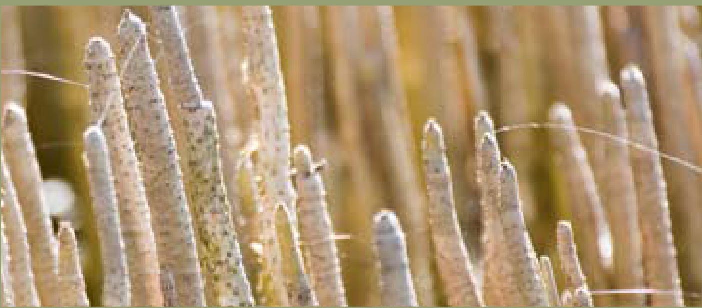
Soil indicators of Queensland wetlands

Statewide assessment and methodology



Australian Government

Queensland Wetlands Program

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Soil indicators of Queensland wetlands

Statewide assessment and methodology

Authors

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This is the final report for the Soil Indicators of Queensland Wetlands (WL NRM 06) of the Queensland Wetlands Programme, a joint initiative of the Australian and Queensland governments. The Queensland Wetlands Programme was established in 2003 to protect and conserve Queensland's wetlands.

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Selected definitions and abbreviations

ASC	Australian Soil Classification
Chroma	Method for describing soil colour that depicts the purity or strength of the colour
DEWHA	Department of the Environment, Water, Heritage and the Arts (Australian Government)
DIWA	Directory of Important Wetlands in Australia
EPA	Environmental Protection Agency (Queensland Government)
Hydric soil	Soil that is wet long enough to produce anaerobic conditions (at least periodically), thereby influencing the growth of plants
IBRA	Interim Biogeographical Regionalisation for Australia
IRIS	Indicator of Reduction In Soils
NP	National Park
NRW	Department of Natural Resources and Water (Queensland Government)
TC	Total carbon
QWP	Queensland Wetlands Programme
USDA	United States Department of Agriculture
Value	Method for describing soil colour that depicts the lightness and darkness of the colour
Wetland area	For the purposes of this report, a wetland area is wetland or wetland aggregation. There may be several wetland locations in a single wetland area.
Wetland group	A method to describe wetlands specifically related to the Queensland Wetlands Programme soil indicators project. This classification is based on climatic region, wetland system and inundation frequency.
Wetland location	For the purposes of this report, a wetland location is a transect sampled in a wetland area.
Wetland system	There are six wetland systems as defined by the Queensland Wetland Programme Wetland Mapping and Classification project: riverine, lacustrine, palustrine, estuarine, marine and spring wetlands. (http://www.epa.qld.gov.au/wetlandinfo)
Wetland type	A method to describe lacustrine and palustrine wetlands based on the Queensland Wetlands Programme habitat typology. (http://www.epa.qld.gov.au/wetlandinfo)

Executive Summary

Wetland boundaries are dynamic, may change over time and may be difficult to identify depending on the hydrological cycle. Changes are predominantly driven by climate and are affected at different spatial scales over different periods of time. In Australia wetland identification has traditionally been conducted by examining biotic indicators and surface hydrology. Using these indicators alone to determine wetland boundaries can be difficult, especially at a finer scale and in wetlands that have been modified, are predominantly ephemeral or where there is a broad ecotone (transition zone) between the wetland and adjacent landscape. Soils, specifically the features that develop under wet conditions, change slowly and therefore can provide useful information to support wetland identification, delineation and subsequently mapping.

This report details and discusses findings of a statewide assessment of wetland soil indicators conducted by the Department of Natural Resources and Water during 2007 and 2008 under the Queensland Wetlands Programme (QWP).

Because of the difficulties in defining wetlands, and the way in which policy and legislation has developed, there are many different wetland definitions in use in Queensland. The definition developed through the QWP, which is based on the Ramsar definition, includes a component on wetland soil features. For this definition to be used at a finer scale, a scientifically robust method for applying wetland soil indicators is required. Dear and Svennson (2007), in a pilot study, reviewed soil indicators used for wetland identification throughout the world and described those most likely to be applicable to Queensland conditions. To assess their applicability in Queensland landscapes, the proposed soil indicators were tested in 58 wetlands, representing a range of wetland systems, climatic zones and biogeographical regions.

From the results of this study it is concluded that the formation of soil indicators in Queensland is influenced greatly by climatic region (tropical/equatorial, subtropical, semi-arid and arid), wetland system (palustrine, lacustrine and estuarine) and by inundation frequency (periodically or commonly wet).

Indicators that conclusively identify a wetland soil are the accumulation of organic (decomposed plant) material, the presence of sulfidic material and gleyed soil matrix colours. Other indicators such as mottles, segregations, ferruginous root channel and pore linings, as well as decreasing soil matrix chroma, may be relict landscape features and require careful consideration against the current hydrologic regime in order to aid wetland identification. Soil total carbon content (%) can be reflective of wetland status in specific wetland groups but further analysis is required to develop a quantitative value for total carbon content to define a wetland soil. Several other wetland soil indicators including soil oxygen, redox potential and ferrous iron detection were identified as impractical to utilise because of long monitoring periods and the requirement of expensive monitoring equipment.

Six wetlands in Queensland were monitored in an attempt to observe correlations between soil morphological features, the frequency of inundation and the depth of profile saturation. If a relationship can be determined it would make wetland identification an easier process. Unfortunately, a manufacturer's fault caused six of the twelve data loggers installed in wetlands to fail, limiting the analysis of this trial. From the sites where data was available, there is a good correlation between the depth to which redox features (mottles and segregations) are present and seasonal watertable fluctuations in both clay and organic-dominated soil. Organic matter accumulation was only observed in wetlands that were inundated, even those inundated for short periods (<6 days per year).

To detect reducing or anaerobic conditions in the soil, the Indicator of Reduction In Soils (IRIS) method was trialled at three wetlands in south-east Queensland.

The IRIS method was developed in the United States of America (USA) and showed promising results as a simple and inexpensive test to determine the depth at which anaerobic conditions are present in a wetland soil. Reduction was evident at all three wetland sites, with the level of reduction being correlated to total carbon content, soil textures and frequency of inundation. However, further research will be required to determine the proposed length of time for the test and to further develop the relationships identified.

A key using soil indicators to help identify and delineate Queensland wetland soils was developed during this project. This is a user friendly system for applying soil indicators to aid wetland identification across Queensland. This system uses a weights-of-evidence-based approach, consistent with the Wetlands Definition Guideline, being developed through QWP. This approach allows for more conclusive indicators to be utilised on their own for wetland identification, with the less conclusive indicators supported with landscape information. The key assumes the user has a basic knowledge of landscape and soil functions. To date the key has been developed from broad-scale information collected across Queensland without detailed assessment of individual wetlands. Therefore the key should be used only to provide guidance on wetland identification, realising that exceptions may be common in this early stage of development and that further information may be required in any wetland identification process. It is recommended that further observations of wetlands as outlined in the Wetland Definition Guideline be made to improve the robustness of the key. As more soil information for wetlands in Queensland is collected the key should be further developed, to update and refine the indicators.

1. Introduction

Queensland's wetlands are diverse and widespread with more than four per cent of the state classified as wetlands (EPA 1999). Mapping and classification of Queensland wetlands has recently been undertaken through the QWP (EPA 2005). Wetlands play a number of roles in the environment and are vital for ecosystem function because they act as the ecotone between aquatic and terrestrial environments (Mitsch and Gosslink 1993). As wetlands perform numerous beneficial functions, mapping wetlands and defining the location of individual wetlands is a critical component of wetland management.

In Australia the primary responsibility for managing wetlands rests with the respective Australian and state governments (DEWHA 2008), and because wetlands feature in such a wide variety of landscapes across Queensland, they are affected by many pieces of legislation (http://www.epa.qld.gov.au/wetlandinfo/site/PPL.html). Queensland also has the highest diversity of wetland types in Australia, which increases the need for scientific tools to support the management of these natural resource assets. Mapping and defining where wetlands occur is the first step in effectively managing them. Accurately mapping the distribution and extent of wetlands is important to protect their unique biodiversity and to plan for rural and urban development. This is especially important and challenging in Queensland where climate variability is high in the driest and most climatically variable continent (Gentilli 1971).

Objectives

The aim of the QWP is to support the conservation and management of Queensland's wetlands. In this program the soil indicators project supports the mapping and management of wetlands.

The study had three objectives:

1. ***Refine the knowledge and understanding of soil indicators in Queensland wetlands***

   In Queensland the understanding of wetland soil indicators is poor and their use for wetland identification has not been scientifically tested or incorporated in a management and legislative framework. There is a need to test identified indicators utilised for wetland delineation in other parts of the word across different soil, landform, climate and vegetation associations to ensure that they are appropriate for the Queensland environment.

2. ***Advance the use of soil morphology to identify wetlands***

   Soil indicators, as a tool to identify wetlands have not been utilised in the context of supporting management and the potential development of a regulatory framework in Queensland.

3. ***Develop guidelines for field assessment***

   In addition to developing soil indicators for wetland identification in the Queensland environment, a set of guidelines for their application is required. A scientifically defensible and consistent approach is necessary if the use of wetland soil indicators is to support existing legislation or regulation.

Therefore this study is fundamental to expanding the knowledge of wetland soil in Queensland and will provide a strong basis for further research. The inclusion of soil indicators in management and policy pertaining to wetlands is essential to developing a clear set of guidelines to support other QWP activities.

Introduction

Background

The wetland definition in Queensland

The QWP define a wetland as (EPA 2005):

Areas of permanent or periodic/intermittent inundation, with water that is static or flowing fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed 6 m. To be a wetland the area must have one or more of the following attributes:

i) at least periodically the land supports plants or animals that are adapted to and dependent on living in wet conditions for at least part of their life cycle, or

ii) the substratum is predominantly undrained soils that are saturated, flooded or ponded long enough to develop anaerobic conditions in the upper layers, or

iii) the substratum is not soil and is saturated with water, or covered by water at some time.

Examples under this definition include:

- those areas shown as a river, stream, creek, swamp, lake, marsh, waterhole, wetland, billabong, pool or spring on the latest Sunmap 1:25,000, 1:50,000, 1:100,000 or 1:250,000 topographic map[1]
- areas defined as wetlands on local or regional maps prepared with the aim of mapping wetlands
- wetlands Regional Ecosystems (REs) as defined by the Queensland Herbarium
- areas containing recognised hydrophytes as provided by the Queensland Herbarium
- saturated parts of the riparian zone
- artificial wetlands such as farm dams
- water bodies not connected to rivers or flowing water such as billabongs and rock pools.

Examples under this definition exclude:

- areas that may be covered by water but are not wetlands according to the definition
- floodplains that are intermittently covered by flowing water but do not meet the hydrophytes and soil criteria
- the riparian zone above the saturation level.

The definition is targeted to Queensland conditions with terms like 'intermittent' and 'periodic' in order to capture the ephemeral nature of some arid and tidal environments (EPA 1999). A large proportion of Queensland wetlands are ephemeral and may be dry for many years between periods of inundation.

Wetland boundaries are dynamic, with changes predominantly driven by climate and hydrological cycles. Climate affects wetlands at different spatial scales and over different periods of time. Wetland mapping has traditionally been conducted by examining biotic indicators and surface hydrology and this has been effectively used to map wetlands in Queensland through the QWP Wetlands Mapping and Classification Project at a scale of 1:50,000 or down to 1 ha (EPA 2005). Using these indicators alone in determining wetland boundaries at fine scales can be difficult, especially where wetlands are modified, predominantly ephemeral or there is a broad ecotone between the wetland and adjacent landscape. Soil, and specifically the morphology that develops in soil under wet conditions, changes little over time. In environments where wetland vegetation and hydrology are dynamic there is a need to develop the soil component of the definition to provide a more robust wetland identification tool.

Soil indicators are utilised in other parts of the world for wetland identification, delineation and management. Dear and Svensson (2007), in a pilot study, conducted through QWP reviewed the use of soil indicators internationally and support the use in Queensland for wetland management and identification. A list of soil indicators utilised for wetland delineation, and contextual information that may support wetland identification, was compiled in the pilot study and these are reproduced in Appendix 1. This literature review highlighted the use of hydric soil indicators for wetlands, particularly in North America.

1 This footnote forms part of the original QWP definition. Although the abovementioned Geodata feature codes are generally typical of wetland systems, they are by no means exclusively typical of such systems or an exhaustive list of topographic features which may be wetlands.

However, Queensland landscapes are drier and more weathered, hence hydric soil indicators require extensive testing in the Queensland environment to ensure they are appropriate and are developed in a rigorous scientific process.

Definition of 'upper layers' in a wetland

The QWP definition of a wetland does not quantitatively define the 'upper layers' of the soil profile. For the definition to be used in policy or management this measure needs to be refined to reflect conditions in Queensland wetlands.

Wetland identification systems throughout the world and in particular the USA describe soil profiles to a depth of 0.5 m in order to observe and understand the hydrologic processes occurring at the site. The USA requires most wetland soil indicators to be present in the upper 0.3 m of the soil profile to classify as a jurisdictional wetland. The majority of indicators used in the USA system occur in soil horizons (layers) starting within the top 0.3 m (USDA 2006). As it is not exclusive that all indicators occur within 0.3 m of the soil surface, indicators may start in this layer and extend down the profile. Indicator depths in the USA are correlated to the rooting zone of wetland vegetation, which is where the largest root mass is present (Tiner 1999). If a soil is saturated for periods of time sufficient for wetland vegetation to establish, it is likely that this saturation, and the vegetation roots themselves, will have an effect on soil morphological characteristics. A similar depth has been adopted in the South African model (Marnewecke and Kotze 1999) with indicators occurring in the top 0.3 to 0.4 m below any organic surface layer.

