by removing sand so that minor phases in the fine fraction could be identified and characterised using scanning electron microscopy (SEM) and transmission electron microscopy (TEM) as shown in Figures 12 and 13. Coffee rock materials were polished and investigated as a bulk material using SEM.

All soil horizons of Bassendean sands consist mainly of rounded quartz grains with the fine fraction constituting of less than 1% of the bulk material. However, coffee rock horizons contained various amounts of amorphous material cementing the sand grains. The cementing material in the coffee rock consists mainly of amorphous alumino-silicate and organic matter as shown in Figure 14. Occasionally the coffee rock was found to be cemented by alumino-silicate mixed with organic matter and ferruginous material. Apparently, the dark coffee like colour in this material is derived from organic matter rather than iron phases. The amorphous alumino-silicate in coffee rock is massive so that it is expected to have little surface area and ion exchange capacity.

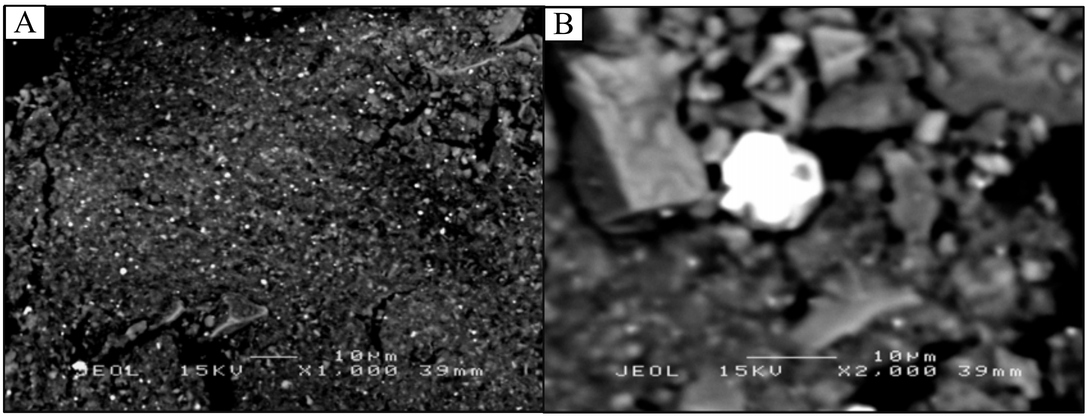


Figure 12: (A) Scanning electron micrographs of fine fraction of soil with pH_{FOX} *of 1.6 and* S_{CR} *and 0.013%. (B) A magnified view showing framboidal pyrite of about 10 µm diameter. Site: 61602179; Sample depth: 375-400cm.*

The presence of inorganic sulfur was readily recognised in the fine fractions of the soils with detectable S_{CR} values in the bulk samples. The dominant form of inorganic sulfur is pyrite in all soil types. It occurs in various shapes and sizes including 1-10µm framboids (Figure 12) and sub-micron single crystal pyrite (Figure 13). Framboidal pyrite was detected in coffee rock (5–6m deep, Site 616-02-82) together with single crystal pyrite. These microcrystalline pyrite single grains were found in most sandy samples with relatively low content S_{CR} values being recorded in the bulk analysis. Elemental sulfur was also identified in some samples using TEM.

Bassendean sands contain negligible clay and carbonate minerals due to their extensively leached nature. Only minor amounts of kaolin were detected using synchrotron X-ray diffraction in the fine fraction of Bassendean sands. Consequently, the cation exchange capacity and acid neutralising capacity of these sands is extremely low or negligible.

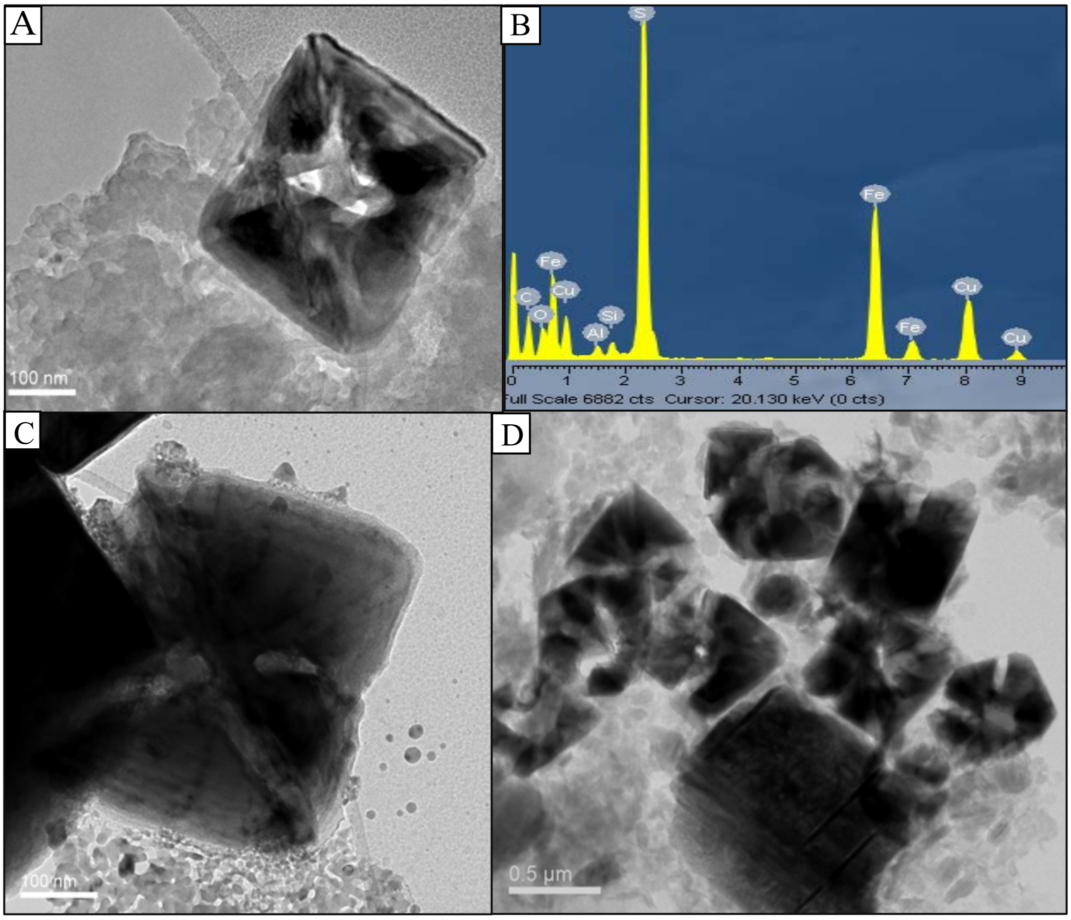


Figure 13: Transmission electron micrographs of 10-50nm size pyrite single crystals showing porous morphology. (B) An X-ray spectrum demonstrating iron sulfide composition of the crystals.

As discussed earlier, a significant proportion of samples from Bassendean sands recorded low pH_{FOX} values while their S_{CR} values were less than 0.02%S. A representative set of these profiles was investigated using microanalytical techniques to determine the reasons for the low pH_{FOX} values. Fine fractions of these samples showed no detectable pyrite in x-ray diffraction analysis. However, pyrite was detected in all samples using electron microscopy and synchrotron x-ray diffraction in some of the profiles as shown in Figures 12 and 13. Fine grained microcrystalline

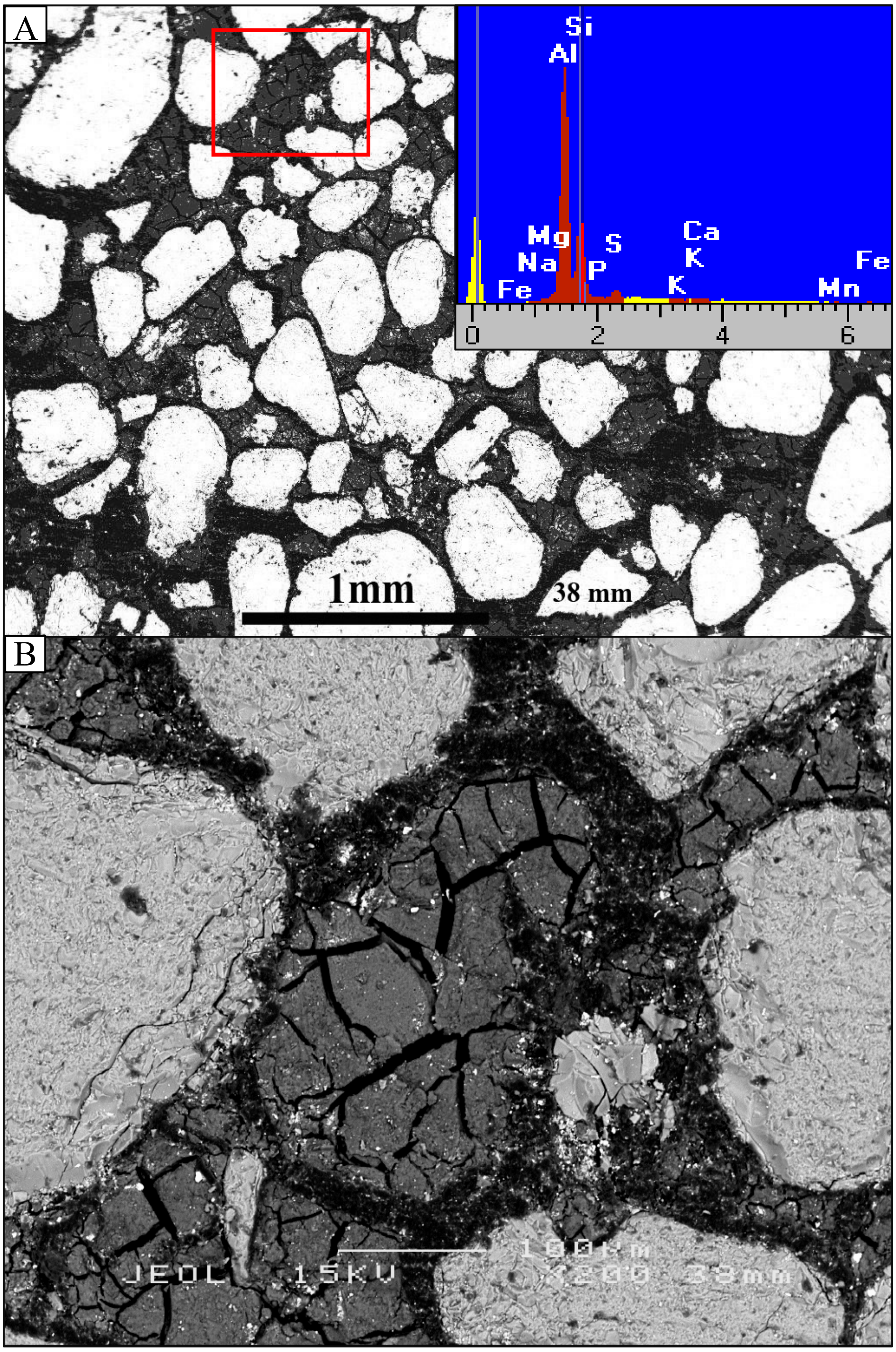


Figure 14: Back scattered electron micrographs of 'coffee rock' material. (A) Well rounded quartz grains cemented by gel-like aluminosilicate material. X-ray spectrum demonstrates aluminosilicate composition of the indurating material. (B) A magnified view of inset area in (A).

kaolinite was the only clay mineral recognised in Bassendean sands. It occurred in very small quantities throughout the profile. Poor ion exchange capacity together with small quantities of clay minerals is expected to offer only minimal buffering capacity for the bulk sand material.

4.4 Chromium reducible sulfur

Samples for laboratory based analysis for sulfur were recovered based on the field pH_F and pH_{FOX} data. Soil samples with pH_{FOX} <3 and pH_F >4 were considered to host significant levels of sulfides, and were therefore sampled for laboratory based sulfur analysis. At each location the coring extended to a depth of 6m-8m and segments with low pH_{FOX} values were then selected for laboratory analysis. Extra samples were also taken where the soil segments of low pH_{FOX} values extended over different soil materials. Altogether 423 samples were taken from a total of 133 sites for S_{CR} analysis.

Figure 15 shows the distribution of ASS samples recovered at various depths for laboratory analysis. The majority of the samples were derived from less than 2m deep, which typically corresponds with the ground water depth at the selected sites. More than 40 of these samples consist of white to grey sands below the B horizon. The sands from B horizon consisting of brown sands and sometimes coffee rock materials are usually found below the watertable. About 40 of the samples fall in the category of brown sands (incipient coffee rock) and coffee rock. Less than 15 of the samples were derived from estuarine sediments including peats and clay and organic matter rich sediments. None of these samples were clay rich as clay rich soils in the investigated area always had pH_{FOX} value above 3. Generally the soil samples recovered for laboratory analysis were taken from below the groundwater table.

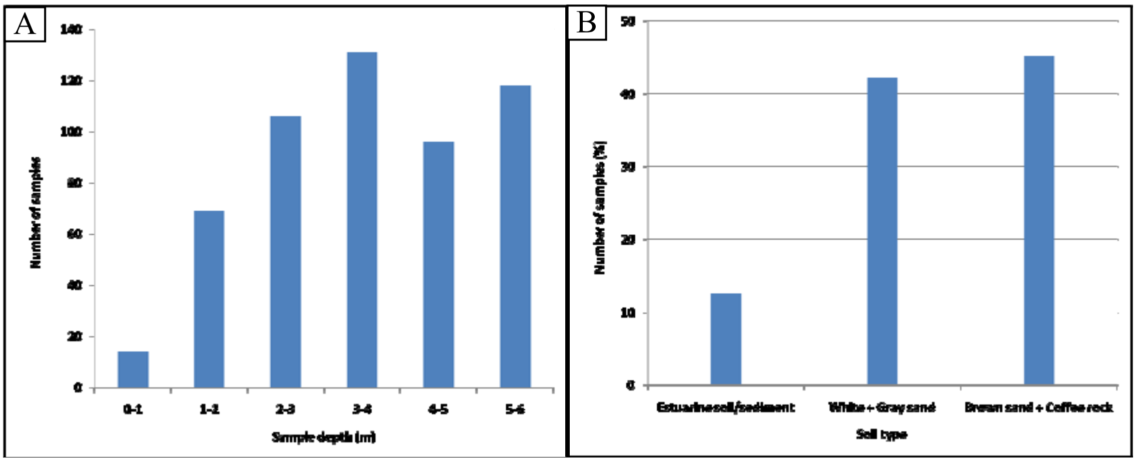


Figure 15: Distribution of depth of ASS materials below ground level. For the majority of the sites, ASS material occued within the top 3 metres of the soil profiles.

White and brown sands within BDS accounted for about 80 of the samples, while the remaining samples were dominated by estuarine sediments. Estuarine sediments have a high probability of recording low pH_{FOX} and containing sulfides. Fewer sediment samples submitted to the laboratory were recovered from estuarine sediments relative to damplands where pure Bassendean sand dominates.

Plots of various pH measurements made in the field and laboratory are shown in Figure 16. The majority of samples recorded pH_{FOX} between 1.5 and 2.5 while pH_F varied from 3 to 8. A smaller number of samples recorded pH_{FOX} well above 3. These samples were selected for further analysis due to their extreme reaction with hydrogen peroxide.

A plot of S_{CR} against pH_{FOX} is shown in Figure 17 with different colour codes for the soil type of each sample. In general, the highest level of S_{CR} was observed in samples with pH_{FOX} less than

2.5. A much stronger relationship between S_{CR} and pH_{FOX} is not expected as the latter is affected strongly by soil buffering capacity against acidity.

Estuarine samples consistently showed high S_{CR} content with a median of 0.47%S and a low pH_{FOX} value of around 1.8. A few estuarine samples showed high S_{CR} levels at pH_{FOX} more than 4. These materials have a significant level of acid buffering provided by clays which keeps the pH_{FOX} above 4.

White/grey sands showed S_{CR} similar to that of coffee rock and brown sands. The highest S content found in these Bassendean sand materials was 0.5% S. The median S_{CR} content was 0.02%S while median pH_{FOX} value was 2.0.

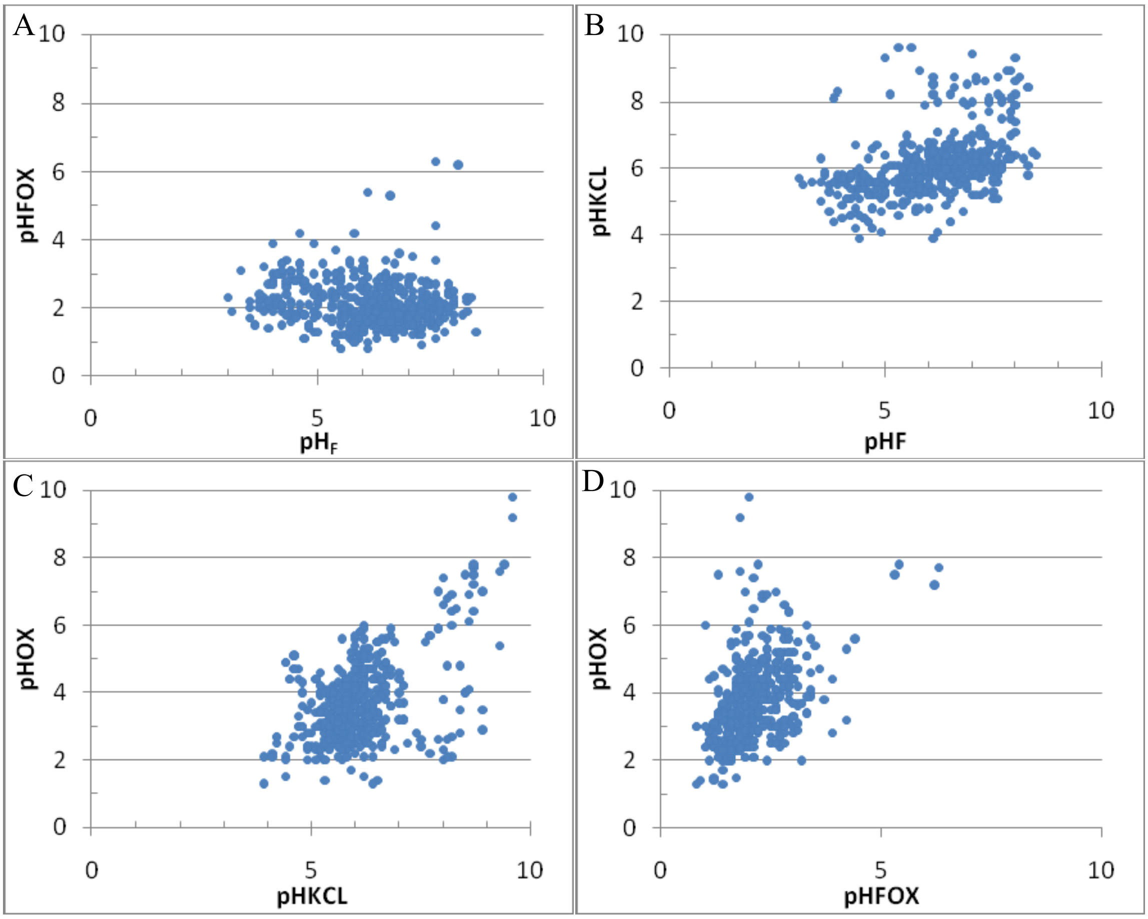


Figure 16: Comparison of pH measurements made in the field with those measured in the laboratory.

Out of a total of 503 samples plotted in Figure 17, the majority of samples (282) have S_{CR} 0.02% or less. These data points are not readily visible as they overlap at 0.02% S at pH_{FOX} level along the x- axis. These samples were exclusively white/grey sand or brown sands derived from Bassendean sands. In order to provide more details, the numbers of data points overlapping at 0.02%S are plotted against pH_{FOX} in Figure 18. A large number of samples with S content 0.02% have pH_{FOX} centred on 1.8. The highest S_{CR} and lowest pH_{FOX} along with interpreted ASS characteristics of all investigated sites is given in Appendix 3.

These sandy samples are derived from the 160 sites underlain by Bassendean sands out of the total 200 sites investigated in this study. These sample sites represent a significant geographical area within the Perth metropolitan area. The S_{CR} content in the sandy soils of the BDS is lower than the ASS action trigger of 0.03%S, which means no ASS management is required for any proposed ground disturbing activity. Low pH_{FOX} values recorded from these sites suggest that these soils can acidify to very low pH when exposed to air.

It is evident that the Bassendean sands that recorded low pH_{FOX} values and low S_{CR} values (<0.03%S) can become acidic due to the poor acid buffering capacity of these sands. Mineralogical analysis of these sandy soils has confirmed quartz sand as the dominant mineral with negligible clay and carbonates materials. In absence of acid buffering potential, very small amounts of sulfides are capable of producing very low pH_{FOX} values. Hence soil incubation and column leaching studies were conducted as a part of this mapping project. The findings of these experiments are discussed in the following section.

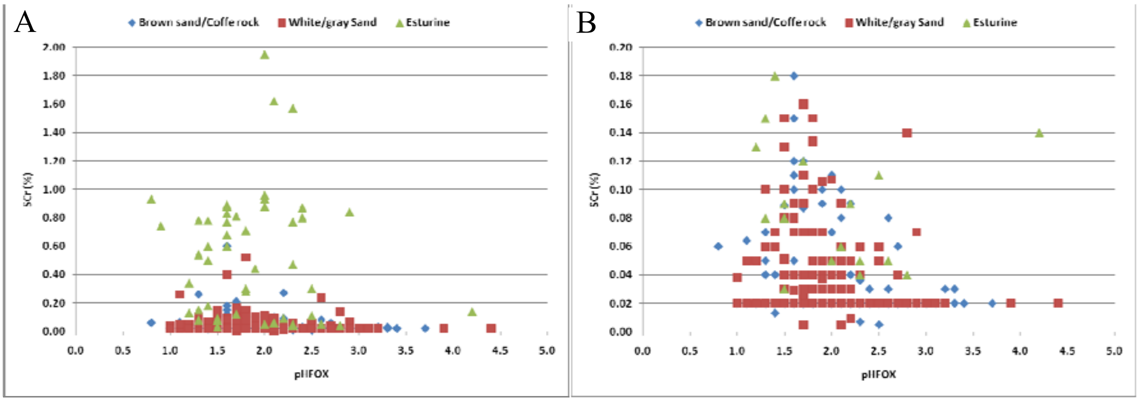


Figure 17: Plots of S content against pH_{FOX} of the samples. The data points are colour coded for the type of sample material.

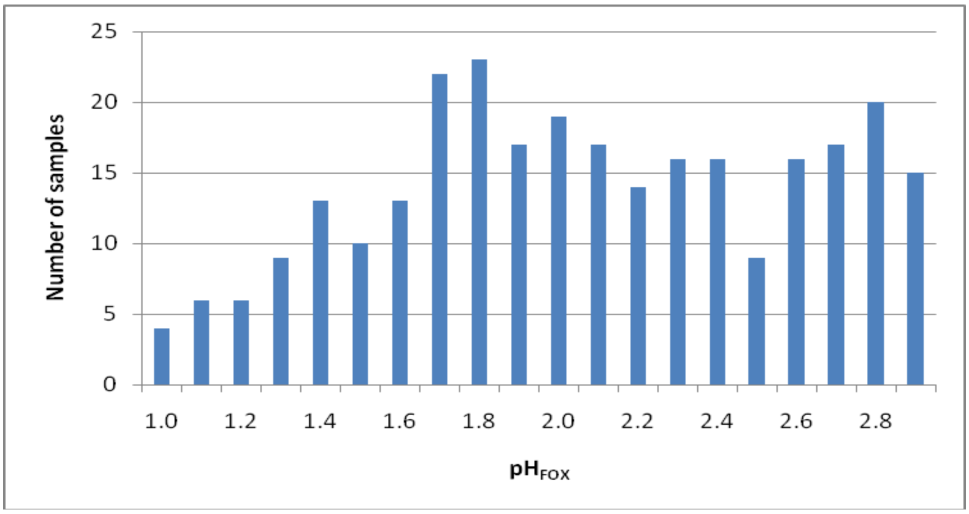


Figure 18. The number of overlapped samples points with 0.02 %S in Figure 17 plotted against pH_{FOX}

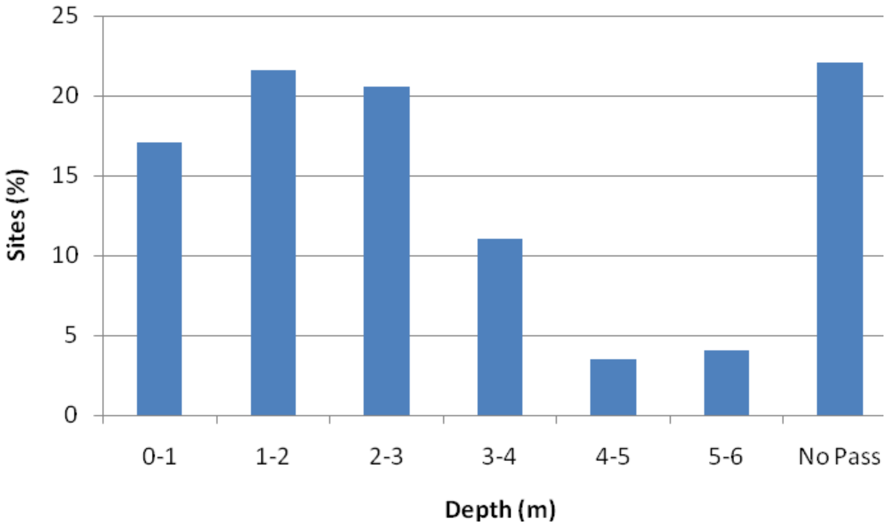


Figure 19: Distribution of depth of ASS materials below ground level. For the majority of the sites, ASS materials occur within the top 3 metres of the soil profiles.