For the purposes of Queensland wetland identification it is proposed to increase the depth within which hydric soil features are exhibited to 0.5 m. This was done to account for the drier and more ephemeral conditions experienced in Queensland.

Impractical soil indicators for wetland identification in Queensland

For indicators to inform decision making there is a need to ensure they are fit for purpose and practical.

Some of the indicators identified by Dear and Svensson (2007) are impractical to record during a single site survey, do not provide enough information to support wetland identification or required the purchase of expensive equipment and monitoring over significant periods to best reflect seasonal watertable variation. For a consistent approach to wetland identification the indicators must be easily described in the field, measurable over time and space, and have the potential to accurately identify a wetland in Queensland. For this reason, several indicators were deemed not to meet these criteria. Table 1 outlines indicators that are currently not recommended for use as wetland soil indicators in Queensland presently and which are not trialled in the current study. Table 2 is a list of the indicators that will be trialled in the current study.

Table 1. Soil indicators currently considered impractical for wetland identification in Queensland

Indicator	Recommendation or limitation
Soil oxygen	Method can be inaccurate without the correct installation of equipment. Time consuming and requires the purchase of expensive equipment
Ferrous iron detection	Can be inaccurate across many soil types and produce false positive results
Redox potential	Expensive and time-consuming method. Does not take into account seasonal variations of anaerobic conditions

Table 2. Soil indicators trialled in the current study

Indicator	
Organic material	Soil–water interface
Streaked organic matter	Oxidised rhizosphere
Gleyed matrix	Pore linings
Redox depletions	Groundwatertable depth
Decreasing matrix chroma, mottle hue and chroma	Cation exchange capacity
Mottles	Particle size analysis
Segregations	Hydrogen sulfide
Mottle and segregation boundaries	Methane gas
Salt profile	
Pyrite present	pH

Frequency and duration of saturation and the effect on soil indicators

The length of inundation or saturation in wetland soil influences the type and intensity of soil hydromorphic characteristics (Vepraskas *et al.* 2004). The relationship between duration and frequency of inundation and the presence of redox features (mottles, segregations and depleted soil colours) is not well understood. If the relationship between the type and abundance of redox features and the frequency and duration of inundation could be explained, it would make wetland identification a simpler process. A number of studies have investigated the correlation between the presence of redox features and saturation with generally positive relationships, but this only holds true for limited climatic ranges and soil types (Vepraskas et al. 2004).

In addition, some features, particularly redox features, may persist in soil from previous drainage regimes. Without current watertable information they can be an inaccurate reflection on the current status of the wetland. Where soil features may exist from previous hydrologic regimes, evidence is required of a current regime for these indicators to be utilised for wetland identification.

Indicator of Reduction In Soils (IRIS)

A new method of determining anaerobic conditions in soil has recently been developed and tested in the USA. The Indicator of Reduction In Soils or IRIS method involves the use of synthetic iron oxides to indicate the presence of reducing conditions in soil. PVC pipes are coated with a paint prepared from a synthetic iron oxide, and placed in the wetland soil. Upon removal the pipes are visually assessed for the loss of the iron oxide paint from the surface, which indicates that reduced conditions are present (Castenson and Rabenhorst 2006, Jenkinson and Franzmeier 2006). The synthetic iron oxide (ferrihydrite) paint is predominantly composed of Fe (III) which gives the paint a distinct reddish colour. Under saturated or anaerobic conditions Fe (III) is quickly reduced to the colourless and highly mobile Fe (II).

This technique has delivered promising results and further research is being conducted in the USA (Rabenhorst and Burch 2006). The IRIS technique is now incorporated in the Hydric Soil Technical Standard notes (USDA 2008), which are an update of the publication Field indicators of hydric soils in the United States (USDA 2006).

2. Methodology

Site selection

The process of selecting wetlands to be sampled for the assessment of appropriate soil indicators was conducted in consultation with numerous Queensland-based soil science, wetland and botany experts. As the field study progressed it was apparent that similar wetlands had differing soil characteristics and that many would need to be sampled to develop the initial relationship between the indicators and climate, soil type and landscapes across Queensland. A total of 58 wetland locations were selected as part of the assessment (Table 3). Although every attempt was made to sample across a wide range of wetland types there are areas in Queensland that are not represented owing to insufficient time and access limitations.

Wetlands sampled during the study were representative of different aspects of the Queensland landscape and focused on areas that were relatively undisturbed or where natural processes dominated. Site selection was based on several criteria: climate, soil type, biogeographical zone and wetland system.

Climatic regions

Four main climatic regions were identified in Queensland by the QWP Wetland Habitat Typology study (QWP 2008). The regions (arid, semi-arid, subtropical and tropical/equatorial) were identified using the Koppen method of climate classification and intersected with the Interim Biogeographical Regionalisation for Australia (IBRA) sub-regions (QWP 2008). It was appropriate to use these regions as a basis for site selection as they represent the main climatic regions in Queensland (Figure 1). A limited number of wetlands occur in the temperate region which was therefore considered a low priority for site selection. For brevity in this document the tropical/equatorial climatic region is referred to hereafter as the tropical climatic region.

Biogeographical zone

Attempts were made to capture representative wetlands in each of Queensland's IBRA bioregions, as the bioregions are influenced by major geomorphic features (IBRA 2008) (Figure 2 and Table 3).

Wetland systems

During site selection a decision was made to focus on palustrine, lacustrine and, where possible, estuarine wetland systems as they are more likely to have soil information that would aid identification. Marine and riverine wetlands were a low priority as the former has a limited soil component and the later has fairly well defined boundaries. The definition of the wetland systems as used by the QWP (2008) are:

Palustrine: primarily vegetated non-channel environments of less than 8 ha. They include billabongs, swamps, bogs, springs, soaks etc. and have more than 30 per cent emergent vegetation.

Lacustrine: open-water dominated systems larger than 8 ha (lakes). This definition also applies to modified systems which possess characteristics similar to lacustrine systems.

Estuarine: those with oceanic water sometimes diluted with freshwater run-off from the land

Existing wetland information

There is an extensive knowledge-base for wetlands across Queensland with many represented in the Directory of Important Wetlands in Australia or DIWA (Environment Australia 2001). The directory is an inventory of nationally important wetlands across Australia with 210 listed in Queensland. Wetlands are included in the directory based on the following criteria:

1. It is a good example of a wetland type occurring within a biogeographic region in Australia.
2. It is a wetland which plays an important ecological or hydrological role in the natural functioning of a major wetland system/complex.
3. It is a wetland which is important as the habitat for animal taxa at a vulnerable stage in their life cycles, or provides a refuge when adverse conditions such as drought prevail.
4. The wetland supports 1% or more of the national populations of any native plant or animal taxa.
5. The wetland supports native plant or animal taxa or communities which are considered endangered or vulnerable at the national level.

6. The wetland is of outstanding historical or cultural significance.

During the site selection process the initial focus was on DIWA wetlands that fulfilled criteria 1, 2 and 3. The DIWA was considered a good starting point as the QWP Wetland Mapping and Classification project had not completed all of the mapping for Queensland when the project began.

Soil types

Wetland soil indicators can vary greatly between soil texture groups; therefore it was important to sample across soil types to establish the relationship between soil indicators and different soil textures. Soils were divided into organic and non-organic soil groups, with the non-organic soils further split into sands and clays.

A full list of wetlands selected with brief descriptions is given in Appendix 2. Table 3 provides a summary of the wetland areas sampled in this study and Table 4 provides a summary of generalised categories of wetlands sampled during the study.

Table 3. **Wetland areas sampled in soil indicator study**

Wetland name	Climatic region	IBRA sub-region	In DIWA	Wetland system	Wetland type
Diamantina overflow swamps—Durrie Station	Arid	Channel country	Yes	Palustrine	Arid floodplain swamp
Cooper Creek overflow swamps	Arid	Channel country	Yes	Palustrine	Arid floodplain swamp
Lake Mipia Area	Arid	Channel country	Yes	Lacustrine	Arid floodplain lake
Lake Didichie (Moonda Lake Area)	Arid	Channel country	Yes	Lacustrine	Arid floodplain lake
Lake Nappernicia	Arid	Channel country	No	Lacustrine	Arid non-floodplain swamp
Lake Machattie	Arid	Channel country	Yes	Lacustrine	Arid floodplain lake
Eyre Creek overflow swamps (2 locations)	Arid	Channel country	Yes	Palustrine	Arid floodplain swamps
Arid zone closed depression	Arid	Channel country	No	Palustrine	Arid floodplain swamp
Semi-arid closed depression	Semi-arid	Mulga Lands	No	Palustrine	Semi-arid floodplain swamp
Lake Numulla	Semi-arid	Mulga Lands	Yes	Lacustrine	Semi-arid floodplain lake
Lake Wyara	Semi-arid	Mulga Lands	Yes	Lacustrine	Semi-arid saline lake
Lake Kapoonyee	Semi-arid	Mulga Lands	No	Lacustrine	Semi-arid floodplain lake
Lake Bindegolly	Semi-arid	Mulga Lands	Yes	Lacustrine	Semi-arid floodplain lake
Wyandra claypans aggregation	Semi-arid	Mulga Lands	Yes	Palustrine	Semi-arid floodplain swamp
Lake Dartmouth	Semi-arid	Mulga Lands	Yes	Lacustrine	Semi-arid floodplain lake
Murrawondah Lakes (2 locations)	Semi-arid	Mulga Lands	Yes	Lacustrine	Semi-arid floodplain lakes
Lake Wombah	Semi-arid	Mulga Lands	Yes	Lacustrine	Semi-arid floodplain lake
Currawinya claypan	Semi-arid	Mulga Lands	No	Palustrine	Semi-arid floodplain swamp
Eubenangee Swamp (2 locations)	Tropical	Wet Tropics	Yes	Palustrine	Coastal and sub-coastal floodplain grass, sedge, herb swamp

Wetland name	Climatic region	IBRA sub-region	In DIWA	Wetland system	Wetland type
Tam O'Shanter NP	Tropical	Wet Tropics	Yes	Palustrine	Coastal and sub-coastal floodplain tree swamp (palm)
Bribie Island (2 locations)	Subtropical	South-east Queensland	Yes	Palustrine	Coastal and sub-coastal non-floodplain grass, sedge herb swamp and coastal and sub-coastal non-floodplain tree swamp (melaleuca and eucalyptus spp.)
Wivenhoe Dam	Subtropical	South-east Queensland	No	Lacustrine (artificial wetland)	No type—artificial
North Stradbroke Island (3 locations)	Subtropical	South-east Queensland	Yes	Lacustrine and Palustrine	Coastal and sub-coastal non-floodplain sand lake (perched) and coastal and sub-coastal non-floodplain grass, sedge, herb swamp
Carbrook Wetlands aggregation	Subtropical	South-east Queensland	Yes	Palustrine	Coastal and sub-coastal floodplain trees swamp (melaleuca and eucalyptus spp.)
Goorganga Plain (3 locations)	Subtropical	Central Queensland coast	Yes	Palustrine and estuarine	Coastal and sub-coastal floodplain grass, sedge, herb swamp and no type - estuarine wetland

Wetland name	Climatic region	IBRA sub-region	In DIWA	Wetland system	Wetland type
Cape Flattery (2 locations)	Tropical	Cape York	Yes	Lacustrine and palustrine	Coastal and sub-coastal non-floodplain grass, sedge, herb swamp and coastal and sub-coastal non -floodplain sand lake (window)
Marina Plains—Lakefield aggregation (4 locations)	Tropical	Cape York	Yes	Palustrine	Coastal and sub-coastal floodplain grass, sedge, herb swamp and coastal and sub-coastal floodplain tree swamp (melaleuca and eucalyptus spp.)
Batavia Downs ferricrete ring swamp	Tropical	Cape York	No	Palustrine	Coastal and sub-coastal non-floodplain tree swamp (melaleuca and eucalyptus spp.)
Archer River swamp	Tropical	Cape York	No	Palustrine	Coastal and sub-coastal non-floodplain tree swamp (melaleuca and eucalyptus spp.)
Northern Holyroyd Plain aggregation	Tropical	Cape York	Yes	Palustrine	Coastal and sub-coastal floodplain tree swamp (melaleuca and eucalyptus spp.)
Southern Gulf aggregation (2 locations)	Tropical	Gulf Plains	Yes	Palustrine and estuarine	Coastal and sub-coastal non-floodplain grass, sedge, herb swamp and No type—estuarine
Normanton Marine Plain	Tropical	Gulf Plains	No	Estuarine	No type — estuarine wetland

2. Methodology

Wetland name	Climatic region	IBRA sub-region	In DIWA	Wetland system	Wetland type
Double Lagoon	Tropical	Gulf Plains	No	Palustrine	Coastal and sub-coastal floodplain tree swamp (melaleuca and eucalyptus spp.)
12 Mile waterhole	Tropical	Gulf Plains	No	Palustrine	Coastal and sub-coastal floodplain grass sedge herb swamp
Smithburne - Gilbert Fan aggregation (2 locations)	Tropical	Gulf Plains	Yes	Palustrine	Coastal and sub-coastal floodplain grass, sedge, herb swamp
Melaleuca citrolens chain of pools	Tropical	Gulf Plains	No	Palustrine	Coastal and sub-coastal non-floodplain tree swamp (melaleuca and eucalyptus spp.)
Melaleuca viridiflora drainage depressions (3 locations)	Tropical	Gulf Plains	No	Palustrine	Coastal and sub-coastal floodplain tree swamps (melaleuca and eucalyptus spp.)
Drainage depression near Staaten River	Tropical	Gulf Plains	No	Palustrine	Coastal and sub-coastal floodplain tree swamp (melaleuca and eucalyptus spp.)
St George - Balonne River floodplain (2 locations)	Semi-arid	Brigalow Belt	Yes	Lacustrine	Semi-arid floodplain lakes
Condamine wetlands	Subtropical	Brigalow Belt	No	Palustrine	Coastal and sub-coastal floodplain tree swamp (melaleuca and eucalyptus spp.)
Goondiwindi wetlands	Subtropical	Brigalow Belt	No	Palustrine	Coastal and sub-coastal floodplain tree swamp (melaleuca and eucalyptus spp.)