5 Laboratory based oxidation

Field and laboratory investigations discussed in the previous chapter showed that the Bassendean sands of the Swan Coastal Plain recorded S_{CR} content lower than the current action criterion for ASS management. The action criteria developed by Ahern et al (1998) for ASS management are based on soil textures for various soil types in Queensland and New South Wales. According to the action criterion for sandy soil materials with clay content <5%, the equivalent S_{CR} content <0.03%S is not expected to strongly acidify when exposed to air. However, the results of the current investigation confirmed that pH_{FOX} of these sandy soils with a S_{CR} content lower than the action criteria can acidify to pH 3 and often as low as pH 1.8. Considering a large proportion of Perth metropolitan area is located on the BDS, an action trigger based on S_{CR} alone, without consideration of the low pH_{FOX} values, is of concern. Inappropriate soil disturbance, including groundwater abstraction, in vulnerable sandy soils can lead to significant environmental harm if the pH_{FOX} values indicate extreme soil oxidation during disturbance.

Determining soil pH in a 30% hydrogen peroxide (H_2O_2) solution is a common field screening method to detect the presence of sulfides in the field. The sulfide reaction with H_2O_2 produces the worst case scenario where soil is completely oxidised. Hence a pH_{FOX} can be considered to a large extent an estimation of equilibrium pH after natural oxidation of the sulfidic material. However, certain organic species in equilibrium with aerated soils can also be readily oxidised by H_2O_2, producing acidity and giving a false indication of potential ASS. It is unclear to what extent pH_{FOX} is a reflection of final natural oxidation pH, particularly for poorly buffered sands such as Bassendean.

With this background, sandy materials from a number of sites with pH_{FOX} <3.0 were selected for soil column and chip tray experiments. The sulfur content of these soils was below the action criterion <0.03% where no management is required for any soil disturbances. The aim of the experiments was to determine pH and titratable acidity levels likely to result from natural oxidation of these soils. This information will help develop future direction for management of sandy soils that have the potential to generate acidity.

5.1 Chip tray incubation

Soil cores were obtained from six sites with varying S_{CR} content. Soil pH was measured in the field. Chip trays were filled at 0.25m intervals representing the soil profiles. The soil in chip trays was kept moist at room temperature with the lids partially closed to control evaporation. When necessary, the trays were sprayed with deionised water to maintain the soil moisture. Soil pH was measured every two weeks over a 10-week period.

A set of histograms of pH_{FOX} and pH measured during the soil incubation period is represented by pH_{INCU} for four representative soil profiles is shown in Figure 20. One soil profile was used as a control site because the sulfur content throughout the investigated depth was less than the detection limit of 0.005%S, and pH_{FOX} was between 4 and 5. Any reduction in pH_{INCU} during the incubation period is likely to be due to factors other than sulfides. Two soil profiles were representative of Bassendean sands that recorded pH_{FOX} less than 3 and sulfur content lower than the action criteria. The fourth soil profile (Figure 20D) had sulfur content higher than the action criteria and was included for comparison.

The pH$_{INCU}$ of the control decreased less than 1 unit over 10 weeks compared to the field pH, and remained well above 4. It is evident that the incubation procedure did not reduce the pH significantly in the absence of sulfide. However the pH$_{INCU}$ for the other soil profiles shown in Figure 20 decreased sharply to less than 3 within eight weeks, the most significant decline in pH$_{INCU}$ is in the first two weeks. The lowest pH$_{INCU}$ achieved was from a soil profile with S$_{CR}$ 0.06%S.

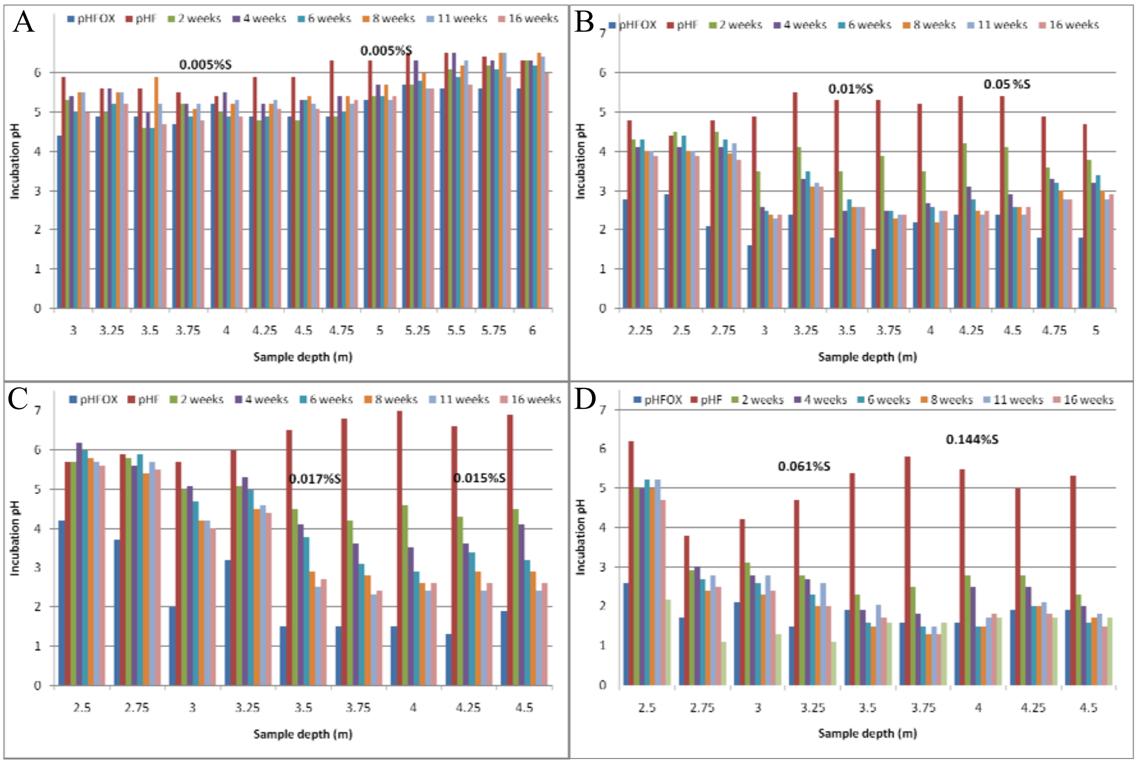


Figure 20: Histograms showing pH$_{FOX}$, pH$_{F}$ and incubation pH for a representative set of soil cores.

A plot between pH$_{FOX}$ and pH$_{INCU}$ is shown in Figure 21. The pH$_{INCU}$ is generally greater than pH$_{FOX}$ by 1-2 units. Some of the samples shown in Figure 21 show much higher pH$_{INCU}$ than the expected trend. Samples that showed this trend were predominantly near surface samples. This behaviour was also evident in plots of pH against soil depth. The pH$_{FOX}$ dropped significantly compared to pH$_{F}$ near surface, while incubation pH declined only marginally. It appears that near surface horizons of these soils contain some organic components that oxidise in hydrogen peroxide but remain unaffected by the incubation process.

A similar observation was made in the broader mapping program. At a number of locations pH$_{FOX}$ of permanently unsaturated horizons near the surface dropped strongly over one to two metres. As sulfidic materials are neither detected nor expected to survive in this zone, a possible explanation of this reduction of pH$_{FOX}$ is oxidation of certain type of organic matter that leads to acidification. However, a low pH$_{FOX}$ is not typical of surface horizons, suggesting that oxidation of a certain type of organic matter species led to a lower pH$_{FOX}$.

In summary, the room temperature incubation of Bassendean sand materials with sulfur content below the action criteria resulted in extreme acidification marked by soil pH as low as 2. The pH$_{INCU}$ is often one unit higher than the pH$_{FOX}$ so the latter can be used as a reliable predictor of the incubation pH, and potential ASS. However, the occurrence of certain organic matter species in the near surface horizon may result in false positives.

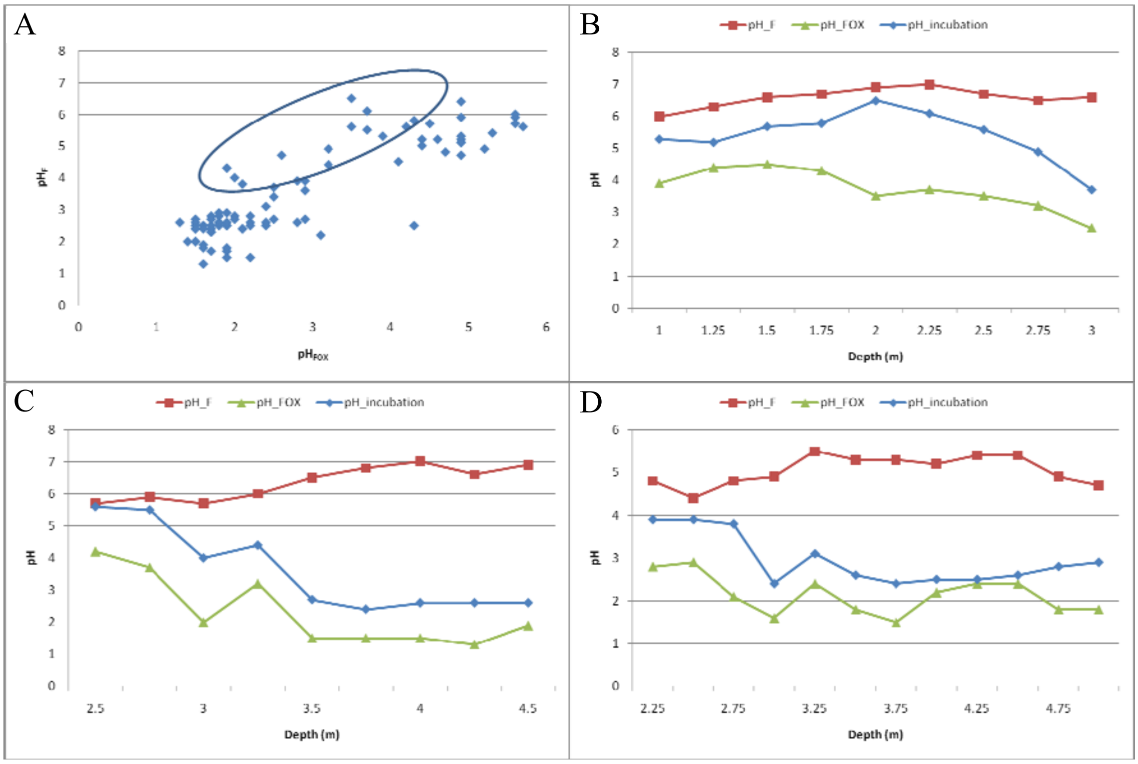


Figure 21: pH_{FOX} against pH_F (A) and measured pH values against pH_F and pH incubation for representative set of soil profiles (B,C and D).

5.2 Leaching column oxidation

In addition to the chip-tray incubation studies, the Bassendean sands with a low S_{CR} content were also allowed to oxidise in vertical columns. The column studies allowed a larger amount of soil to be oxidised with periodic leaching and recharging of the column to simulate seasonal groundwater movement. Soil materials for these experiments were selected from sites that showed uniform pH_{FOX} values over depth intervals of a few metres. The pH_{FOX} of all soil materials was well below 3 while sulfur content of all materials, with the exception of two sites, was below the action criterion of 0.03%.

Histograms of pH_{FOX}, pH_F, and pH from the leachate for each of the six cycles are shown in Figure 22. The first and second bars for each site represent pH_{FOX} and pH_F respectively. The remaining bars represent pH from the pH leachate from subsequent cycles over time. Except for Banjup and Gnangara, leachate pH dropped sharply for the initial two cycles and then gradually stabilised in subsequent cycles.

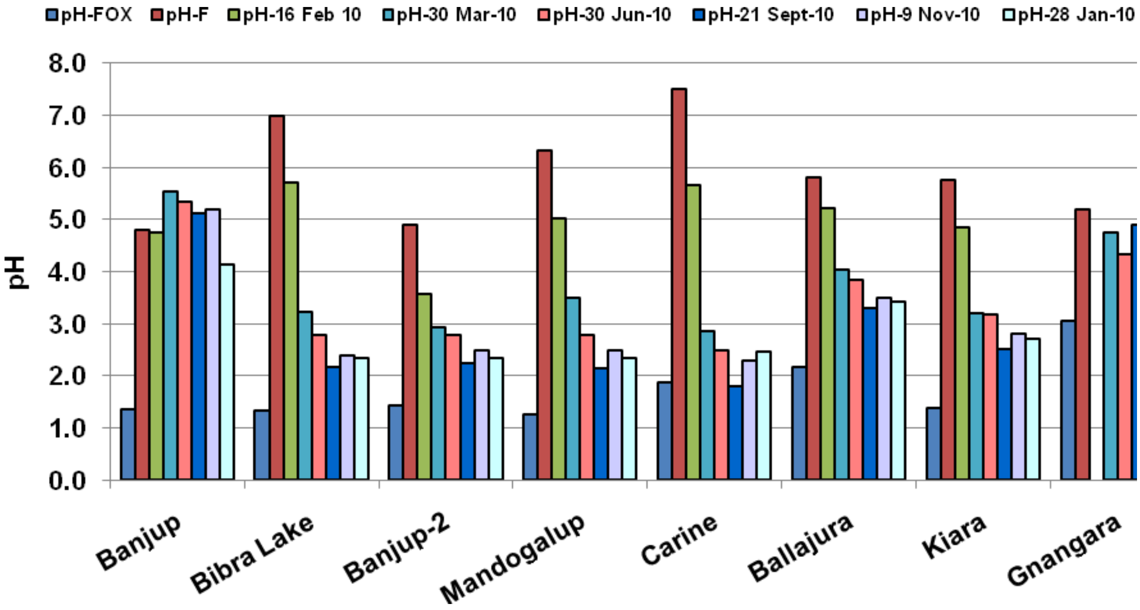


Figure 23: Histograms showing pH_{FOX}, pH_F and periodic pH from subsequent leaching cycles for various soil sites.

The measured pH from the subsequent leaching cycles for all the soil columns with sulfur content less than 0.03%S declined to well below 4. In particular the Ballajura soil column, with pH_{FOX} 2 and S_{CR} 0.005%S, recorded a leachate pH of 3.2. However leachate pH from Bibra Lake, Banjup-2 and Kiara was below 3. As expected, the two sites (Mandogalup and Carine) with sulfur content above 0.03%S produced acidic leachate pH of less than 3.

It is noted that the leachate from the Banjup soil column did not differ significantly from its initial pH_F although its initial pH_{FOX} was low. This profile contains significant amounts of coffee sand/rock materials, the main component of which is a complex amorphous material consisting of hydrous aluminosilicate and organic matter. It is likely that dissolution of amorphous aluminosilicate could be buffering the acidity in the soils with gel-like amorphous materials, protecting the pyrite crystals from oxidation.

The soil column for Gnangara displayed minimal reduction in leachate pH. However, it was noted that the Gnangara sandy soils are highly leached and drained so that negligible acid producing materials could be found within the soil profile.

In summary, natural oxidation of Bassendean sands in soil columns with a sulfur content below the action criteria produced acidic leachate pH of 2. This sharp decrease in soil pH is consistent with the results of the incubation study.

Conclusions

The primary aim of this study was to assess the extent and severity of ASS occurrence in the Perth metropolitan area. The investigations were focussed on estuarine sediments and low lying areas of the BDS where the groundwater table is within 3m of natural surface. The geological formations adjacent to BDS, i.e. SDS and Pinjarra plain, contain abundant acid neutralising limestone and clays respectively. Therefore, only estuarine sediments and the margins of these formations were investigated.

Estuarine sediments typically exhibit dark-grey to black colours, indicating a high organic content of partially decomposed organic matter. Peat, clay, silt and sands of varying degrees of sphericity and sorting were common components of the estuarine sediments. However, the depth and thickness of discrete layers varied greatly at various locations, and showed no relationship to the underlying geological formation. The estuarine sediments within the SDS were indistinguishable from those in the BDS.

Topographic lows in areas underlain by the BDS host humus podzols with strongly a cemented dark brown, organic B horizon compared to the iron-humus podzols and iron podzols that occur in the topographic mid slopes and crests respectively. These observations are, in general, consistent with those made by McArthur and Bettenay (1960). The thickness of the E horizon varied from less than a metre in low lying areas to several metres on topographic crests. Organic B horizons described by McArthur and Bettenay (1960), also known as ‘coffee rock’, were often found just below the water table in the damplands of the BDS. Also common in these areas were friable brown sands which appeared to be a precursor of ‘coffee rock’ formation. All the soils of the BDS, in areas other than the estutarine environment, are sandy and highly leached and, consequently, incapable of buffering soil acidification.

Estuarine sediments commonly contain ASS materials with a S_{CR} greater than the action criteria of 0.03%S. The probability of ASS occurrence within the estuarine environment is relatively high as only rarely were clay rich sediments found to be non sulfidic. The field observations confirm the accuracy of the predictive ASS risk maps that classified these areas as high to moderate ASS risk.

Areas outside the estuarine environment are dominated by soils of the BDS which covers much of the Swan Coastal Plain within the Perth metropolitan area. These sandy soils consist of white, grey and brown sands that differ mainly due to the presence of minor coloured constituents such as organic matter and iron oxides. The highest sulfur content found in the Bassendean materials was 0.5%S. However, the vast majority of these areas recorded a S_{CR} content ≤0.02%S, which is lower than the ASS action trigger at 0.03%S.

An important observation made in this survey was the low pH_{FOX} associated with the low sulfur content of the BDS. A pH_{FOX} of about 2 associated with a S_{CR} content ≤0.02%S was consistently recorded in the study for a large geographical area of Bassendean sands. This level of pH_{FOX} indicates that inappropriate land disturbing activities on BDS can have the potential to cause extreme soil acidification.

Soil column and chip-tray studies conducted on selected Bassendean sands with a S_{CR} content ≤0.02%S also demonstrated that natural oxidation of these sands can produce a soil pH well below 3. This is a serious environmental concern because current action criteria do not take pH_{FOX} value into consideration when the inorganic sulfur content of Bassendean sands is <0.03%S.

The low pH_{FOX} values shown in Bassendean sands with a S_{CR} value <0.03% are attributed to their poor acid buffering capacity. Mineralogical analysis of these materials has shown that quartz sand is the dominant mineral, while acid buffering materials such as clays or carbonates are found in negligible amounts. In the absence of these natural buffers, small amount of sulfides are sufficient to produce very low pH_{FOX} values. Sulfides were confirmed by micro analytical techniques that detected nanocystalline pyrite in these sands.

The current criteria to trigger ASS management are based on guidelines developed by Ahern et al (1998) for sampling and analysing ASS soils in Queensland. The sandy materials referred by Ahern et al (1998) in the texture based criteria may contain up to 5% clay, which is sufficient to sustain soil pH exceeding 4. In contrast, Bassendean sands are extremely sandy with <1% clay and their carbonate content is almost negligible. It appears that Bassendean sands need to be differentiated from the coarse texture category as specified by Ahern et al (1998) and assigned a lower action trigger level.

In conclusion ASS occurrence is commonly found in sumplands near wetlands, lakes and along the Swan and Canning River System. However, ASS found in damplands and in higher topographic landscapes, in particular those located in the BDS may need further consideration for classification due to their vulnerability to acidification.

Access to ASS risk maps and ASS summary of investigated sites are available via a web-based Shared Land Information Platform (SLIP) hosted by Landgate. The weblink is www.landgate.wa.gov.au

References

Ahern, C.R., Ahern, M.R. and Powell, B., 1998, Guidelines for sampling and analysis of lowland acid sulfate soils (ASS) in Queensland 1998, Department of Natural Resources, Indooroopilly, Queensland, Australia.

Ahern, C.R., Sullivan, L.A., McElnea, A.E. 2004. Laboratory Methods Guidelines 2004 – Acid Sulfate Soils. In: 'Queensland Acid Sulfate Soil Technical Manual'. Department of Natural Resources, Mines and Energy, Indooroopilly, Queensland, Australia.

Atkinson, G., Naylor, S.D., Flewin, T.C., Chapman, G.A., Murphy, C.L., Tulau, M.J., Milford, H.B. and Morand, D.T. 1996. 'DLWC acid sulfate soil risk mapping', in R.J. Smith & Associates and ASSMAC (eds), Proceedings 2nd National Conference of Acid Sulfate Soils , pp. 57.

Appleyard, S., Wong, S., Willis-Jones, B., Angeloni, J. and Watkins, R., 2004. Groundwater acidification caused by urban development in Perth, Western Australia: source, distribution and implications for management. Australian Journal of Soil Research, 42, 579-585.

Appleyard, S. and Cook T. 2008. Reassessing the management of groundwater use from sandy aquifers: acidification and base cation depletion exacerbated by drought and groundwater withdrawal on the Gnangara Mound, Western Australia. Hydrology Journal, 17: 579-588.

Creeper Nathan, Rob Fitzpatrick, Paul Shand Peter Self, Rob Kingham (2010) A systematic analyses procedure incorporating the chip-tray incubation method for the hazard assessment of Acid Sulfate Soils in the Murray Darling Basin. In 'World Congress of Soil Science, Soil Solutions for a Changing World 1 – 6 August 2010, Brisbane, Australia'. (Published on CDROM).

Davidson, W.A. 1995. Hydrogeology and groundwater resources of the Perth Region, Western Australia. Western Australia Geological Survey, Bulletin 142.

Degens, B. 2006. Metadata Statement for the Acid Sulfate Soil Risk Map, Swan Coastal Plain, Western Australia. Department of Enviroment and Conservation Government of Western Australia.

Degens, B. P. 2009, Acid Sulfate Soil Survey of Superficial Geological Sediments Adjacent to the Peel-Harvey Estuary, Department of Environment and Conservation, Government of Western Australia.

Degens, B. and Wallace-Bell, P. 2009. Acid sulfate soil survey of the shallow regolith on the Scott Coastal Plain. Department of Water. Report HG24.

Dent, D. 1986. Acid sulfate soils: a baseline for research and development. Publication 39. International Institute for Land Rehabilitation and Improvement ILRI, Wageningen, The Netherlands.

Department of Environment, 2004. Acid Sulfate Soils Guideline Series: Identification and investigation of acid sulfate soils. October 2004. http:\\acidsulfatesoils.environment.wa.gov.au

Rob FitzpatrickA,B Gerard GrealishA,B, Paul ShandA, Richard MerryA, Nathan CreeperA, Mark ThomasA, Andrew BakerA, Brett ThomasA,B Warren HicksA and Nilmini JayalathA (2010) Chip-tray incubation: A new field and laboratory method to support Acid Sulfate Soil Hazard Assessment, Classification and Communication. In 'World Congress of Soil Science, Soil Solutions for a Changing World 1 – 6 August 2010, Brisbane, Australia'. (Published on CDROM).

Fitzpatrick, R.W., Merry R.H, Cox J.W., Rengasamy P and Davies P.J., 2003. Assessment of physico-chemical changes in dryland saline soils when drained or disturbed for developing management options. Technical Report 02/03. CSIRO Land and Water, Adelaide, South Australia, Australia.

Gozzard, J.R., 2007. Geology and landforms of the Perth Region. Western Australian Geological Survey, 126 pp.

Graham, T.L. and Larsen, R.M., 2000. Coastal geomorphology: progressing the understanding of acid sulfate soil distribution. In: 'Acid Sulfate Soils: Environmental Issues, Assessment and Management.

Technical Papers'. Ahern, C.R., Hey, K.M., Watling, K.M. and Eldershaw, V.J. (eds). Brisbane 20-22 June 2000, Department of Natural Resources, Indooroopilly, Queensland, Australia. pp 13.1-13.10.

Gunn, R.H., Beattie, J.A., Reid, R.E. and van de Graff, R.H.M., 1998. Australian Soil and Land Survey Handbook: Guidelines for conducting surveys. Inkata Press, Melbourne.

Hill A.L., Semeniuk C.A., Semeniuk V., Del Marco A. (1996) Wetlands of the Swan Coastal Plain. Volume 2a. Wetland Mapping, Classification and Evaluation, Main Report. Water and Rivers Commission, Western Australia.