Table 4. Generalised categories of wetlands sampled in soil indicator study

Climatic region	% of wetlands sampled	Wetland system	% of wetlands sampled
Tropical	41	Palustrine	65
Subtropical	21	Lacustrine	29
Semi-arid	22	Estuarine	5
Arid	16		

2. Methodology

Figure 1. Wetland areas sampled across climatic regions

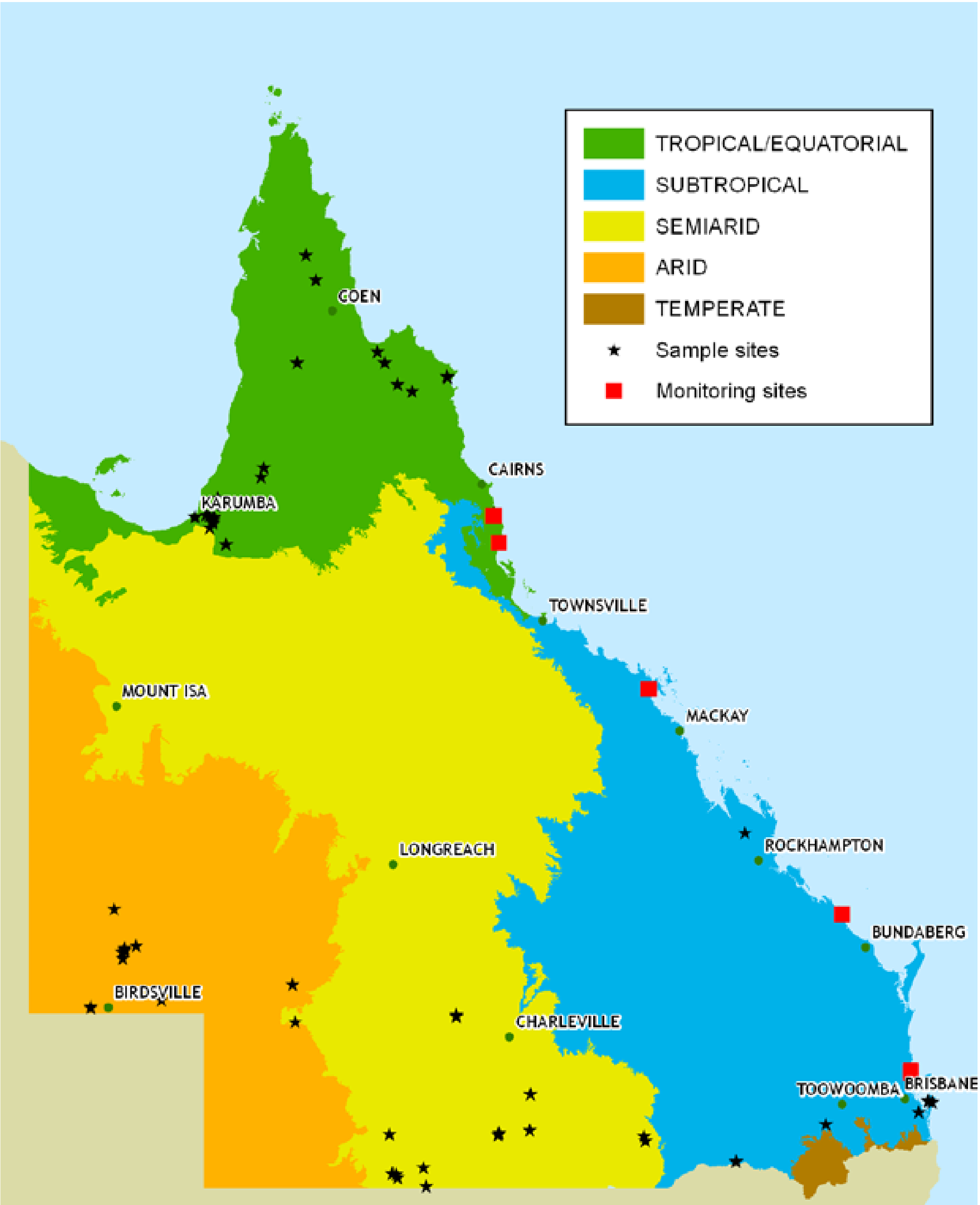
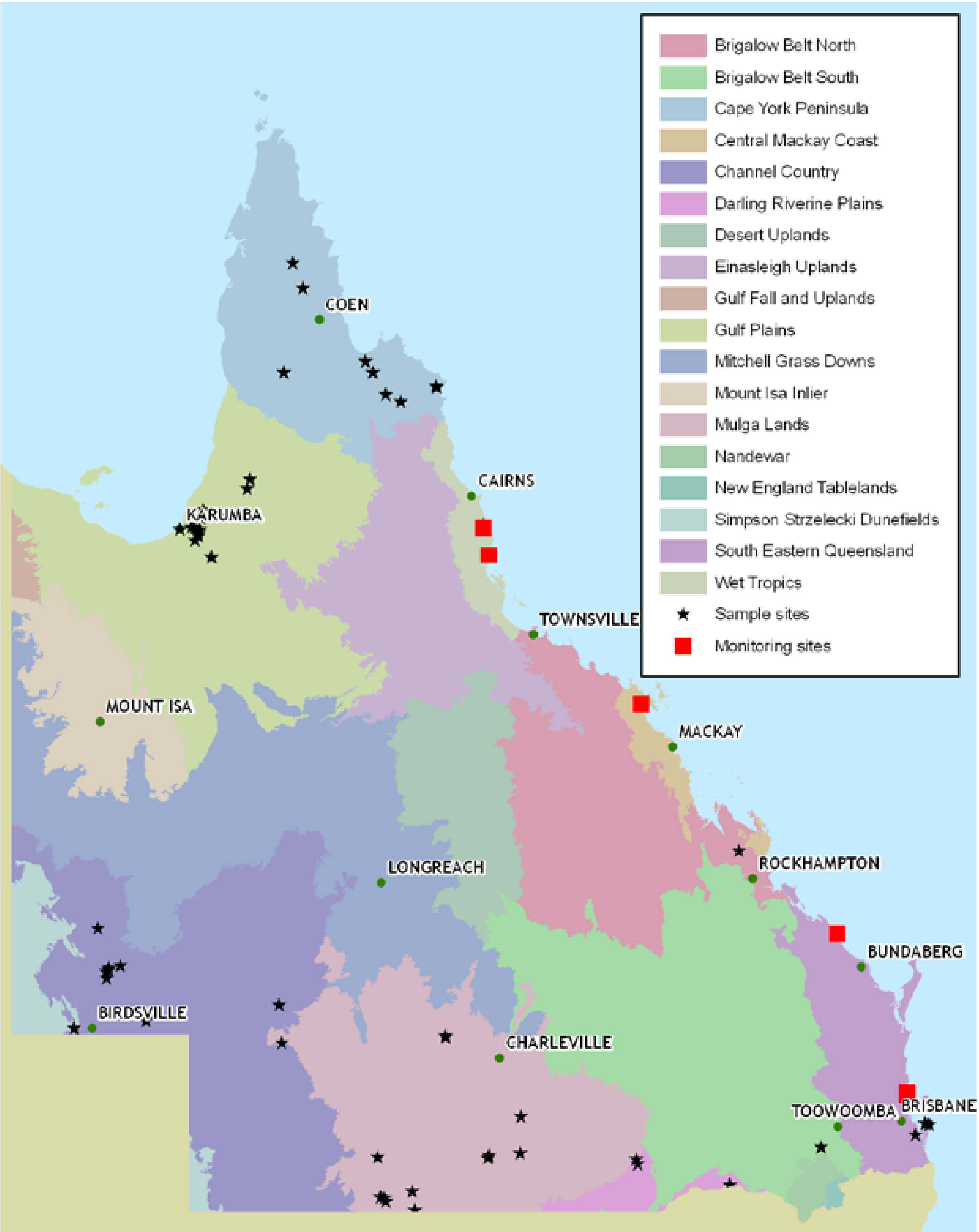


Figure 2. Wetland areas sampled across biogeographical regions



Wetland groups

Wetlands were grouped to examine the differing soil indicators that formed between them. These groups were based on climatic regions, whether they were palustrine, lacustrine or estuarine wetland systems and whether they were periodically inundated (either seasonally or intermittently) or commonly wet (inundated permanently in most years).

Table 5. Matrix of wetland groups studied according to climatic region, wetland system and degree of inundation

	Tropical	Subtropical	Semi-arid	Arid
Palustrine				
Periodically inundated	✓	✓	✓	✓
Commonly wet	✓	✓		
Lacustrine				
Periodically inundated			✓	✓
Commonly wet	✓	✓		
Estuarine				
Periodically inundated	✓	✓		
Commonly wet				

Table 5 identifies the groups included in this study. It should be noted that as the soil work was focused on site-specific wetlands the degree of inundation was considered an important attribute in determining soil indicators. The groups described below are specific to soil work alone as inundation frequency is not incorporated in the wetland types described by the QWP habitat typology (QWP 2008).

Site sampling procedures

Transect sampling was used to capture changes occurring across the ecotone of the wetland with a minimum of one transect per wetland area sampled. Transects crossed the margin of the wetland where the broadest transition zone was present. Sites along the transect were chosen with reference to landform and vegetation (Figure 3).

It is important to define the different zones in which sites along transects were selected. These definitions will be utilised throughout the document.

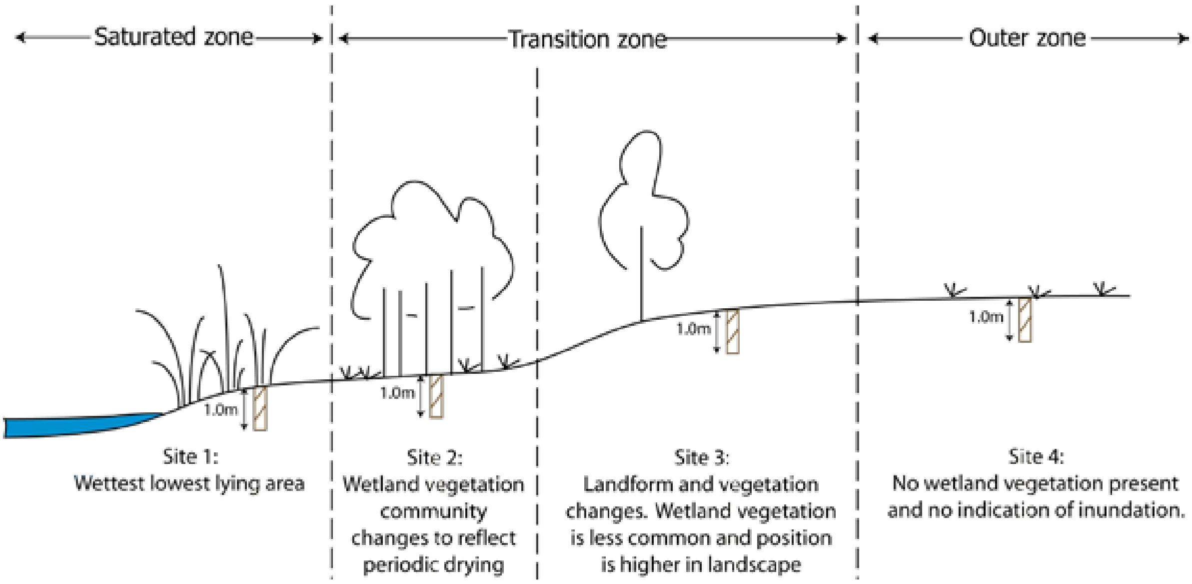
Transects identified three primary zones: saturated, transitional and outer. These zones can be characterised as:

1) Saturated zone: The wettest lowest-lying area at a wetland location. For wetlands that were dry when sampled this was the lowest part of the wetland that could be accessed. For wetlands that were inundated when sampled this is the area at the water's edge.

2) Transition zone: This area appeared to be inundated intermittently or seasonally. There is evidence of saturation through vegetation or landform features. The transition zone may have many sites sampled to reflect different changes in vegetation and landform.

3) Outer zone: Above the high-water mark.
No evidence of inundation at any time.
This constitutes non-wetland areas.