Isbell, R.F., 1996. The Australian Soil Classification. Australian soil and land survey handbook series. CSIRO Publishing, Victoria.

Malcolm, D.T., Pointon, S.M. and Ahern, C., 2006. Challenging the Conceptual Model used for Acid Sulfate Soil Mapping on the East Coast of Australia. Proceedings of "18th World Congress of Soil Science" July 9-15 2006. Philadelphia, Pennsylvania, USA. Accessed at: http://www.ldd.go.th/18wcss/techprogram/P18418.HTM

McArthur, W.M., 1991. Reference soils of south-western Australia. Australian Society of Soil Science (WA Branch Inc.).

McArthur, W.M. and Bettenay, E., 1960. Development and distribution of soils of the Swan Coastal Plain, Western Australia. CSIRO Division of Soils, Soil Publication No. 35.

Merry, R.H., Fitzpatrick, R.W., Barnett, E.J., Davies, P.G., Fotheringham, D.G., Thomas, B.P. and Hicks, W.S., 2003. South Australian inventory of acid sulfate soil risk (atlas). South Australian Inventory of Acid Sulfate Soil Risk (Atlas). Final project report to Coastal Acid Sulfate Soils Program (CASSP). March, 2003. 38 pp.

Naylor S.D., Chapman G.A., Atkinson G., Murphy C.L., Talau M. .J, Flewin T.C., Milford H.B., Morand D.T. (1998). Guidelines for the use of acid sulfate soil Risk Maps. 2nd Ed. (Department of Land and Water Conservation, New South Wales)

Playford, P.E., Cockbain, A.E. and Low, G.H., 1976. Geology of the Perth Basin, Western Australia. Western Australia Geological Survey, Bulletin 124.

Powell, B. and Ahern, C.R., 2000. Nature, origin and distribution of acid sulfate soils: issues for Queensland. In: 'Acid Sulfate Soils: Environmental Issues, Assessment and Management. Technical Papers'. Ahern, C.R., Hey, K.M., Watling, K.M. and Eldershaw, V.J. (eds). Brisbane 20-22 June 2000, Department of Natural Resources, Indooroopilly, Queensland, Australia. Pp 1.1-1.12.

Prakongkep, N., Gilkes, R.J., Singh, B. and Wong, S. 2011. Mineralogy and chemistry of sandy acid sulfate soils in the Perth metropolitan area of Swan Coastal Plain. Technical report, The University of Western Australia, Nedlands.

Rampant, P., Brown, A. and Croatto, G., 2003. Acid sulfate soil hazard maps: Guidelines for coastal Victoria. Centre for Land Protection Research Report No. 12, March 2003. Department of Primary Industries, Epsom, Victoria.

Semeniuk V. and Semenuik C. 2005. Wetland sediments and soils on the Swan Coastal Plain, southwestern Australia: types, distribution, susceptibility to combustion, and implications for fire management. Journal of the Royal Society of Western 88: 91-120.

Sammut, J., 2000. An introduction to acid sulfate soils. 2nd Ed. Environment Australia and Agriculture, Fisheries and Forestry – Australia (http://www.deh.gov.au/coasts/cass/pubs/acidsulfate.pdf).

Smith, C.D., Malcolm, D.T., Adams, J.J., Manders, J.A. and Hall, I.R., 2000. Acid sulfate soils mapping in south-east Queensland. In: 'Acid Sulfate Soils: Environmental Issues, Assessment and Management. Technical Papers'. Ahern, C.R., Hey, K.M., Watling, K.M. and Eldershaw, V.J. (eds). Brisbane 20-22 June 2000, Department of Natural Resources, Indooroopilly, Queensland, Australia. Pp 17.1-17.16.

Western Australian Planning Commission, 2003. Planning Bulletin 64. acid sulfate soils. ISSN 1324-9142

Appendix 1: Investigation site details

The 8 digit site code used in this report consists of a basin number, area number within the basin (two digits following basin number) and site number within an area (last three digits).

Bore ID	Suburb	Easting	Northing	Zone	Elevation (mAHD)	GWL (mbgl)
616-02-001	South Perth	392354	6461755	50	3	1.5
616-02-002	South Perth	393337	6462049	50	2	1.0
616-02-003	South Perth	394136	6462092	50	3	1.0
616-02-004	Burswood	395392	6463072	50	5	2.0
616-02-005	Burswood	395251	6464257	50	2	2.5
616-02-006	Burswood	394808	6465449	50	3	1.5
616-02-007	Ascot	397124	6466065	50	1	0.2
616-02-008	Ascot	397885	6466451	50	2	1.5
616-02-009	Redcliff	400107	6467450	50	2	2.5
616-02-010	South Guildford	401368	6468308	50	1	0.2
616-02-011	South Guildford	402124	6469568	50	2	1.8
616-02-013	Caversham	403160	6471543	50	5	4.0
616-02-015	Wattle Grove	404768	6459282	50	5	2.0
616-02-016	Maylands	397397	6464875	50	3	3.0
616-02-017	Ashfield	400589	6468181	50	2	2.0
616-02-018	Bayswater	398342	6467229	50	6	1.5
616-02-020	Perth	392780	6465315	50	13	2.0
616-02-021	North Perth	391219	6466718	50	15	2.0
616-02-022	Leederville	389846	6466906	50	14	2.0
616-02-023	Glendalough	387974	6467408	50	9	1.0
616-02-024	Woodlands	386621	6468934	50	8	1.0
616-02-025	Thornlie	399861	6453180	50	13	1.1
616-02-026	Thornlie	400064	6451337	50	17	0.5
616-02-027	Karawara	394039	6458757	50	6	3.8
616-02-028	Ferndale	399659	6455989	50	7	1.5
616-02-029	Canning Vale	398765	6449620	50	23	1.2
616-02-030	Southern River	400894	6449498	50	20	0.8
616-02-031	Huntingdale	401796	6449010	50	21	0.8
616-02-032	Canning Vale	397379	6448841	50	25	0.2
616-02-033	Southern River	400332	6448156	50	20	1.0
616-02-034	Southern River	401582	6447792	50	22	1.2
616-02-035	Gosnells	404756	6448285	50	22	1.5
616-02-036	Canning Vale	397313	6447391	50	27	1.8
616-02-037	Southern River	402615	6446301	50	22	0.5
616-02-038	Harrisdale	398716	6446726	50	25	2.0
616-02-039	Southern River	400298	6446808	50	22	2.0
616-02-040	Jandakot	394506	6446511	50	28	2.5
616-02-041	Banjup	397253	6446249	50	28	2.0
616-02-042	Como	392672	6458203	50	4	0.3
616-02-043	Forrestdale	400225	6445376	50	22	0.5
616-02-044	Jandakot	392822	6445666	50	27	1.0
616-02-045	Banjup	395713	6445448	50	28	1.0
616-02-046	Forrestdale	397253	6445432	50	26	1.0
616-02-047	Southern River	401932	6444289	50	23	0.5
616-02-048	Forrestdale	400016	6444251	50	23	1.0
616-02-049	Banjup	393529	6444361	50	26	1.0
616-02-050	South Perth	392837	6460638	50	17	4.8
616-02-051	Piara Waters	397350	6444078	50	26	0.5

Bore ID	Suburb	Easting	Northing	Zone	Elevation (mAHD)	GWL (mbgl)
616-02-052	Forrestdale	400000	6443652	50	24	0.5
616-02-053	Banjup	395637	6443700	50	27	1.0
616-02-054	Atwell	393611	6442810	50	26	0.5
616-02-055	Piara Waters	398532	6443565	50	26	0.5
616-02-056	Atwell	392841	6443340	50	26	1.5
616-02-057	Cannington	399956	6457794	50	11	4.0
616-02-058	Forrestdale	401115	6443169	50	24	1.0
616-02-059	Queenspark	400176	6458630	50	7	0.5
616-02-060	Banjup	394491	6441920	50	26	1.5
616-02-061	Cannington	401572	6458932	50	11	0.5
616-02-062	Forrestdale	397222	6441622	50	27	3.5
616-02-063	Forrestdale	396193	6441650	50	29	2.5
616-02-064	Aubin Grove	392625	6441442	50	26	1.5
616-02-065	Banjup	394566	6440470	50	27	1.0
616-02-066	Willetton	395263	6454591	50	12	2.8
616-02-067	Brentwood	390972	6453930	50	12	3.8
616-02-068	North Lake	390092	6449904	50	17	2.0
616-02-069	South Lake	390759	6446989	50	21	1.5
616-02-070	Bibra Lake	388867	6447938	50	14	1.5
616-02-071	Beeliar	390087	6444353	50	16	1.5
616-02-072	Success	392046	6443531	50	22	2.0
616-02-073	Success	391037	6441580	50	13	1.5
616-02-074	Ferndale	398445	6455183	50	6	1.5
616-02-075	Lynwood	398640	6453978	50	11	1.2
616-02-076	Welshpoll	399955	6459557	50	12	3.0
616-02-077	Forrestdale	397341	6440422	50	25	1.0
616-02-078	Banjup	394107	6439393	50	26	1.0
616-02-079	Forrestdale	397061	6439547	50	26	2.0
616-02-080	Oakford	396844	6437072	50	25	0.5
616-02-081	Mandogalup	392037	6436996	50	26	2.0
616-02-082	The Spectacles	390864	6435510	50	26	0.5
616-02-083	Bertram	391356	6432572	50	17	1.0
616-02-084	Oakford	398621	6434253	50	23	1.5
616-02-085	Kenwick	401450	6454410	50	3	1.5
616-02-086	Oakford	400758	6433025	50	9	1.5
616-02-087	Bertram	392830	6433210	50	18	1.5
616-02-088	Oldbury	395942	6432539	50	21	0.5
616-02-089	Bertram	391763	6431491	50	12	0.5
616-02-090	Redcliff	401099	6464126	50	19	2.5
616-02-091	Baldivis	391846	6427710	50	5	1.0
616-02-092	Wellard	393849	6428175	50	9	1.5
616-02-093	Bechenham	401045	6455288	50	2	3.0
616-02-094	Langford	400214	6455355	50	2	0.5
616-02-095	Cannington	398737	6456729	50	1	3.5
616-02-096	Wilson	397239	6456321	50	1	1.0
616-02-097	Ferndale	397248	6455484	50	0	0.5
616-02-098	Riverton	396654	6455190	50	3	2.0
616-02-099	Wilson	396336	6456859	50	3	0.5
616-02-100	Salter Point	393871	6456775	50	2	2.0
616-02-101	Woodlands	385897	6469359	50	9	1.5
616-02-102	Churchlands	386360	6467084	50	8	1.5
616-02-103	Wembley	388663	6466333	50	14	1.5
616-02-104	Coolbinia	391967	6465608	50	15	2.8
616-02-105	Balcatta	388714	6472242	50	13	1.7
616-02-106	Stirling	387786	6472269	50	14	1.8
616-02-107	Stirling	387214	6472028	50	12	1.5
616-02-108	Stirling	386868	6472311	50	11	1.8

Bore ID	Suburb	Easting	Northing	Zone	Elevation (mAHD)	GWL (mbgl)
616-02-109	Gwelup	385539	6472309	50	8	1.6
616-02-110	Carine	385551	6472881	50	11	1.8
616-02-111	Carine	385027	6475042	50	5	1.8
616-02-112	North Beach	382533	6474982	50	2	1.0
616-02-113	Kingsley	387845	6479247	50	28	0.5
616-02-114	Kingsley	387633	6480653	50	26	1.5
616-02-115	Woodvale	386985	6481719	50	20	0.5
616-02-116	Woodvale	386257	6482874	50	19	1.0
616-02-118	Yokine	392817	6469210	50	24	3.5
616-02-119	Dianella	393496	6471447	50	27	3.5
616-02-120	Morley	396310	6471651	50	28	3.5
616-02-121	Bedford	395167	6469734	50	23	1.5
616-02-122	Bedford	394772	6468816	50	25	2.4
616-02-123	Bayswater	396772	6467825	50	23	1.0
616-02-124	Bayswater	396583	6468763	50	21	2.0
616-02-125	Embelton	396861	6470033	50	28	5.0
616-02-126	Embelton	397121	6470400	50	24	3.0
616-02-127	Bayswater	398284	6469855	50	25	2.0
616-02-128	Bassendean	399234	6470013	50	22	3.0
616-02-129	Ashfield	399553	6468726	50	15	1.5
616-02-130	Perth	390563	6463068	50	2	0.8
616-02-131	East Perth	393440	6464077	50	9	2.0
616-02-132	Belmont	398785	6465290	50	4	1.5
616-02-133	Perth	394288	6463218	50	1	2.0
616-02-134	Perth	394544	6463618	50	2	2.0
616-02-135	Belmont	399150	6463348	50	14	2.0
616-02-136	Cloverdale	400331	6462294	50	16	1.8
616-02-137	Kewdale	399388	6461473	50	13	1.5
616-02-144	Hazelmere	405197	6468350	50	12	2.5
616-02-145	South Guildford	403501	6467840	50	13	2.2
616-02-146	South Guildford	402916	6468601	50	10	1.8
616-02-147	Redcliff	399954	6465782	50	19	1.5
616-02-148	Baldivis	390498	6422991	50	10	1.2
616-02-149	Baldivis	391702	6421493	50	10	2.0
616-02-150	Baldivis	390526	6421389	50	5	1.5
616-02-151	Baldivis	393389	6426552	50	10	1.4
616-02-152	Baldivis	393160	6424793	50	10	1.2
616-02-153	Baldivis	391587	6426236	50	5	2.4
616-02-154	Baldivis	394371	6423323	50	10	2.2
616-02-155	Baldivis	389498	6425147	50	8	2.5
616-02-156	Baldivis	391939	6419228	50	3	nd
616-02-157	Baldivis	390955	6417786	50	5	2.0
616-02-158	Baldivis	389935	6419606	50	5	2.9
616-02-159	Baldivis	389461	6417063	50	5	3.2
616-02-160	Baldivis	392866	6418296	50	5	2
616-02-161	Baldivis	395724	6419492	50	5	4
616-02-162	Baldivis	391949	6415405	50	5	1.5
616-02-163	Baldivis	394291	6414331	50	15	1.20
616-02-164	Baldivis	391946	6417355	50	5	1.20
616-02-165	Baldivis	393033	6413964	50	15	4.5
616-02-166	Hopeland	394228	6415723	50	10	3
616-02-168	Alexander Heights	393521	6478072	50	39	4.0
616-02-169	Ballajura	394021	6477487	50	39	5.5
616-02-170	Ballajura	394026	6476250	50	35	3.0
616-02-171	Ballajura	395199	6477065	50	37	5.0
616-02-172	Koondoola	392448	6476323	50	53	>6.0

Bore ID	Suburb	Easting	Northing	Zone	Elevation (mAHD)	GWL (mbgl)
616-02-173	Ballajura	395408	6476019	50	35	0.0
616-02-174	Ballajura	397141	6476407	50	34	3.1
616-02-175	Noranda	395135	6474108	50	30	2.0
616-02-176	Noranda	394336	6473359	50	34	>5.0
616-02-177	Noranda	395485	6472952	50	30	2.8
616-02-178	Noranda	397581	6472815	50	29	3.5
616-02-179	Kiara	399578	6472999	50	24	3.2
616-01-03	Gnangara	397363	6479724	50	42	4.3
616-01-05	Gnangara	396557	6483685	50	55	6.0
616-01-11	Gnangara	389683	6489744	50	50	3.5
616-01-13	Gnangara	391960	6487651	50	53	5.7
616-01-14	Gnangara	393730	6487747	50	60	13.1
616-01-16	Gnangara	395786	6485916	50	60	7.4
616-01-17	Gnangara	393756	6483401	50	46	5.0
616-01-18	Gnangara	400108	6479762	50	39	4.8
616-01-19	Gnangara	388032	6493396	50	46	4.0
616-01-23	Gnangara	396388	6479703	50	40	4.0
616-01-24	Gnangara	398896	6479739	50	39	3.0
616-01-25	Whiteman	395363	6478044	50	38	2.5
616-01-26	Cullacabardee	396604	6477918	50	37	3.5
616-01-27	Whiteman	397515	6477961	50	36	4.0
616-01-28	Whiteman	395095	6479016	50	40	4.0
616-01-29	Whiteman	401187	6478337	50	30	2.5
616-01-30	Whiteman	399921	6478199	50	31	3.5
616-01-31	Whiteman	398784	6478125	50	34	2.5
616-01-32	Whiteman	397896	6478014	50	37	2.0
616-01-33	Henley Brook	402094	6475977	50	21	3.0
616-01-34	Whiteman	402459	6472833	50	24	3.0
616-01-35	Hanley Brook	403827	6478292	50	22	5.0
616-01-36	Hanley Brook	401911	6479815	50	36	2.5
616-01-37	Hanley Brook	402824	6480655	50	34	2.0
616-01-38	Ellenbrook	401259	6482321	50	44	3.8
616-01-41	Caversham	403560	6474896	50	15	1.5
616-01-42	Caversham	401638	6474869	50	14	1.5
616-01-43	Vines	405075	6485241	50	28	2.0
616-01-44	Vines	404233	6485309	50	33	2.0
616-01-46	Vines	405366	6486928	50	27	5.0
616-01-47	Henley Brook	403924	6479590	50	27	4.0
616-01-48	Henley Brook	405010	6479328	50	17	5.0

Appendix 2: Field and laboratory methods

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 program.

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).

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% peroxide (H_2O_2) should be recorded at 0.25 m or within each horizon
- Depth of water table (mbgl)
- Profiling should continue to 1-2 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 ½ teaspoon of the soil into the pH_F test tube** and place the other **½ 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 ASS 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 ASS 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. Phosphoric acid stabilisers often added by the chemical companies results 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% 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 and store the rest in darkness at 5 degrees C in a well-labelled container. 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. 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 to** record the measured calibration**.** Records of the probe calibration can give the field officer an indication of the condition 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 0.25 m or at least one per horizon whichever is the lesser.**

5) **Remove approximately 1 teaspoon from the profile. Place approximately ½ teaspoon of that soil into the pH_F test tube and place ½ 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) **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% 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.**

7) **Add a few drops of 30% 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 ASS 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 90°C. 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 25°C.

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).
- 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.
- 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.
- 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 DEC chain-of-custody forms 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 deionised 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 a set of every 20 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 until DEC 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 3: ASS characteristics of the investigated sites

Bore ID	ASS depth (m)	Lowest pH_{FOX}	Highest S_{CR} (% S)	ASS Characteristics
616-02-001	4	1.7	0.03	ASS identified in bluish white sand layer from 4.25m to 5.50m bgl with S_{CR} up to 0.03% S.
616-02-002	2	2.1	0.06	ASS identified in bluish sand from 2.0m - 4.0m bgl with Scr up to 0.06% S and TPA up to 0.07% S.
616-02-003	2	1.5	0.83	ASS identified in peat layer from 2.00m - 4.25m bgl with Scr up to 0.83% S, TAA up to 0.76% S and TPA up to 2.86% S.
616-02-004	2	1.7	1.57	ASS identified in dark waterlogged clay from 3.00 - 5.75m bgl with Scr up to 1.57% S and TPA up to 1.61% S .
616-02-005	NP	5.1	NA	No ASS or AASS detected.
616-02-006	0	2	1.95	AASS and ASS identified in top 4.00m with Scr up to 1.95%, TAA up to 0.08% S and TPA up to 2.45% S.
616-02-007	NP	3.3	<0.02	No AASS or ASS material identified.
616-02-008	2	1.3	0.15	ASS occurs in dark grey sand from 2.00m - 3.00m bgl with Scr up to 0.15% S and TPA up to 0.17% S
616-02-009	0	2	<0.02	ASS occurs in dark grey loamy sand in top 2.0m with TAA up to 0.06% S and TPA up to 0.12% S. Goundwater table is below 2.0m and acidity is only derived by peroxide reaction. S_{CR} is below detection limit.
616-02-010	0.25	1.5	0.09	Dark grey coarse sand contain ASS from 0.25m - 4.00m bgl with S_{CR} up to 0.09% S, TAA up to 0.05% S and TPA up to 0.27% S.
616-02-011	2	1.6	0.96	ASS occurs in dark clay rich horizons from 2.00m bgl with S_{CR} up to 0.96% S, TAA up to 0.15% S and TPA up to 2.60% S.
616-02-013	2.75	4.4	0.04	Red brown clay loam from 5.75m to 6.00m bgl contains S_{CR} up to 0.04% S and TPA up to 0.04% S. pHFOX is however above 5.1.
616-02-015	2.5	2.1	0.005	Light brown sand from 2.25m to 2.50m bgl depths contains ASS with S_{CR} 0.005% S, TAA <0.02% S and TPA <0.02%S
616-02-016	0.75	2.4	0.1	ASS identified from 3.25m - 3.75m bgl in brown loamy sand with S_{CR} up to 0.06% S, TAA up to 0.03% S and TPA up to 0.16% S.
616-02-017	0	1.1	0.4	ASS occurs variably in dark greyish brown loam from 0.00m to 3.00m bgl, containing S_{CR} up to 0.04% S, TAA up to 0.03% S and TPA up to 0.61% S.
616-02-018	NP	5.4	NA	No ASS or AASS identified, place appears to be a former landfill site.
616-02-020	1.75	1.7	<0.02	ASS occurs in dark grey and brown sand from 1.75m to 4.75m bgl with TPA up to 0.05% S. pHFOX is about 2.0
616-02-021	2.75	1.8	0.04	ASS occurs in light grey sand from 2.75m – 3.00m bgl and in lower layer from 5.75 to 6.00m bgl with S_{CR} 0.04% S and TPA up to 0.09% S.
616-02-022	4	1.7	0.81	ASS identified in peat from 4.00 - 4.75m bgl with S_{CR} 0.81% S, TAA up to 0.53% S and TPA 8.59% S.
616-02-023	1.25	1.9	0.16	ASS occurs in dark to greyish brown sand from 1.25m - 4.00m bgl with S_{CR} up to 0.16 % S and TPA 0.38% S.
616-02-024	1.25	2.3	<0.02	ASS occurs in grey sand from 1.50m - 4.00m bgl with TPA up to 0.03% S.
616-02-025	2.5	2.8	<0.02	In light brown grey sand, ASS has pH as low as 2.8 from depth 2.50m – 2.75m bgl. S_{CR} 0.02%S.
616-02-026	5.25	1.8	0.03	ASS occurs in brown grey sand from 5.25m - 5.75m bgl with S_{CR} 0.03% S and TPA 0.04% S.
616-02-027	2.5	3.1	<0.02	No ASS identified. Grey to brown sand from 1.50m to 3.00m bgl and at 3.75m to 4.00m bgl however contains TAA up to 0.10% S and TPA up to 0.37% S.
616-02-028	0.25	1.6	1.62	AASS is present in surface brown layer from 0.00m - 0.50m bgl and ASS is present from 0.50m -1.75m bgl and at 5.00m to 5.50m bgl in organic rich clay with S_{CR} up to 1.62% S, TAA up to 0.22% S and TPA up to 2.03% S.
616-02-029	2.25	1.8	0.52	ASS occurs in light grey sand from 2.25m - 6.00m bgl with S_{CR} up to 0.52% S.
616-02-030	2.75	1.7	0.11	ASS occurs in pale brown sand and coffee rock from 2.75m - 4.75m bgl with S_{CR} up to 0.11% S.
616-02-031	1.75	1.8	0.1	ASS identified in coffee rock and brown sand from 1.75m – 2.00m bgl and from 3.25 to 5.25m bgl with S_{CR} up to 0.10% S, TAA 0.03% S and TPA up to 0.10% S.
616-02-032	2.25	2.6	<0.02	Coffee rock from 1.75m - 4.00m bgl with ASS layer having TAA 0.03% S and TPA up to 0.16% S.