Figure 3. Diagrammatic representation of transect sampling at a wetland location



Descriptions and laboratory analysis

Soils were described and sampled to a depth of 1.0 m where possible, with the presence or absence of wetland indicators listed in Appendix 1 recorded.

The study focused on looking at the surface 0.5 m of the soil profile; however, soils were described to 1.0 m to gain an understanding of the processes occurring at the site. Microrelief and other surface characteristics as well as hydrophytic flora and fauna were also described.

Laboratory analysis was conducted for each soil profile with soils sampled (where possible) at 0–0.1 m, 0.2–0.3 m and 0.4–0.5 m depths. Every sample was analysed for pH, electrical conductivity (EC), nitrate (NO_3^-), and chloride (Cl^-) to confirm field observations. Every sample was also analysed for total carbon (TC) and total nitrogen (TN). Additional testing, performed on selected sites, included cations, trace elements and analysis for sulfidic material. All analyses were consistent with national standards in field sampling and laboratory analysis.

Indicator depth analysis

The depth within which soil indicators were observed was analysed to determine the depths where soil indicators must be present to classify as a wetland soil. This depth will clarify the term 'upper layers' in the current QWP definition.

Two groups of wetland sample sites were analysed; those in the saturated zone and those in the transition zone. As sites in the outer zone exhibit minimal hydric soil indicators they were not included in the analysis. In total, 54 wetlands (out of the 58 sampled for the study) were included in this analysis. Four wetlands were excluded from the analysis as they had sites in the saturated zone where their total described soil depth was less than 0.3 m or the wetland did not have a well defined transition zone.

Soil indicators were observed:

- within 0.3 m of the soil surface
- within 0.3–0.5 m of the soil surface
- below 0.5 m.

Results from this analysis are presented in the determining depth to wetland soil indicators section on page 19.

2. Methodology

Monitoring trial

A monitoring trial was conducted to study the relationship between length and frequency of inundation and the effect on soil indicators. Water level monitoring equipment (Figure 4) was installed at six wetlands to provide information on the:

- frequency of inundation
- duration of inundation
- depth of saturation in the soil profile.

This data was compared to the wetland soil indicators described for each soil profile.

The selected monitoring sites were a subset of the wetlands sampled outlined in Table 3. Monitoring locations were chosen based on climatic zone, soil type and wetland system. Given the 18-month timeframe of the study and the need to monitor at least one wet–dry cycle, climatic regions with seasonally reliable rainfall (subtropical and tropical) were chosen. Freshwater palustrine wetlands were targeted to limit the amount of variation that would inevitably occur in a short-term study. Similarly, wetlands with soil textures ranging from organic to sand and clay were targeted to capture the different soil features that may have formed. The wetlands selected for the monitoring trial were:

- Eubenangee Swamp (northern transect) (No.14, Appendix 2)
- Tam O'Shanter NP (No. 1, Appendix 2)
- Goorganga Plain (No. 23, Appendix 2)
- Deepwater NP (location used in pilot study Svensson and Dear 2007)
- Bribie Island—lower swamp crossing (No. 22, Appendix 2)
- Bribie Island—middle swamp crossing (No. 27, Appendix 2)

Water-table well installation

Two watertable wells were installed at each of the six wetlands—one in the saturated zone and the other in the transition zone (Figure 5).

Data loggers recorded water-level depth (surface and groundwater) and temperature daily at six-hourly intervals (0300, 0900, 1500, 2100). The results from the trial are discussed in the monitoring trial section on page 45.

Figure 4. Components of water-table wells and installed water-table well at Deepwater National Park.

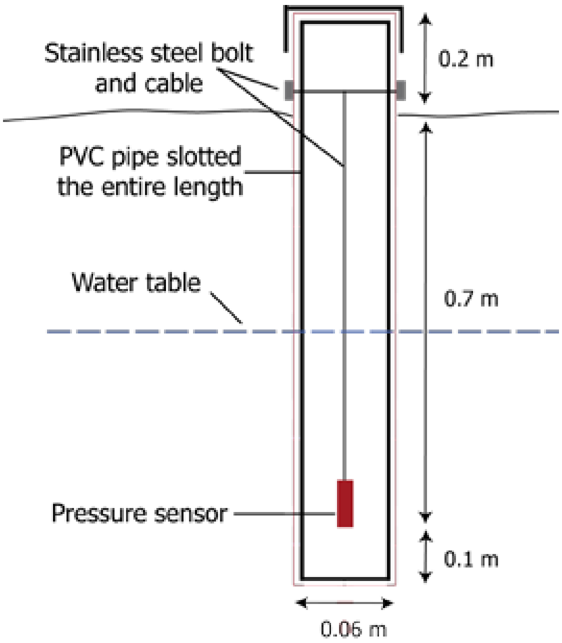
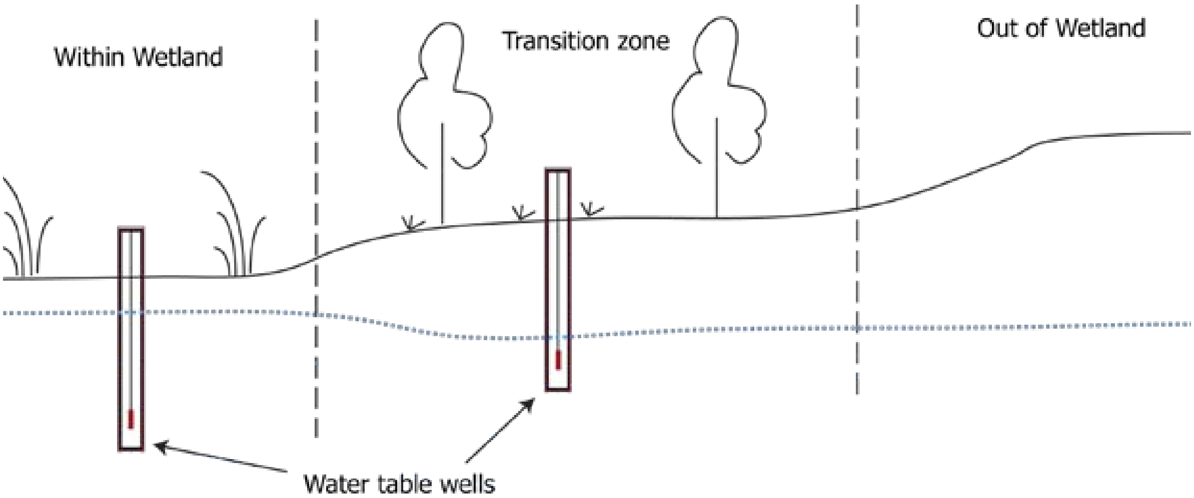


Figure 5. Depiction of water-table wells installed along transect



Indicator of Reduction In Soils (IRIS) trial

The IRIS method was trialled in several Queensland wetlands to determine if it would give an accurate indication of the depth to which anaerobic conditions were present. The results were compared to the inundation frequency and soil features of the wetlands. This test is inexpensive and less time consuming than others to determine a reduced environment in soils. It could help determine if anaerobic conditions are present in soil where easily identifiable hydric soil indicators are not present—i.e. due to the natural lack of iron there is less likelihood of soil dominated by sand producing features such as mottles, ferruginous root linings and segregations.

Site selection

The trial was undertaken at three wetlands in the subtropical climatic region in south-east Queensland. These were a subset of the wetlands sampled outlined in Table 3. The wetlands were chosen for their proximity to Brisbane for ease of access in installing and removing the trial pipes.

The three wetlands were:

- Bribie Island—lower swamp crossing (No. 22, Appendix 2)
- Bribie Island—middle swamp crossing (No. 27, Appendix 2)
- Carbook Wetlands aggregation (No. 26, Appendix 2)

Synthesis of ferrihydrite paint and construction of pipes

The method for synthesis of the ferrihydrite paint is described in Appendix 4.

The PVC pipes were cleaned and sanded before application of paint. Two pipes were inserted into the soil at 13 previously described sample sites, giving a total of 26 pipes at Bribie Island and Carbrook. A method was devised to minimise paint loss from the surface of the painted pipes. An unpainted PVC pipe of the same length and width was first inserted into the soil, removed and replaced by a painted pipe in one fluid movement, attempting not to rotate the painted pipe during insertion.

After 21 days the tubes were carefully removed, again attempting not to rotate them. Immediately after removal the tubes were washed with de-ionised water, photographed and inspected for evidence of reduction. Some paint removal was observed to have occurred due to insertion or extraction of the pipes; however, the marks left were very distinctive, and can be easily disregarded upon final inspection (Figure 6). Results from this trial are discussed in the Indicator of Reduction in Soils trial section on page 50.

Figure 6. Narrow strips of ferrihydrite paint removed on installation

Installation marks

15cm

3. Results

3

Determining depth to wetland soil indicators

Wetland soil indicators (Appendix 1) were recorded within 0.3 m of the soil surface for the majority of the wetlands sampled for sites in both the saturation zone and in the transition zone (Figure 7). For most of these sites, indicators extended to depths of 0.5 m and many sites had indicators beyond this depth. There is no compelling evidence from the sites studied to suggest that a depth below 0.3 m is required for indicators to be present to enable identification of a wetland soil in Queensland.

Soil indicator trends between climatic regions

Climate is an important driver determining the presence of several soil indicators. Initial analysis of the study sites showed several differences and broad trends between indicators across climatic regions irrespective of wetland type (Table 6). Climatic regions or, more importantly, rainfall and evaporation are major drivers for the frequency and duration of saturation in wetlands.

The presence of organic material and total carbon levels differed significantly between climatic regions.

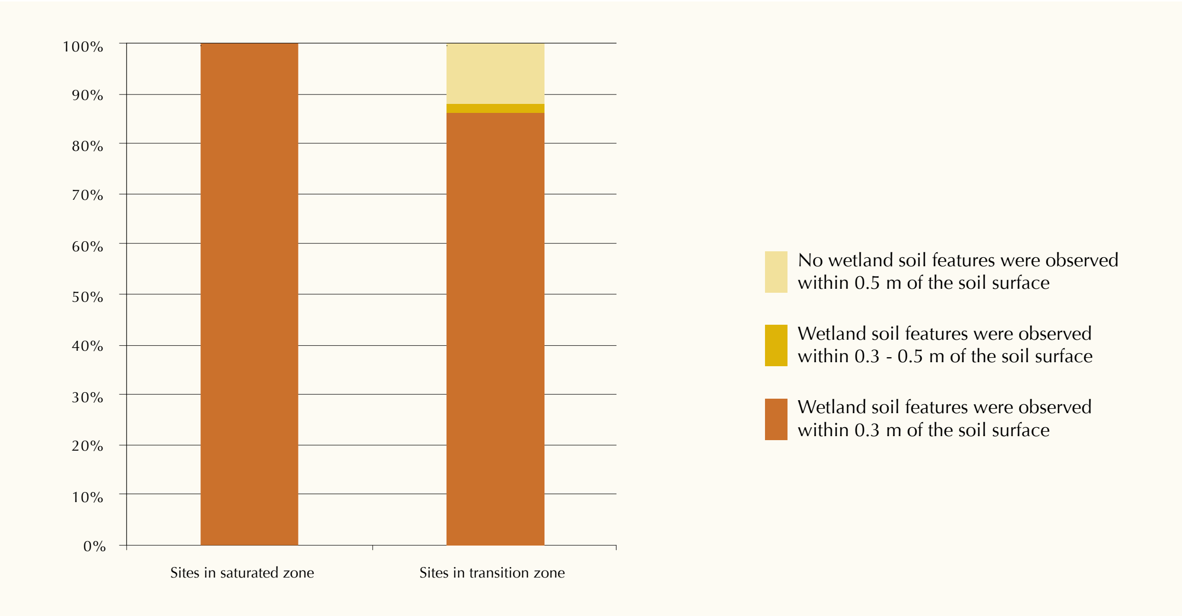
Organic material was observed in the majority of wetlands in the subtropical climatic region and in a few wetlands in the tropical climatic region but not in the arid or semi-arid climatic region.

The average total carbon content (in the surface 0.1 m) for sites in the saturation zone ranged from 18.8 per cent in the subtropical region to 0.22 per cent in the arid region (Figure 8).

Sites sampled in the saturated zone showed trends in soil matrix chroma values between different climatic regions. Vepraskas (1998) suggests that soils with chroma values of less than 2 have been saturated for long periods. Chroma values of 1 were recorded for all sites in the subtropical region, the majority of sites in the tropical region and in areas that appeared to be permanently inundated in the semi-arid region. Wetlands in the arid region and semi-permanent wetlands of the semi-arid region had chroma values of 2 or 3 for sites in the saturated zone.

Indicators such as mottles, segregations, ferruginous root channel and pore linings and sulfidic material were identified across all climatic regions with no general trends apparent.