616-02-033	3	2	<0.02	ASS in light grey sand from 0.25m - 4.00m bgl with TPA up to 0.06% S.
616-02-034	2	2.7	<0.02	AASS identified from 2.00m - 2.50m bgl and ASS in coffee rock from 3.0m bgl with TAA 0.26% S and TPA up to 1.09% S.
616-02-035	NP	4.1	NA	No ASS or AASS detected.
616-02-036	NP	1.7	0.02	ASS occurs in light white, pale brown and coffe sand from 0.00m - 6.00m bgl with TPA up to 0.07% S.
616-02-037	4.5	1.6	0.04	ASS occurs in light grey sand from 4.50m to 6.00m bgl with S_{CR} 0.04% S.
616-02-038	0.5	2.7	0.02	Actual ASS identified in grey and brown soils from 0.50m – 3.00m bgl and ASS identified in coffee rock sand below 4.00m bgl with TAA 0.16% S and TPA 0.62% S.
616-02-039	NP	3.9	NA	No ASS or AASS identified in soil profile. pHFOX above 4.0 and pHF above 4.5
616-02-040	2	1.8	0.02	ASS occurs in coffee rock from 2.00m - 4.00m bgl with TPA up to 0.08%S.
616-02-041	NP	2.9	NA	No ASS or AASS identified but coffee rock present onsite.
616-02-042	0.5	1.8	0.04	ASS occurs in grey and white sand from 0.50m to 4.0m bgl with S_{CR} up to 0.04% S, and TPA up to 0.03% S.
616-02-043	1.5	2.2	0.03	ASS identified in dark brown coffee rock from 1.50m and 4.00m bgl with S_{CR} up to 0.03% S, TAA up to 0.14% S and TPA up to 0.94% S.
616-02-044	1.25	3	0.02	ASS identified sporadically in light grey sand between 0.0m to 2.25m bgl with pH as low as 2.8.
616-02-045	2	2	0.07	AASS and ASS identified sporadically between 2.00m and 5.75m bgl in brown sand with S_{CR} up to 0.07% S, TAA up to 0.15% S and TPA up to 0.08% S.
616-02-046	1.25	1.5	0.05	Actual ASS & ASS identified in incipient coffee rock from 1.25m bgl to 6.00m bgl with S_{CR} up to 0.05% S, TAA up to 0.07% S and TPA up to 0.19% S.
616-02-047	NP	3.7	NA	No ASS or AASS identified.
616-02-048	3.5	2	0.05	ASS identified in white pale brown sand from 3.50m bgl with S_{CR} 0.05% S.
616-02-049	0.5	1.3	0.02	Actual ASS indentified in light grey sand from 0.50m - 6.00m bgl and ASS identified intermittently and in incipient coffee rock with TAA up to 0.05% S and TPA up to 0.16% S.
616-02-050	NP	4.7	NA	No ASS or AASS present pHFOX > 5.0
616-02-051	2.75	1.6	0.05	ASS identified in dark grey sand from 2.75m to 4.00m bgl with S_{CR} up to 0.05% S.
616-02-052	2	1.2	0.02	ASS identified in incipient coffee rock 2.00m bgl with TAA up to 0.08% S and TPA up to 0.54% S.
616-02-053	1.25	2.3	0.06	ASS identified in brown coffee rock from 2.00m to 6.00m bgl with S_{CR} up to 0.06% S, TAA up to 0.03% S and TPA up to 0.07% S.
616-02-054	2.5	1.3	0.05	ASS identified in very dark greyish brown sand and coffee rock from 2.50m to 3.25m bgl and from 4.25m to 6.00m bgl with S_{CR} up to 0.05% S and TPA up to 0.10% S.
616-02-055	NP	4	NA	No ASS or AASS identified, coffee rock onsite at 2.00m bgl.
616-02-056	5.25	1.7	0.05	ASS identified in coffee rock at 5.25m bgl with S_{CR} up to 0.05% S.
616-02-057	NP	4	NA	No ASS identified.
616-02-058	2.75	1.7	0.02	Actual ASS and ASS identified below 2.75m bgl in dark brown coffee rock with TAA up to 0.27% S and TPA up to 1.26%S.
616-02-059	1.5	1.4	0.07	ASS identified in dark grey to brown sand from 1.75m to 4.00m bgl with S_{CR} up to 0.07% S and TPA up to 0.05% S.
616-02-060	1.75	3.2	0.02	No ASS identified
616-02-061	2.5	1.9	0.05	ASS identified in grey and brown sand from 2.50m to 4.00m bgl with S_{CR} up to 0.05% S and TPA up to 0.10% S.
616-02-062	0	1.9	0.02	Actual ASS occurs at 0.00m to 2.50m bgl and ASS occurs from 2.75m to 3.75mgl identified in yellowish brown sand with TAA 0.05% S and TPA up to 0.33% S.
616-02-063	0.25	1.2	0.02	AASS and ASS identified in white and brown sand from 0.25m to 6.00m bgl with TPA up to 0.04% S.
616-02-064	1	1.7	0.04	AASS and ASS identified in pale brown sand and coffee rock respectively from 1.00m to 6.00m bgl with S_{CR} up to 0.04% S and TPA 0.04% S.
616-02-065	0.25	1.4	0.02	ASS identified in coffee rock from 1.75m bgl with TAA up to 0.03% S and TPA up to 0.10% S.
616-02-066	4.75	1.9	0.03	ASS identified in grey sand from 4.75m bgl with S_{CR} up to 0.03% S and TPA up to 0.03% S. Coffee rock onsite.
616-02-067	5.75	1.7	0.03	ASS identified in grey sand at 5.75m bgl with S_{CR} up to 0.03% S and TPA up to 0.03% S.

616-02-068	3	1.6	0.02	ASS identified in grey brown sand from 3.00m bgl with TPA up to 0.04% S.
616-02-069	NP	3.2	NA	No ASS or AASS identified but coffee rock onsite from 2.00m bgl.
616-02-070	2.75	1.4	0.8	ASS identified in peaty material from 3.00m bgl with S_{CR} up to 0.80% S, TAA up to 0.08% S and TPA up to 7.94% S.
616-02-071	3.75	1.3	0.1	ASS identified in grey sand and coffee rock from 4.0m to 6.0m bgl with S_{CR} up to 0.10% S and TPA up to 0.14% S.
616-02-072	2.75	2.4	0.1	ASS identified in white sand from 2.75m to 6.00m bgl with TPA up to 0.04% S.
616-02-073	NP	3.6	NA	No ASS or AASS identified but coffee rock is present below 2.0m bgl.
616-02-074	NP	2.2	0.02	No ASS or AASS identified.
616-02-075	4	1.4	0.07	ASS identified in grey clayey sand below 4.00m bgl with S_{CR} up to 0.07% S and TPA up to 0.06% S.
616-02-076	2.75	2.3	0.02	ASS identified in brown sand from 2.75m to 3.75m bgl with pH as low as 2.3.
616-02-077	1.75	2.3	0.02	ASS identified intermitenlty in narrow bands of brown sand and coffee rock from 1.75m bgl with TPA up to 0.14% S.
616-02-078	1.75	1.4	0.02	ASS identified in brown sand and coffee rock below 1.75m bgl with TPA up to 0.11% S.
616-02-079	2	2.6	0.03	ASS identified in dark brown sand and coffee rock between 3.50m and 3.75m bgl with S_{CR} up to 0.03% S, TAA 0.08% S and TPA up to 0.42% S.
616-02-080	2	2.1	<0.02	ASS identified in incipient coffee rocks below 2.00m bgl with low pH as low as 2.1.
616-02-081	4	1.1	0.06	ASS identified in coffee sand below 4.00m bgl with S_{CR} up to 0.06% S and TPA up to 0.16% S.
616-02-082	1.5	1.3	0.26	ASS identified in greyish brown sand below 1.50m bgl with S_{CR} up to 0.26% S and TPA up to 0.37% S.
616-02-083	NP	2.8	NA	No ASS or AASS identified but peat and coffee rock onsite.
616-02-084	2.25	1.5	0.6	ASS identified in coffee rock and brown sand below 2.25m bgl with S_{CR} up to 0.60% S and TPA up to 1.39% S.
616-02-085	0.5	1.4	0.8	ASS identified below 0.50m bgl in yellow and brown clay, grey sand and peat with S_{CR} up to 0.80% S, TAA up to 0.05% S and TPA up to 1.70% S.
616-02-086	NP	5.6	NA	No ASS or AASS identified.
616-02-087	NP	3.1	NA	No ASS or AASS identified but coffee rock onsite.
616-02-088	NP	3.2	NA	No ASS or AASS identified but coffee rock onsite.
616-02-089	0.5	1.5	0.15	ASS identified below 0.50m bgl In grey sand with S_{CR} up to 0.15% S, TAA up to 0.03% S and TPA up to 0.19% S.
616-02-090	NP	3	NA	No ASS or AASS identified.
616-02-091	NP	1.6	NA	No AASS ot ASS identified.
616-02-092	1.75	2.7	0.21	ASS identified below 1.75m bgl in coffee rock with S_{CR} up to 0.21% S, TAA up to 0.05% S and TPA up to 0.30% S.
616-02-093	1.25	2.7	0.04	ASS identified from 0.00m to 0.50m bgl in yellowish brown loam with S_{CR} up to 0.04% S.
616-02-094	0	1.4	0.09	ASS identified in brown loam and grey sand intermittently from 0.00m-2.00m, 3.75m to 4.25m and from 5.25m bgl with S_{CR} up to 0.11% S, TAA up to 0.08% S and TPA up to 0.11% S.
616-02-095	NP	5.3	NA	No AASS ot ASS identified
616-02-096	0.75	2.4	0.07	ASS identified in brown, yellow and grey soil from 1.00m - 2.50m bgl with S_{CR} up to 0.07% S and TPA up to 0.09% S.
616-02-097	1	2	0.04	ASS identified in grey and yellow sand from 1.00m - 2.25m bgl with S_{CR} up to 0.04% S and TPA up to 0.03% S.
616-02-098	1.75	1.4	0.22	ASS identified in greyish brown sand from 2.00m bgl with S_{CR} up to 0.22% S and TPA up to 0.42% S.
616-02-099	1.75	2	0.84	ASS identified in peatish bands and dark grey sand below 2.00m bgl with S_{CR} up to 0.84% S and TPA up to 0.38% S.
616-02-100	0.75	1.3	0.08	ASS identified in dark brown grey sand and peat 1.00m bgl with S_{CR} up to 0.08% S and TPA up to 0.24% S.
616-02-101	0.5	1	0.74	ASS identified below 2.25m in peaty clay and grey sand with S_{CR} up to 0.74% S, TAA up to 0.16% S and TPA up to 6.97% S.
616-02-102	0.75	1.3	0.14	ASS identified in grey sand, 1.75m bgl with S_{CR} up to 0.14% S and TPA up to 0.05% S.
616-02-103	2.5	1.4	0.13	ASS identified in grey sand, 2.50m bgl with S_{CR} up to 0.13% S and TPA up to 0.27% S.
616-02-104	3	1.4	0.02	ASS identified in brown loose sand 3.00m bgl with pH as low as 1.4.
616-02-105	1.75	0.8	0.93	ASS identified in peaty clay between 1.75m - 5.00m bgl with S_{CR} up to 0.93% S, TAA up to 0.79% S and TPA up to 10.8% S.
616-02-106	0	1.6	0.05	AASS and ASS identified throughout the soil profile with S_{CR} up to 0.05% S and TPA up to 0.09% S.