Figure 7. Trends between indicators identified in upper 0.3 m and 0.5 m of the soil profile



3. Results

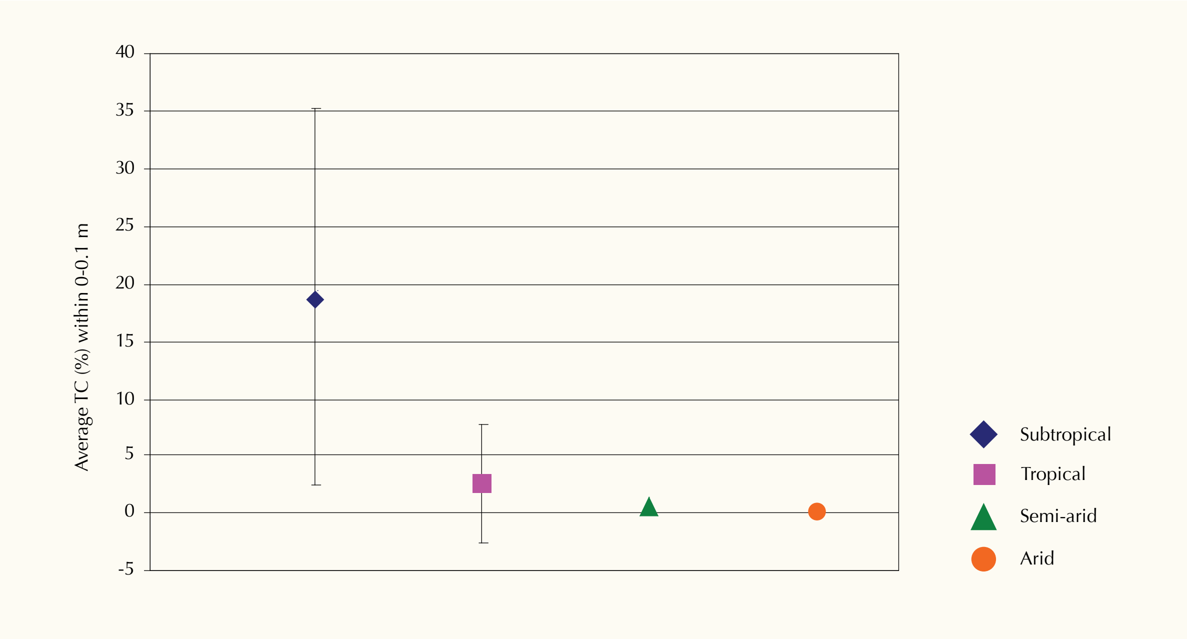
Table 6. Wetland soil indicators observed across different climatic regions for wetlands sampled in this study

Indicators	Tropical	Sub-tropical	Semi-arid	Arid
Organic material	Observed in few wetlands	Observed in majority of wetlands	No organic material observed	No organic material observed
Streaked organic material	Streaked organic material observed in two wetlands	No streaked organic material observed	No streaked organic material observed	No streaked organic material observed
Total carbon content*	0.07% to 24.3%	0.54% to 41%.	All sites <2%	All sites <1%
Mottles	Observed in majority of wetlands	Observed in majority of wetlands	Observed in majority of wetlands	Observed in majority of wetlands
Segregations (iron and manganese)	Observed in majority of wetlands	Not observed in majority of wetlands	Not observed in majority of wetlands	Not observed in majority of wetlands
Soil chroma <2**	Observed in majority of wetlands	Observed in majority of wetlands	Observed in majority of wetlands	Wetland chroma values 2 or greater in majority of wetlands
Ferruginous root channels and pore linings	Observed in majority of wetlands	Observed in majority of wetlands	Observed in majority of wetlands	Not observed in majority of wetlands
Acid sulfate material	Observed in coastal wetlands influenced by the input of seawater	Observed in coastal wetlands influenced by the input of seawater	Observed in 2 of 13 wetlands sampled	None observed
Soil–water interface	None observed	None observed	Observed at one wetland	None observed

*Dumas method

**Chroma values taken from the sites in saturated zone

Figure 8. Climatic region trends in average total carbon percentage (TC%) in the upper 0.1 m for sites in the saturated zone.



3. Results

Soil indicator trends in climatic regions

Geomorphic descriptions for sites are used when conducting soil investigations. Where possible these descriptions have been incorporated into the wetland types described in the QWP habitat typology. Table 7 outlines the some of the geomorphic descriptions used for the wetlands sampled during this study and the corresponding wetland types.

Tropical climatic region

Many wetland types were sampled in the tropical climatic region including:

- coastal and sub-coastal non-floodplain tree swamp—palm
- coastal and sub-coastal non-floodplain grass, sedge and herb swamp
- coastal and sub-coastal non-floodplain tree swamp—melaleuca and eucalypt spp.
- coastal and sub-coastal floodplain grass, sedge and herb swamp
- coastal and sub-coastal floodplain tree swamp—melaleuca and eucalypt spp.
- coastal and sub-coastal non-floodplain sand lake—window

Two estuarine systems were also sampled but are not classified under the QWP habitat typology.

Every transect sampled had a site located in the saturated zone. However, there were transects that did not have an obvious transition zone, had multiple sites in the transition zone or did not have a site in the outer zone.

There were four distinct wetland groups represented in the tropical climatic region (as outlined in Table 5).

Table 7. Geomorphic and corresponding QWP habitat typology descriptions

Geomorphic description	Corresponding wetland type
Drainage depression	Coastal, semi-arid or arid floodplain or non-floodplain swamp (all water regimes, soil and vegetation types)
Closed depression	Coastal, semi-arid and arid floodplain or non-floodplain swamp (all water regimes, soil and vegetation types)
Oxbow (current and relict)	Coastal, semi-arid or arid floodplain lake (all water regimes, soil and vegetation types)
Lagoon	Coastal floodplain or non-floodplain swamp (all water regimes, soil and vegetation types)
Swale	Coastal non-floodplain swamp (all soil and vegetation types)
Dune lake	Coastal non-floodplain sand lake—perched or window
Tidal flat (Intertidal and supratidal)	Estuarine system—not included in typology
Lake	Coastal, semi-arid or arid floodplain or non-floodplain lake (all soil types and water regimes)
Playa	Semi-arid and arid floodplain and non-floodplain lakes (all water regimes)

1) Tropical: palustrine—periodically inundated

The wetlands sampled in this group are numbers 1–13; Appendix 2, Plate 1. All wetlands sampled appeared to be seasonally inundated. The wetland soil indicators observed or measured, compared to the total number of sites sampled along the transect, are outlined in Table 8.

- Half of the sites described outside the wetland had mottling present as a result of the regional hydro-pedological environment. Soil texture did not appear to affect the presence of mottling, though most wetlands sampled had clay textures.
- Mottling was observed in sandier soils in the saturated zone and outer zone of the wetland.
- The higher number of segregations recorded in the drier transition zone is consistent with segregation formation being promoted by periodic saturation rather than continuous saturation.
- Soil matrix chroma of less than or equal to 2 was observed in the majority of sites along the transect. This can be attributed to the seasonality of rainfall in the tropical region. As the landscape is seasonally saturated this may lead to low chroma values in soil outside the wetland environment.

Table 8. Indicators within 0.3 m of the soil surface for tropical palustrine—periodically inundated wetlands

Indicators	Saturated zone	Transition zone	Outer zone
Organic material	1/16	0/18	0/14
Average TC(%) for 0–0.1 m	1.26%	1.00%	1.05%
Mottling	16/16	12/18	7/14
Segregations	3/16	6/18	4/14
Ferruginous root channels and pore linings	8/16	7/18	4/14
Sulfidic material	0/16	0/18	0/14
Soil chroma ≤2	12/16	14/18	9/14

3. Results

1

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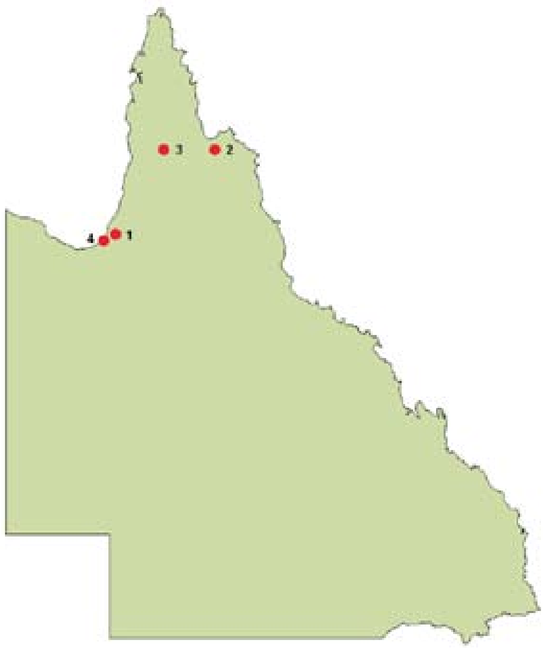
Plate 1.

1. Coastal and sub-coastal floodplain tree swamp (melaleuca and eucalyptus spp.), Karumba, north Queensland.
2. Coastal and sub-coastal floodplain grass, sedge, herb swamp, Lakefield NP, north Cape York Peninsula.
3. Coastal and sub-coastal floodplain tree swamp (melaleuca and eucalyptus spp.), northern Holyroyd Plain, Cape York Peninsula.
4. Coastal and sub-coastal non-floodplain grass. sedge, herb swamp , Karumba, north Queensland



2) Tropical: palustrine—commonly wet

The wetlands sampled in this group are numbers 15-18; Appendix 2, Plate 1. The wetland soil indicators observed or measured, from the total number of sites sampled along the transect, are outlined in Table 9.

Two transects in this wetland type had soils classified as Organosols by the Australian Soil Classification or ASC (Isbell 2002). Organosols are by definition predominantly composed of organic material and this skewed the results of the TC(%) analysis. To differentiate TC(%) levels between transect sites the soils were split into two groups: organic soils and non-organic soils.

- Streaked organic material was observed at one site in a coastal dune system dominated by sandy soils.
- Mottling was observed in organic soils and clay soils but not in the sandier soil.
- Segregations were not observed in organic or sandy soils.
- Ferruginous root channel and pore linings were not observed in organic or sandy soils.
- Soil matrix chroma did not provide an indication of the wetland boundary in those dominated by sandy soils.

Table 9. Indicators within 0.3 m of the soil surface for tropical palustrine—commonly wet wetlands

Indicators	Saturated zone	Transition zone	Outer zone
Organic material	2/5	2/7	0/4
Streaked organic material	1/5	0/7	0/4
Average TC(%) for 0–0.1 m (all soils)	7.9%	4.1%	3.0%
Average TC(%) for 0–0.1 m (organic soils)	16.6%	8.1%	5.6%
Average TC(%) for 0–0.1 m (non-organic soils)	2.1%	1.1%	0.45%
Mottling	2/5	5/7	0/4
Segregations	0/5	1/7	0/4
Ferruginous root channels and pore linings	1/5	1/7	1/4
Sulfidic material	0/5	0/7	0/4
Soil chroma ≤2	5/5	6/7	2/4

3. Results

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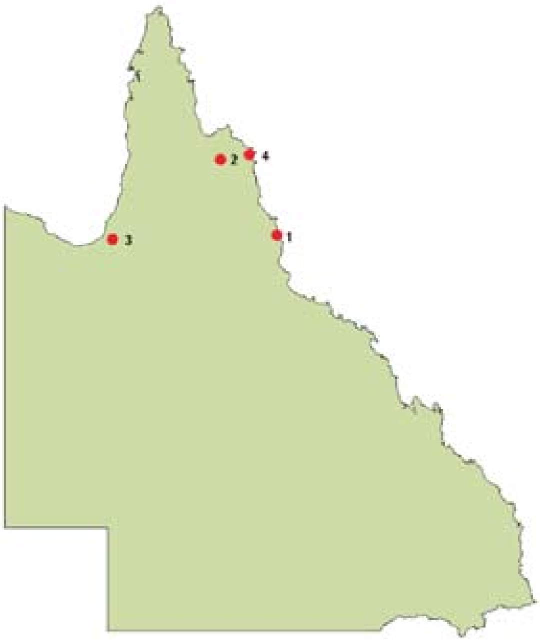


Plate 2.

1. Coastal and sub-coastal floodplain grass, sedge, herb swamp, Eubenangee Swamp, north Queensland.
2. Coastal and sub-coastal floodplain grass, sedge, herb swamp, Lakefield NP, Cape York Peninsula.
3. Coastal and sub-coastal floodplain grass, sedge, herb swamp, Normanton , north Queensland.
4. Coastal and sub-coastal non-floodplain grass, sedge, herb swamp, Cape Flattery, Cape York Peninsula.

3) Tropical: lacustrine—commonly wet

One wetland was sampled in this wetland group. This was number 19; Appendix 2, Plate 3. The wetland soil indicators observed or measured, from the total number of sites sampled along the transect, are outlined in Table 10.

- Streaked organic matter was observed at two sites dominated by sandy soils.
- Mottles were observed in the transition zone which would be subject to more periodic saturation allowing the formation of mottles, even in sandier soil.
- Soil matrix chroma was not a good indicator of the wetland boundary as low chroma values were observed at all sites along the transect.

Table 10. Indicators within 0.3 m of the soil surface for tropical lacustrine—commonly wet wetlands

Indicators	Saturated zone	Transition zone	Outer zone
Organic material	2/2	1/1	0/1
Streaked organic matter	2/2	0/1	0/1
Average TC(%) for 0–0.1 m	2.3%	0.4%	0.78%
Mottling	0/2	1/1	0/1
Segregations	0/2	0/1	0/1
Ferruginous root channels and pore linings	0/2	0/1	0/1
Sulfidic material	0/2	0/1	0/1
Soil chroma ≤2	2/2	1/1	1/1

Plate 3.
Coastal and sub-coastal non-floodplain sand lake (window), Cape Flattery dune lakes, Cape York Peninsula.

4) Tropical: estuarine—periodically inundated

The two wetlands sampled in this group are numbers 20–21; Appendix 2, Plate 4. One wetland was on a relict marine plain and one on a supratidal flat. There were several significant differences between the indicators observed at each wetland. The wetland soil indicators observed or measured, from the total number of sites sampled along the transect, are outlined in Table 11.

- TC was significantly different between the two wetlands sampled. TC increased moving into the wetland in the supratidal flat giving a good indication of the wetland boundary. The lower result for the transition zone can be attributed to the site being on a scalded area with no vegetation present.
- The increase in total carbon content moving from the saturated zone to the outer zone on the relict marine plain can be attributed to the increase in vegetation growth. The saturated zone was a scalded flat with no vegetation, a result of down-cutting from the surrounding environment, with the lower areas more saline and hostile to vegetation growth. With no seasonal growth there is no organic matter accumulation regardless of the duration of saturation.Moving higher in the landscape to the transition zone halophytes and grasses were present.
- Ferruginous root channel and pore linings were present at both wetland areas in sites where there was vegetation growth. These indicators were not observed in the scalded sites.
- Sulfidic material was observed at the sites in the saturated zone for both transects. Sulfidic material was confirmed by field tests and the observation of sulfurous segregations (or yellow jarosite).
-

Table 11. Indicators within 0.3 m of the soil surface for tropical estuarine—periodically inundated wetlands

Indicators	Saturated zone	Transition zone	Outer zone
Organic material	1/2	0/3	0/2
TC(%) for 0–0.1 m (extratidal flat)	1.42%	0.07%	0.91%
TC(%) for 0–0.1 m (relict marine plain)	0.21%	0.45%	1.23%
Mottling	2/2	3/3	2/2
Segregations	0/2	1/3	1/2
Ferruginous root channels and pore linings	1/2	2/3	1/2
Sulfidic material	2/2	0/1	0/2
Soil chroma ≤2	1/2	2/3	1/2

1

2

Plate 4.

1. Relict marine plain, Karumba, north Queensland.
2. Supratidal flat, Normanton, north Queensland.

Subtropical climatic region

Many wetland types were sampled in the subtropical climatic region including:

- coastal and sub-coastal non-floodplain grass, sedge and herb swamp
- coastal and sub-coastal non-floodplain tree swamp—melaleuca and eucalyptus spp.
- coastal and sub-coastal non-floodplain sand lake—perched
- coastal and sub-coastal floodplain grass, sedge and herb swamp
- coastal and sub-coastal floodplain tree swamp—melaleuca and eucalyptus spp.

One estuarine wetland was also sampled but is not classified under the QWP habitat typology.

There were four distinct wetland groups represented in the subtropical climatic region (as outlined in Table 5).

1) Subtropical: palustrine—periodically inundated

The wetlands sampled in this group are numbers 22–26; Appendix 2, Plate 5. Despite being in the same wetland group the wetlands could be further split into differing categories: wetlands that were seasonally inundated (numbers 22, 23 and 26) and wetlands subject to intermittent inundation (numbers 24 and 25).The wetland soil indicators observed or measured, from the total number of sites sampled along the transect, are outlined in Table 12.

- Organic material was observed in sand and clay soils in the seasonally inundated wetlands. Organic material was not observed in any of the intermittently inundated wetlands.
- Ferruginous root channel and pore linings were a good indicator for wetland identification as they were not observed at sites in the outer zone. Ferruginous root channel and pore linings were only recorded in clay soils.
- Sulfidic material was observed at one location in the saturated zone that was influenced by the input of seawater.

Table 12. Indicators within 0.3 m of the soil surface for subtropical palustrine—periodically inundated wetlands

Indicators	Saturated zone	Transition zone	Outer zone
Organic material	3/5	3/7	2/4
Average TC(%) for 0–0.1 m (all soils)	12.4%	10.5%	2.5%
Average TC(%) for 0–0.1 m (seasonally inundated)	17.2%	12.1%	3.1%
Average TC(%) for 0–0.1 m (intermittently inundated)	2.7%	1.6%	2.0%
Mottling	2/5	4/7	1/4
Segregations	0/5	0/7	0/4
Ferruginous root channels and pore linings	3/5	3/7	0/4
Sulfidic material	1/5	0/7	0/4
Soil chroma ≤2	5/5	7/7	4/4

1

2

Plate 5.

1. Coastal and sub-coastal floodplain tree swamp (seasonally inundated), Goorganga Plain, central Queensland.
2. Coastal and sub-coastal floodplain tree swamp (intermittently inundated), Condamine, south-west Queensland.

2) Subtropical: palustrine—commonly wet

Four wetlands were sampled in this wetland group; numbers 27–30; Appendix 2, Plate 6. The wetland soil indicators observed or measured, from the total number of sites sampled along the transect, are outlined in Table 13.

- Organic material was a good indicator of the wetland boundary as it was only observed in the saturated zone and transition zone. Fibric and sapric materials were both observed.
- Mottling was mainly observed in the transition zone, which is consistent with an area being subject to watertable fluctuation. Permanent saturation is likely to have retarded the formation of mottles in the wetland. Mottling was not recorded in sandy or organic soils.
- Ferruginous root channel and pore linings were observed in clay or loamy soils with none observed in sandy or organic soils.
- Sulfidic material was observed (by the detection of hydrogen sulfide gas and the presence of sulfurous segregations or yellow jarosite) in the saturated zone only, particularly in the organic-dominated swamps, which were influenced by the input of seawater.

Table 13. Indicators within 0.3 m of the soil surface subtropical palustrine—commonly wet wetlands

Indicators	Saturated zone	Transition zone	Outer zone
Organic material	8/8	3/5	0/4
Average TC(%) for 0–0.1 m (all soils)	25.45%	6.95%	3.29%
Average TC(%) for 0–0.1 m (organic soils)	30.2%	12.9%	2.61%
Average TC(%) for 0–0.1 m (clay soils)	8.36%	8.38%	2.87%
Mottling	0/8	4/5	1/4
Segregations	0/8	0/5	0/4
Ferruginous root channels and pore linings	0/8	4/5	1/4
Sulfidic material	4/8	0/5	0/4
Soil chroma ≤2	8/8	4/5	4/4

1

2

Plate 6.

1. Coastal and sub-coastal floodplain grass, sedge, herb swamp (clay soils), Goorganga Plain, central Queensland.
2. Coastal and sub-coastal non-floodplain grass, sedge herb swamp (organic soils), North Stradbroke Island, south-east Queensland.

3) Subtropical: lacustrine—commonly wet

Two wetlands were sampled in this group; numbers 31–32; Appendix 2, Plate 7. The indicators observed differed significantly between them. The two wetlands were a perched lake with organic soils and a reservoir, or artificial wetland, with clay soils.

The dam, or artificial wetland, was built in 1985 and at the time of sampling was at 16 per cent capacity. The wetland soil indicators observed or measured, from the total number of sites sampled along the transect, are outlined in Table 14.

- Organic materials: fibric and sapric materials were observed at the perched lake with sapric material more prominent towards the fringes of the wetland.
- Mottles were observed only in clay soils in the artificial wetland.
- Ferruginous root channel and pore linings were observed at the reservoir transect only in the outer zone. Water levels in the dam would have reached this height at some point, therefore it is deemed possible to have relict wetland soil features present.
- Soil matrix chroma and soil colour provide an indication of wetland boundary in the artificial wetland, with matrix chroma increasing from the saturated zone to the outer zone. Chroma values did not provide evidence of a wetland boundary at the perched lake.
- Gley soil colours were observed in the saturated zone of the artificial wetland.

Table 14. Indicators within 0.3 m of the soil surface for subtropical lacustrine—commonly wet wetlands

Indicators	Saturated zone	Transition zone	Outer zone
Organic material	3/4	1/1	0/2
Average TC(%) for 0–0.1 m (all soils)	23.38%	0.54%	0.85%
Average TC(%) for 0–0.1 m (perched lake)	31.9%	No clear transition zone	1.4%
Average TC(%) for 0–0.1 m (artificial wetland)	0.8%	0.54%	0.6%
Mottling	1/4	1/1	1/2
Segregations	0/4	0/1	0/2
Ferruginous root channels and pore linings	0/4	0/1	1/2
Sulfidic material	0/4	0/1	0/2
Soil chroma ≤2	4/4	1/1	1/2

1

2

Plate 7.

1. Coastal and sub-coastal non-floodplain sand lake—perched, North Stradbroke Island, south-east Queensland.
2. Artificial wetland (no typology classification), Wivenhoe Dam, south-east Queensland.

4) Subtropical: estuarine—periodically inundated

One wetland was sampled in this group. This was mangrove-dominated wetland on a flat which graded from intertidal to supratidal; number 33; Appendix 2, Plate 8. The wetland soil indicators observed or measured, from the total number of sites sampled along the transect, are outlined in Table 15.

Table 15. Indicators within 0.3 m of the soil surface for subtropical estuarine—periodically inundated wetlands

Indicators	Saturated zone	Transition zone	Outer zone
Organic material	1/1	0/1	0/1
TC(%) for 0–0.1 m	13.1%	4.2%	3.0%
Mottling	1/1	1/1	1/1
Segregations	0/1	1/1	0/1
Ferruginous root channels and pore linings	0/1	0/1	1/1
Sulfidic material	0/1	0/1	0/1
Soil chroma ≤2	1/1	1/1	1/1

Intertidal zone

Supratidal zone

Plate 8.
Estuarine wetland. Goorganga Plain, central Queensland.

Semi-arid climatic region

Several wetland types were sampled in the semi-arid climatic region including:

- semi-arid floodplain swamp
- semi-arid floodplain lake
- semi-arid saline lake.

There were three distinct wetland groups represented in the semi-arid climatic region (as outlined in Table 5).

1) Semi-arid: palustrine—periodically inundated

The wetlands sampled for this group were numbers 34–36; Appendix 4, Plate 9.

The wetland soil indicators observed or measured, from the total number of sites sampled along the transect, are outlined in Table 16.

- Segregations were only present in the saturated zone. This is consistent with the formation of segregations in areas prone to periodic saturation; however, the overall lack of segregations observed suggests this is not a reliable indicator for use in wetland identification.
- Ferruginous root channel and pore linings were only observed at sites in the transition zone and outer zone. These features may reflect relict conditions and do not provide a good indication of the wetland boundary.

Table 16. Indicators within 0.3 m of the soil surface for semi-arid palustrine—periodically inundated wetlands

Indicators	Saturated zone	Transition zone	Outer zone
Organic material	0/3	0/2	0/3
Average TC(%) for 0–0.1 m	0.36%	0.51%	0.34%
Mottling	1/3	2/2	1/3
Segregations	1/3	0/2	0/3
Ferruginous root channels and pore linings	0/3	1/2	1/3
Sulfidic material	0/3	0/2	0/3
Soil chroma ≤ 2	3/3	2/2	1/3

1

2

Plate 9.

1. Semi-arid floodplain swamps, Wyandra claypan, south-west Queensland.
2. Currawinya claypan, south-west Queensland.

2) Semi-arid: lacustrine—periodically inundated

There were six wetlands sampled as part of this group; numbers 37–42; Appendix 2, Plate 10. The wetland soil indicators observed or measured, from the total number of sites sampled along the transect, are outlined in Table 17.

- Mottling was observed at all sites in the saturation zone and decreased moving out of the wetland; however, features were recorded in the outer zone making this difficult to use for wetland identification.
- Segregations were only recorded at one site in the transition zone. This is consistent with the formation of segregations in areas that are prone to periodic saturation; however, the overall lack of segregations observed suggests this is not a reliable indicator for use in wetland identification.
- Soil matrix chroma values were the most indicative of the wetland boundary with chroma values of less than or equal to 2 observed in the saturated zone and the transition zone with increasing chroma values in the outer zone.

Table 17. Indicators within 0.3 m of the soil surface for semi-arid lacustrine—periodically inundated wetlands

Indicators	Saturated zone	Transition zone	Outer zone
Organic material	0/6	0/6	0/6
Average TC(%) for 0–0.1 m	0.46%	0.56%	0.57%
Mottling	6/6	3/6	2/6
Segregations	0/6	1/6	0/6
Ferruginous root channels and pore linings	1/6	2/6	1/6
Sulfidic material	0/6	0/6	0/6
Soil chroma ≤2	6/6	5/6	3/6

1

2

Plate 10.
Semi-arid floodplain lakes,

1. Murrawondah Lakes, Mulga Lands, south-west Queensland.
2. Lake Munya (oxbow lake), St George, Balonne River floodplain, south-west Queensland.

3) Semi-arid: lacustrine—commonly wet

There were four wetlands sampled in this group; numbers 43–46; Appendix 2, Plate 11. The wetland soil indicators observed or measured, from the total number of sites sampled along the transect, are outlined in Table 18.

- There is statistical evidence to support the use of TC(%) to provide information for wetland identification in this wetland type. With no vegetation present at the sites sampled in these wetlands this increase is being attributed to microscopic algae being present. The results from the outer zone are skewed because a site had an total carbon of 1.7 per cent. This was due to the site being on a newly formed lunette with buried vegetation visible in the soil profile.
- The buried vegetation present in a site in the outer zone was sparse and did not appear to have accumulated under saturated conditions. As such it was not considered organic material (as defined in Appendix 5).
- Gley matrix colours were observed in the saturated zone only, at 75 per cent of sites. Sulfidic material was present at two wetlands in the saturated zone only.
- A soil–water interface[2] was observed at one site in the saturated zone. This is the only observation of this indicator in all the wetlands sampled in the current study.