616-02-107	1	1.8	0.1	ASS identified in peat grey and brown sand from 1.0m -7.0m bgl with S_{CR} up to 0.10% S, TAA up to 0.10% S and TPA up to 0.28% S.
616-02-108	1	1.2	0.34	ASS identified from 1.00m to 1.75m bgl and 3.25m to 7.00m bgl in peat and dark grey sand with S_{CR} up to 0.34% S, TAA up to 0.04% S and TPA up to 3.68% S.
616-02-109	3	1.6	0.09	ASS identified in grey sand below 3.00m with S_{CR} up to 0.09% S and TPA up to 0.12% S.
616-02-110	1.5	1.4	0.07	ASS identified in grey sand below 1.5m with S_{CR} up to 0.07% S and TPA up to 0.21% S.
616-02-111	2.5	1.8	0.07	ASS identified from 2.50m bgl in grey sand with S_{CR} up to 0.07% S and TPA up to 0.08% S.
616-02-112	2.75	1.1	0.6	ASS identified between 2.75m to 3.50m bgl in peat with S_{CR} up to 0.60% S and TPA up to 10.2% S.
616-02-113	1	1.4	0.1	ASS identified in light brown and grey sand, between 1.00m-1.50m bgl and from 2.25m bgl respectively with S_{CR} up to 0.10% S and TPA up to 0.09 %S.
616-02-114	2.25	1.8	0.03	ASS identified from 2.5m bgl in grey sand with S_{CR} up to 0.03% S TPA up to 0.08 %S.
616-02-115	0	1.6	0.02	ASS identified from 0.00m to 1.00m bgl and from 1.75m to 2.50m bgl with TPA up to 0.03 %S.
616-02-116	0.75	1.7	0.02	ASS identified in yellowish and ligh grey sand at various depths below 0.75m with pH as low as 1.7.
616-02-118	NP	4	NA	No ASS or AASS detected.
616-02-119	1	2.5	0.02	ASS identified in light grey and brown sand at various depths below 0.25m with pH as low as 1.7.
616-02-120	NP	3.3	NA	No ASS or AASS detected.
616-02-121	2.5	1.4	0.02	ASS identified below 2.50m depth in light brown and grey sand, with pH as low as 1.4.
616-02-122	3.75	1.6	0.02	ASS identified below 3.75m bgl with TAA up to 0.07 %S and TPA up to 0.19 %S.
616-02-123	2	2.1	0.02	ASS identified below 2.00m depth in brown sand with pH as low as 2.1.
616-02-124	NP	3.6	NA	No ASS or AASS detected but coffee rock onsite.
616-02-125	NP	3.3	NA	No ASS or AASS detected.
616-02-126	3.25	1.9	0.02	ASS identified in grey and yellowish brown sand from 3.00m to 3.50m bgl and from 5.00m bgl with TPA up to 0.05 %S.
616-02-127	1	1.9	0.02	ASS identified from 1.00m to 1.50m bgl in brown sand, and thenfrom 2.75m to 6m bgl with TAA up to 0.04 %S and TPA up to 0.18 %S.
616-02-128	1	2.4	0.02	ASS identified in grey and brown sand at various intervals with pHFOX as low as 2.4.
616-02-129	1.25	1.4	<0.02	ASS identified in peat and brown sand from 1.25m bgl with TPA up to 0.29 %S.
616-02-130	1.25	1.1	0.28	ASS identified in brown and grey sand from 2.25m to 4.25m and from 4.75m bgl with S_{CR} up to 0.28% S and TPA up to 0.73 %S.
616-02-131	2.25	1.7	0.02	ASS identified in dark brown sand from 2.25m to 3.00m bgl with TAA up to 0.04 %S and TPA up to 0.04 %S.
616-02-132	5.25	1.5	0.88	ASS identified in dark grey clay 5.25m below ground with S_{CR} up to <0.78% S and TPA up to 3.48 %S.
616-02-133	2.25	1.3	0.88	ASS identified in dark esturanine peatish clay from 2.50m to 3.50m bgl, 4.00m to 5.0m bgl and from 5.75m bgl with S_{CR} up to <0.78% S, TAA up to 0.03 %S and TPA up to 1.84 %S.
616-02-134	NP	4.2	NA	No ASS or AASS detected.
616-02-135	2.75	1.7	0.06	ASS identified in light brown sand 2.75m bgl with S_{CR} up to 0.06% S and TPA up to 0.08 %S.
616-02-136	3	1.3	<0.02	ASS identified in brown sand from 3.0 to 6.0m bgl depth with TPA up to 0.10 %S.
616-02-137	2.25	1.2	0.08	ASS identified in brown sand 2.25m bgl with S_{CR} up to 0.08% S and TPA up to 0.16 %S.
616-02-144	1.25	1.7	0.02	ASS identified in light grey and brown sand at various depths 1.50m bgl with TPA up to 0.05 %S.
616-02-145	3	1.7	0.02	ASS identified in pale brown and grey sand 3.00m bgl with TPA up to 0.06 %S.
616-02-146	0.75	1.8	0.02	No significant ASS or AASS detected. Only single low pHFOX measurement at 2.25m bgl.
616-02-147	2	1.6	0.13	ASS identified below 2.0m depth in grey sand with S_{CR} 0.15% S, TAA <0.02%S and TPA up to 0.21% S.
616-02-148	1.75	1.4	0.04	ASS identified in brown sand 1.75m bgl with S_{CR} up to 0.04% S and TPA up to 0.03 %S.
616-02-149	3.25	1.3	0.04	ASS identified in dark brown sand 3.25m bgl with S_{CR} up to 0.04% S and TPA up to 0.22 %S.
616-02-150	5.5	2.3	0.02	ASS identified in dark grey sand 5.50m bgl with pH as low as 2.3.

616-02-151	5.75	2.8	0.02	ASS identified in light grey sand at 6.00m bgl with pH as low as 2.8.
616-02-152	0.25	2.8	0.02	ASS identified in dark greyish brown clay from 0.25m to 3.75m bgl with TAA up to 0.06 %S and TPA up to 0.07 %S.
616-02-153	NP	4.1	0.02	No ASS or AASS detected.
616-02-154	3	2.8	0.02	ASS identified in brown loamy sand from 3.00m to 4.25m bgl with TAA up to 0.08 %S and TPA up to 0.08 %S.
616-02-155	1.75	1.9	0.06	ASS identified in grey and brown sand from 1.75m to 4.75m bgl with S_{CR} up to 0.06% S and TPA up to 0.06 %S.
616-02-156	NP	4.2	0.02	No ASS or AASS detected up to 2m depth. Clay subsoil too hard to drill.
616-02-157	5	2	0.02	ASS identified in light grey sand from 5.00m to 6.00m bgl with pHFOX as low as 2.0.
616-02-158	2	1	0.02	ASS identified in brown coffee rock from 2.00m bgl with TAA up to 0.30 %S and TPA up to 1.08 %S.
616-02-159	3.5	1.7	0.02	ASS identified in light grey sand from 3.50m to 5.50m bgl with pHFOX as low as 1.6.
616-02-160	3.5	1.7	0.04	ASS identified in grey sand below 3.50m depth with S_{CR} up to 0.037% S, TAA <0.02 %S and TPA up to 0.04 %S.
616-02-161	4.75	1.1	0.09	ASS identified below 4.50m depth in coffee rock with S_{CR} up to 0.087% S, TAA up to 0.06 %S and TPA up to 0.43 %S.
616-02-162	1.75	0.8	0.06	ASS identified in brown coffee rock 1.75m bgl with S_{CR} up to 0.06% S, TAA up to 0.09 %S and TPA up to 0.26 %S.
616-02-163	4	1	0.02	ASS identified in brown sand 4m bgl with TPA up to 0.06 %S.
616-02-164	2.25	1	0.04	ASS identified in brown coffee rock 2.25m bgl with S_{CR} up to 0.04% S, TAA up to 0.09 %S and TPA up to 0.05 %S.
616-02-165	NP	3.1	0.02	ASS identified in coffee rock 4.75m bgl with TAA up to 0.07 %S and TPA up to 0.19 %S.
616-02-166	NP	3.9	NA	No ASS or AASS detected.
616-02-168	3	2.8	0.02	ASS identified in white and brown sand 3.00m bgl with TAA up to 0.15 %S and TPA up to 0.49 %S.
616-02-169	1.25	1.5	0.02	ASS identified in brown coffee rock 3.75m bgl with TAA up to 0.04 %S and TPA up to 0.22 %S.
616-02-170	3.25	1.6	0.02	ASS identified in brown coffee rock 3.25m bgl with pHFOX as low as 1.6.
616-02-171	3.75	3.8	0.02	No ASS or AASS detected.
616-02-172	0.25	2.2	0.02	No ASS or significant AASS detected.
616-02-173	1.75	2.6	0.02	ASS identified in pale brown sand from 3.00m to 4.25m bgl with pHFOX as low as 2.7.
616-02-174	2.25	1.7	0.02	ASS identified in brown coffee rock 2.25m bgl with TPA up to 0.06 %S.
616-02-175	4	2.1	0.02	ASS identified in pale brown sand 4.0 m bgl with pHFOX as low as 2.1.
616-02-176	NP	3.7	0.02	No ASS or AASS detected.
616-02-177	1.25	2.2	0.02	ASS identified in grey and brown sand at various depths from 1.25m to 3.75m bgl with TPA up to 0.04 %S.
616-02-178	4.25	3.3	0.03	ASS indentified in brown coffee rock at 4.5m bgl depth with S_{CR} up to 0.03% S.
616-02-179	1	1.3	0.24	ASS identified in grey sand and brown coffee rock from 1.00m to 2.00m bgl and from 3.00 to 6.00m bgl with S_{CR} up to 0.24 %S and TPA up to 0.35 %S.
616-01-03	NP	3.8	NP	No ASS or AASS detected.
616-01-05	6.25	2.7	<0.02	ASS identified from 5.00m to 7.25m bgl depth with pHFOX as low as 2.7.
616-01-11	NP	3.6	<0.02	No ASS or AASS detected.
616-01-13	NP	3.2	<0.02	No ASS or AASS detected.
616-01-14	NP	4.2	<0.02	No ASS or AASS detected.
616-01-16	NP	3.5	<0.02	No ASS identified.
616-01-17	NP	3.6	<0.02	No ASS identified. However soil horizon at 6.5m depth contains TPA up to 0.09% S in brown coffee colour sand .
616-01-18	6.25	2.8	<0.02	ASS identified below 6.25m depth in coffee sand with S_{CR} up to <0.02% S, TAA 0.02 %S and TPA 0.02 %S.
616-01-19	2.25	2.2	<0.02	ASS identified in a narrow band between 2.25m and 3.50m depths with S_{CR} up to <0.02% S, TAA 0.07 %S and TPA 0.25 %S.
616-01-23	2.7	2.4	0.02	ASS identified in narrow band of light brown sand at 5.25m depth with S_{CR} up to 0.02% S, TAA <0.02 %S and TPA <0.02 %S.
616-01-24	NP	3	<0.02	ASS identified in drak brown sand at 4.50m depth with S_{CR} up to <0.02% S, TAA 0.02 %S and TPA 0.08 %S.
616-01-25	3.25	2.4	<0.005	ASS identified in fine drak brown sand from 3.25m to 5.00m depth with S_{CR} up to <0.005% S, TAA 0.03 %S and TPA 0.07 %S.

616-01-26	NP	4	NA	No ASS or AASS detected.
616-01-27	NP	4	NA	No ASS or AASS detected.
616-01-28	NP	3.2	NA	No ASS or AASS detected.
616-01-29	3	1.8	0.005	ASS identified in white sand from 3.25m to 5.00m depth with S_{CR} up to <0.005% S, TAA <0.02 %S and TPA 0.02 %S.
616-01-30	3.25	2.3	0.005	ASS identified in dark brown sand below 3.25m depth with S_{CR} up to 0.005% S, TAA 0.02 %S and TPA 0.06 %S.
616-01-31	3	1.3	0.04	ASS identified in grey sand from 3.00m to 5.50m depths with S_{CR} up to 0.04% S, TAA <0.02 %S and TPA 0.06 %S.
616-01-32	NP	4	NA	No ASS
616-01-33	3.25	1.5	0.11	ASS identified in fine grey sand below 3.25m depth with S_{CR} up to 0.11% S, TAA <0.02 %S and TPA 0.13 %S.
616-01-34	3.5	1.4	0.04	ASS identified in dark brown sand below 3.25m depth with S_{CR} up to 0.04% S, TAA 0.03 %S and TPA 0.13 %S.
616-01-35	4.5	2.3	NA	ASS identified in a vary narrow band of grey clay at 4.50m depth with pHFOX of 2.3
616-01-36	2.75	2.4	0.02	ASS identified in coffee rock below 2.75m depth with S_{CR} up to 0.02% S, TAA 0.02 %S and TPA 0.15 %S.
616-01-37	3.25	2.7	0.02	ASS identified in very dark brown sand from 3.25m to 3.75m depth with S_{CR} up to 0.02% S.
616-01-38	2.5	1.8	0.02	ASS identified in coffee sand from 2.50m to 5.75m depth with S_{CR} up to 0.02% S, TAA <0.02 %S and TPA 0.02 %S.
616-01-41	NP	5.6	NA	No ASS or ASS identified. Clay rich soils
616-01-42	NP	4.3	NA	No ASS or ASS identified. Clay rich soils.
616-01-43	4	1.2	0.11	ASS identified in dark grey sand from 4.00m to 6.00m depth with S_{CR} up to 1.13% S and TPA 0.14 %S.
616-01-44	5	2.3	0.01	ASS identified in pale brown sand below 5.00m depth with S_{CR} up to 0.01% S, TAA <0.02 %S and TPA <0.02 %S.
616-01-46	4	1.4	0.09	ASS identified in greyish brown clayey sand from 4.00m to 4.25m depth with S_{CR} up to 0.09% S.
616-01-47	2	1	0.07	ASS identified in dark grey sand below 2.00m depth with S_{CR} up to 0.07% S, TAA <0.02 %S and TPA 0.06 %S.
616-01-48	NP	4.2	NP	No ASS or ASS identified.

---

[1] B horizon: subsoil horizons consisting of one or more mineral layers differing to the A Horizon by: clay, iron, aluminium or organic matter concentrations; structure and/or consistence; and colour.

[2] A horizon: the surface mineral horizons, where there is often accumulation of organic matter. They are usually darker in colour than the lower horizons. If they are lighter in colour, then the horizons have lower silicate clay content.

[3] The deposition of colloids, soluble salts, and suspended mineral particles in a lower soil horizon through the process of eluviation (downward movement) from an upper soil horizon

[4] E horizon: being short for eluviated, is most commonly used to label a horizon that has been significantly leached of its mineral and/or organic content, leaving a pale layer largely composed of silicates. These are present only in older and well-developed soils**.**