Table 18. Indicators within 0.3 m of the soil surface for semi-arid lacustrine—commonly wet wetlands

Indicators	Saturated zone	Transition zone	Outer zone
Organic material	0/4	0/5	0/4
Average TC(%) for 0–0.1 m	1.31%	0.23%	0.08%
Mottling	4/4	3/5	2/4
Segregations	0/4	0/5	0/4
Ferruginous root channels and pore linings	1/4	1/5	0/4
Sulfidic material	2/4	0/5	0/4
Soil chroma ≤2	4/4	4/5	2/4
Soil Water Interface	1/4	0/5	0/4

2 A thin layer of orange/red oxidised soil is present at the surface of the soil–water interface. It is not commonly observed but if present can give an indication of the watertable depth.

1

2

Plate 11.

1. Semi-arid saline lake, Lake Wyara, Currawinya NP , south-west Queensland
2. Semi-arid floodplain lake, Lake Wombah, south-west Queensland

3. Results

Arid climatic region

Several wetland types were sampled in the arid climatic region including:

- arid floodplain swamp
- arid floodplain lake
- arid non-floodplain swamp.

There were three distinct wetland groups represented in the arid climatic region (as outlined in Table 5).

1) Arid: palustrine—periodically inundated

Six wetlands were sampled in this group; numbers 47–52; Appendix 2, Plate 12. The wetland soil indicators observed or measured, from the total number of sites sampled along the transect, are outlined in Table 19.

- Mottling, segregations and ferruginous root channel and pore linings were indicative of the wetland boundary, with observations decreasing moving from the sites in the saturated zone to the outer zone.
- Soil matrix chroma values were good indicators of the wetland boundary, with values of less than or equal to 2 observed in sites in the saturated zone and increasing moving to the outer zone.

Table 19. Indicators within 0.3 m of the soil surface for arid palustrine—periodically inundated wetlands

Indicators	Saturated zone	Transition zone	Outer zone
Organic material	0/6	0/3	0/3
Average TC(%) for 0–0.1 m	0.23%	0.28%	0.20%
Mottling	5/6	2/3	0/3
Segregations	2/6	1/3	0/3
Ferruginous root channels and pore linings	0/6	1/3	0/3
Sulfidic material	0/6	0/3	0/3
Soil chroma ≤2	6/6	3/3	1/3

1

2

Plate 12.
Arid floodplain swamps,

1. Closed depression, Eyre Development Road, Channel Country.
2. Overflow swamps, Durrie Station, Channel Country.

2) Arid: lacustrine—commonly wet

One wetland was sampled in this group—a large freshwater lake dominated by clay soils, which at the time of sampling was inundated; however, it can become dry for months or several years at a time (number 53, Appendix 2, Plate 13). The wetland soil indicators observed or measured, from the total number of sites sampled along the transect, are outlined in Table 20.

- Soil matrix chroma was the only wetland soil indicator that may aid wetland identification with lower values observed in the wetland than in the transition zone.
- No other wetland soil features gave an indication of the boundary of the wetland, therefore there is a need to rely on other contextual information, landform features and vegetation to determine the wetland boundary for this wetland type.

Table 20. Indicators within 0.3 m of the soil surface for arid lacustrine—commonly wet wetlands

Indicators	Saturated zone	Transition zone	Outer zone
Organic material	0/1	0/1	Not sampled
TC(%) for 0–0.1 m	0.25%	0.36%	Not sampled
Mottling	1/1	1/1	Not sampled
Segregations	0/1	0/1	Not sampled
Ferruginous root channels and pore linings	0/1	0/1	Not sampled
Sulfidic Material	0/1	0/1	Not sampled
Soil chroma ≤2	1/1	0/1	Not sampled

Plate 13.
Arid floodplain lake,
Lake Machattie, Channel Country, west Queensland.

3) Arid: lacustrine—periodically inundated

Two wetlands were sampled in this group. One lake was inundated at the time of sampling and the other was dry (numbers 54–55, Appendix 2, Plate 14). The wetland soil indicators observed or measured, from the total number of sites sampled along the transect, are outlined in Table 21.

- Mottling was observed at both wetland sites in the saturated zone, and not observed in the transition zone at one wetland giving an indication of the wetland boundary.
- No other wetland soil features gave an indication of the boundary of the wetland, therefore there is a need to rely on other contextual information, landform features and vegetation to determine the wetland boundary for this wetland type.

Table 21. Indicators within 0.3 m of the soil surface for arid lacustrine—periodically inundated wetlands

Indicators	Saturated zone	Transition zone	Outer zone
Organic material	0/2	0/2	Not sampled
Average TC(%) for 0–0.1 m	0.17%	0.28%	Not sampled
Mottling	2/2	1/2	Not sampled
Segregations	0/2	0/2	Not sampled
Ferruginous root channels and pore linings	0/2	0/2	Not sampled
Sulfidic material	0/2	0/2	Not sampled
Soil chroma ≤2	1/2	1/2	Not sampled

1

2

Plate 14.
Arid floodplain lakes,

1. Lake Mipia Area, Channel Country, west Queensland.
2. Lake Didichie , Channel Country, west Queensland.

3. Results

Monitoring trial

A monitoring trial was conducted (outlined in the monitoring trial section on page 16) in six wetlands across Queensland to monitor depth of saturation and frequency of inundation in comparison to the hydric soil features that formed. Water-level monitoring equipment was placed at two sites in each of the six wetlands, one in the saturated zone and one in the transition zone.

A manufacturer's fault in the logger equipment caused six of the twelve loggers to fail. This has not allowed comparisons between sites in the saturated zone and transition zone at two wetlands (Deepwater NP and Bribie Island—middle swamp crossing). There are also two wetlands (Goorganga Plain and Bribie Island—lower swamp crossing) where both data loggers failed and no information is available.

Eubenangee Swamp

Watertable depth and surface water depth were recorded for seven months from December 2007 to May 2008.

No information is available for dry season levels because the swamp was inundated and it was not possible to install data loggers.

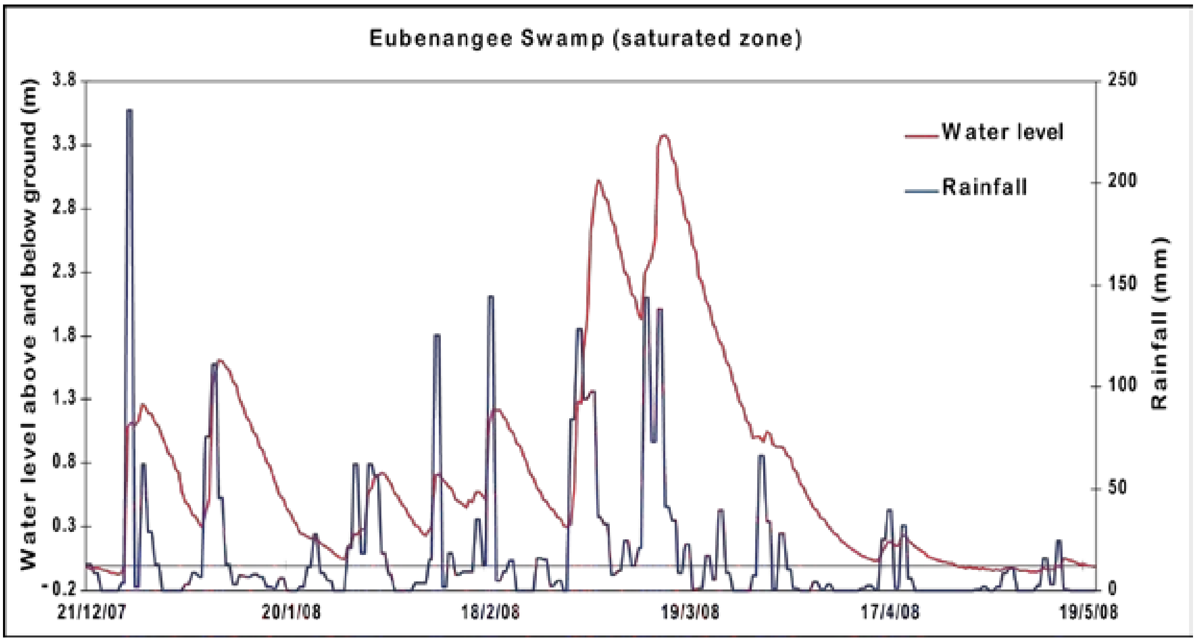
Saturated zone: The watertable remained at less than 0.3 m from the soil surface throughout the trial and was inundated for 85 per cent of the time (Figure 9 and Table 22). Water level rises are correlated with large rainfall events and water is draining away at an average of approximately 0.10 m per day.

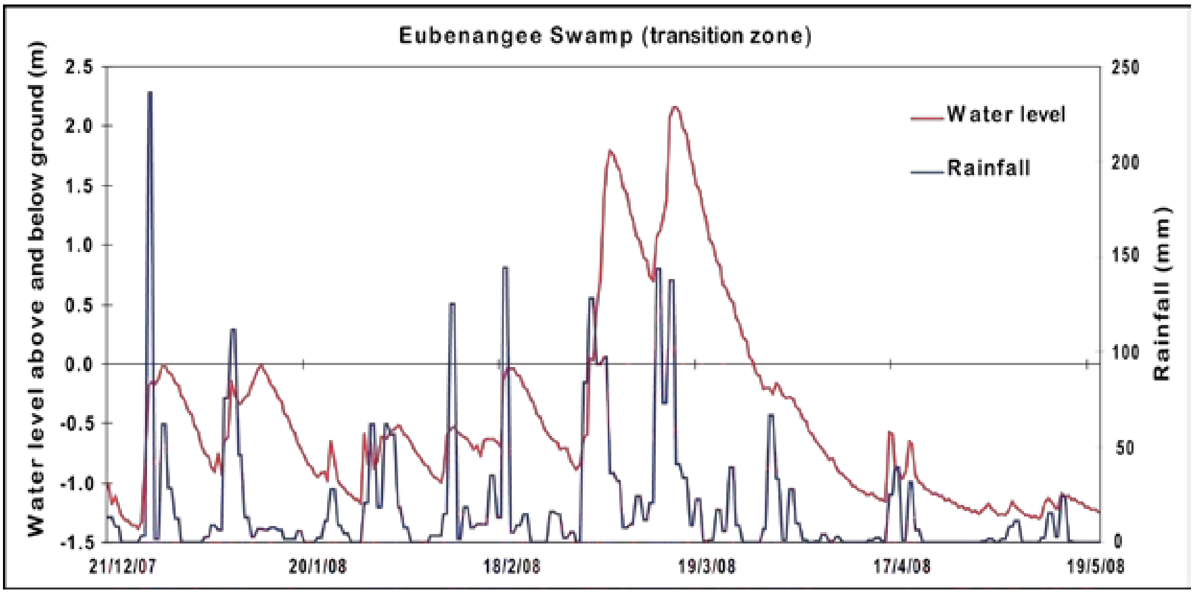
Mottling features are present from 0.2 to 0.8 m; however, this does not correspond with water-table depth fluctuation as the profile remained saturated and inundated for the majority of the trial. Mottling may be indicative of water fluctuation in the dry season. The level of saturation has allowed for the accumulation of organic material to 0.8 m in the soil profile.

Transition zone: The watertable remained at less than 0.3 m from the soil surface for 32 per cent of the trial (Table 22) and was inundated for 16 per cent. Rise in water levels are again correlated with large rainfall events, with water draining at an average of approximately 0.10 m per day.

Mottling features are present at 0.02 to 0.1 m from the soil surface. This is indicative of the wet season watertable fluctuation (Figure 9). The level of saturation has allowed organic material to accumulate to 0.9 m in the soil profile.

Figure 9. Water levels and rainfall at Eubenangee Swamp





Tam O'Shanter NP (Licuala Palm Forest)

Watertable depth and surface water depth were recorded for 12 months (May 2007 to May 2008), capturing information on wet and dry seasons.

Saturated zone: The watertable remained at less than 0.3 m from the soil surface for 20 per cent of the monitoring trial (Table 22). The swamp was not inundated at any time during the trial. Rise in the watertable is associated with rainfall events. Water is draining at an average of approximately 0.12 m per day.

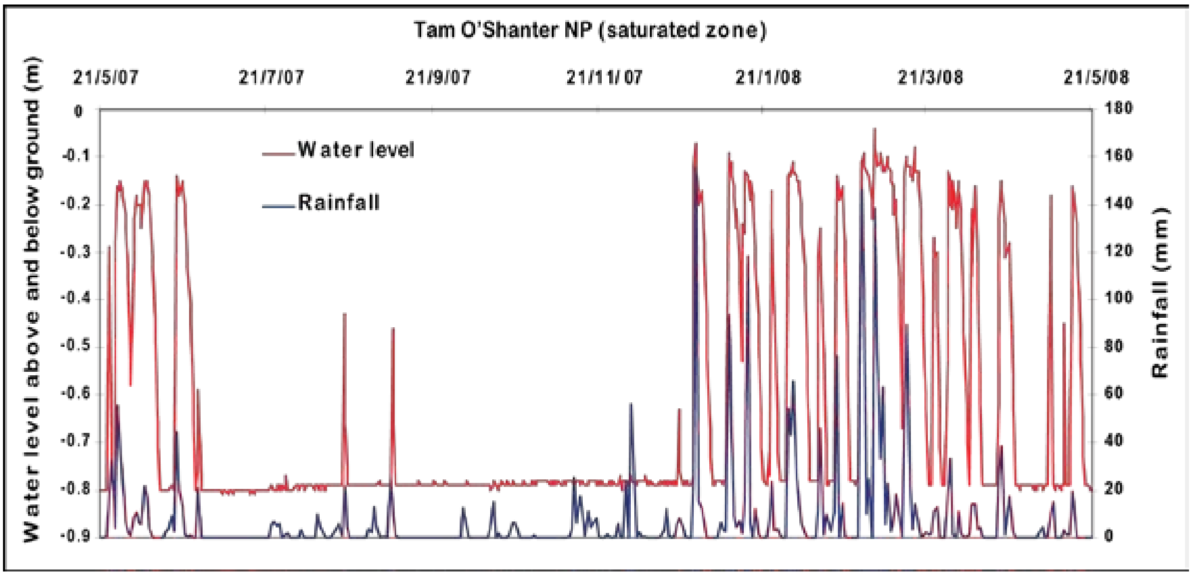
There is good correlation between the depth at which mottling features begin in the soil profile (0.05 m) and the depth to which the watertable fluctuates during the wet season (Figure 10). The lack of inundation has not allowed organic matter to accumulate but the level of saturation is sufficient for redox features to form.

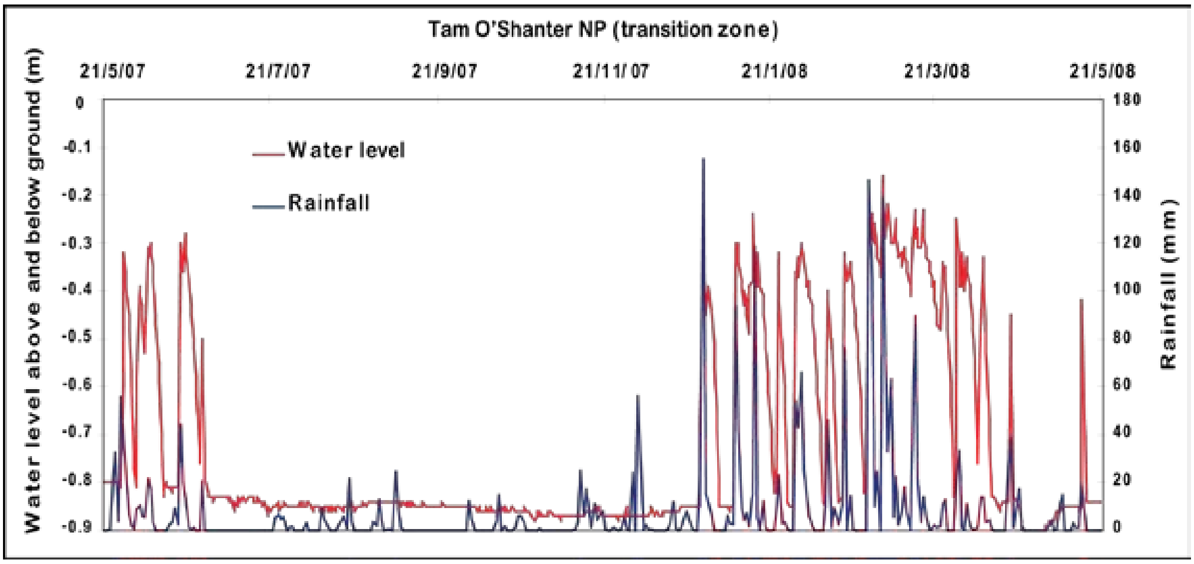
Transition zone: The watertable remained less than 0.3 m from the soil surface for 5 per cent of the time (Table 22). The transition zone was not inundated at any time throughout the trial (Figure 10). The rise in watertable depth is associated with rainfall events and water is draining away at an average of approximately 0.10 m per day.

There is good correlation between the depth at which mottling features and ferruginous segregations are observed in the soil profile (0.25 m) and the depth to which the watertable fluctuates during the wet season. The lack of inundation has not allowed organic matter to accumulate but there is sufficient saturation for redox features to form.

3. Results

Figure 10. Water levels and rainfall at Tam O'Shanter NP





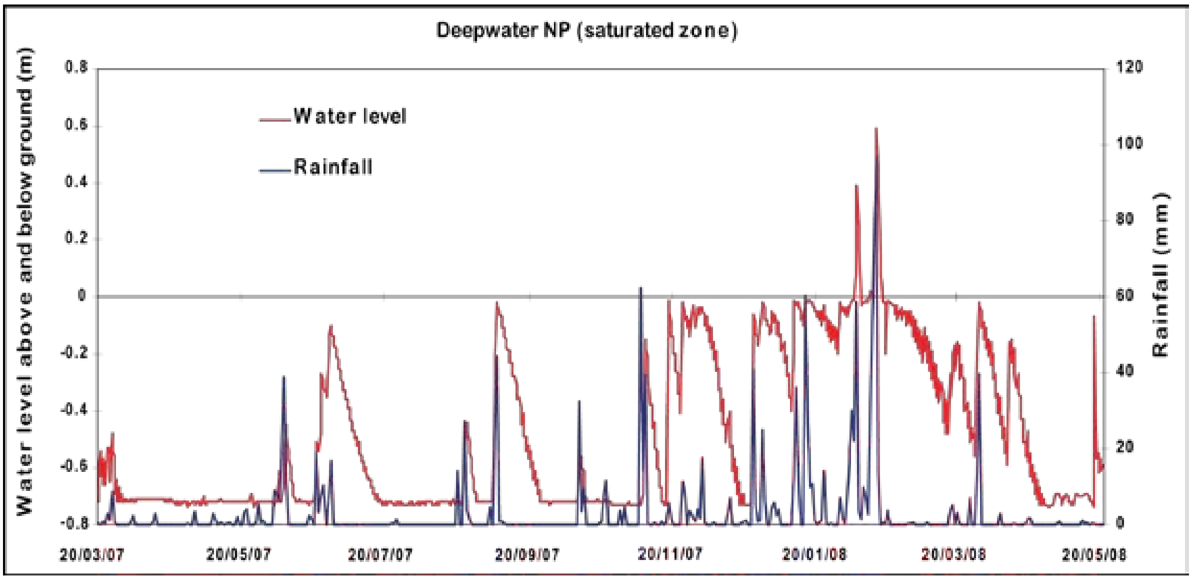
Deepwater NP

Watertable depth was recorded for 14 months (March 2007 to May 2008) capturing information from wet and dry seasons.

Saturated zone: The watertable remained at less than 0.3 m from the soil surface for 43 per cent of the monitoring trial (Table 22). Rise in water levels are correlated with rainfall events with water draining at an average rate of approximately 0.06 m per day.

Ferruginous root channel linings were recorded from 0.4 to 0.57 m. This can be attributed to the water fluctuation throughout this zone. The saturated conditions have allowed the accumulation of organic material to 1.4 m in the soil profile. There were only six days of inundation recorded throughout the trial (Figure 11); however, this is sufficient to allow the accumulation of organic material.

Figure 11. Watertable levels and rainfall at Deepwater NP swamp (saturated zone)



Bribie Island—middle swamp crossing

Watertable depth was recorded for 13 months (March 2007 to April 2008) capturing information from wet and dry seasons.

Saturated zone: The watertable remained at less than 0.3 m from the soil surface for 80 per cent of the trial and the swamp was inundated 58 per cent of the time (Figure 12 and Table 22).

Rise in water levels are correlated with large rainfall events, with water draining at an average rate of approximately 0.005 m per day.

The level of saturation is sufficient for organic matter to accumulate. Organic material is present to 0.7 m but is believed to extend below this depth (0.7 m was the depth of the soil profile described).

Figure 12. Watertable levels and rainfall at Bribie Island—middle swamp crossing (saturated zone)

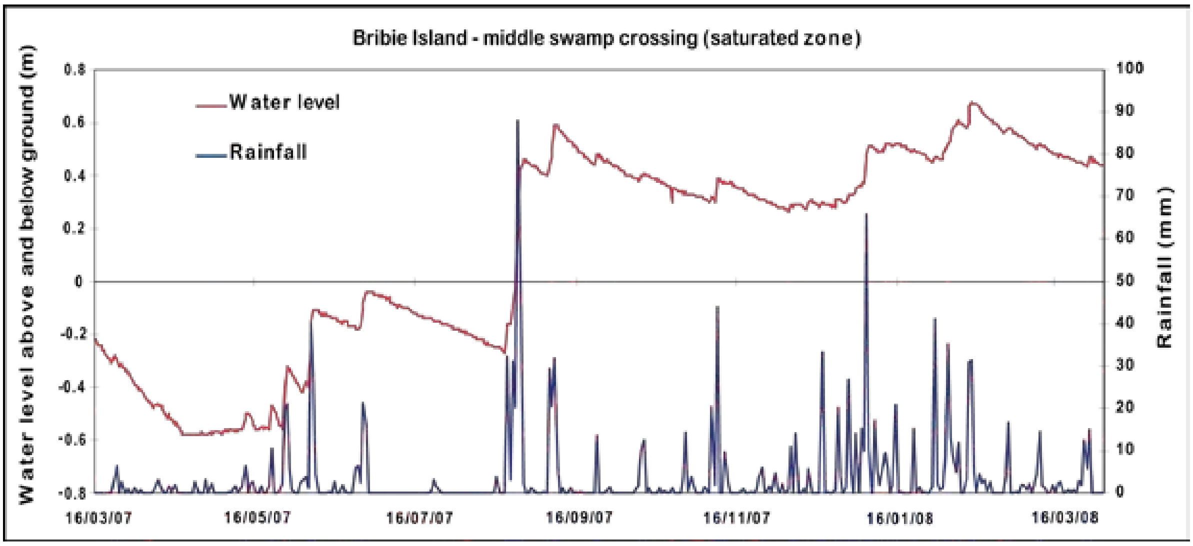


Table 22. Water levels in monitoring trial

Wetland and site position	Days water level <0.3 m	Days inundated
Eubenangee (saturated zone)	148/148 (100%)	127/148
Eubenangee (transition zone)	47/148 (32%)	25/148
Tam O'Shanter NP (saturated zone)	73/365 (20%)	0/365
Tam O'Shanter NP (transition)	17/365 (5%)	0/365
Deepwater NP (saturated zone)	180/421 (43%)	6/421
Bribie Island—middle swamp crossing (saturated zone)	305/377 (80%)	219/377

3. Results

Indicator of Reduction In Soils (IRIS) trial

The following section is an outline of the results from the IRIS trial in south-east Queensland. Twenty-six PVC pipes were coated with a synthetic iron oxide and placed in three wetlands across south-east Queensland to ascertain if the soils were in a reduced state and if the results could be then compared to the soil indicators observed at each site.

Bribie Island—lower swamp crossing

During the trial the swamp was not inundated. It was expected that the pipes at sites in the saturated zone were more likely to indicate reducing conditions but they indicated a distinct lack of reduction in this location (Sites 15 and 16, Figure 13). The pipes in the outer zone, near the start of the sand plain, had more paint removed than those in the swamp. At this wetland there appeared to be a correlation between total carbon content, clay content and the reduction of iron. In areas where very little paint was removed there were high total carbon contents and clay-dominated soils. Reducing conditions occurred at the site outside the wetland (Site 18, Figure 13). This profile had three per cent total carbon at the depth where reduced conditions were indicated by the removal of paint from the tubes. This site also had loamy sand, compared to the clay in the wetland where a reduced environment was not evident.

Bribie Island —middle swamp crossing

This section of the swamp had permanently inundated areas with reduced conditions evident from the complete removal of paint at sites 21 and 22 (Figure 14). These sites were inundated throughout the trial and had very high levels (>12%) of total carbon.

Reduced conditions were indicated in the transition zone by the patchy and sparse removal of paint, as expected in a periodically saturated area subjected at times to an oxidised environment.

High levels of reduction were observed at site 20 (considered out of the wetland) similar to site 18 in the lower swamp crossing trial. High levels (5.49%) of total carbon were present at 0.3 m depth where reducing conditions were observed. A similar pattern was observed at site 24, near the edge of the wetland, where the majority of paint was uniformly removed below 0.25 m. In both profiles the dominant soil texture is loamy sand to sand. The pipes at sites with the least amount of reduction indicated through the patchy removal of paint had clay loam textures.

Carbrook Conservation Park

Reducing conditions were evident at all sites in Carbrook Conservation Park (Figure 15). Site 215 was inundated for the duration of the trial and had complete removal of paint from the pipe. Site 216, on the levee, had lower watertable levels during the trial and patchy removal of paint but indicated more reduced areas than site 217, which had a higher watertable level throughout the trial. All sites had high total carbon levels in the surface (>16%) with levels at a depth greater than 1.6 per cent. All sites at Carbrook were loam to light clay soils. There was prominent dark staining of the pipes at the sites 215 and 217 where acid sulfate soil material was detected. This is not attributed to the high level of total carbon at the sites as similar levels were observed at the Bribie Island middle swamp crossing trial. Sulfidic material was not detected at the Bribie Island middle swamp crossing and the pipes did not have the same dark staining pattern.

Figure 13. IRIS results for Bribie Island lower swamp crossing

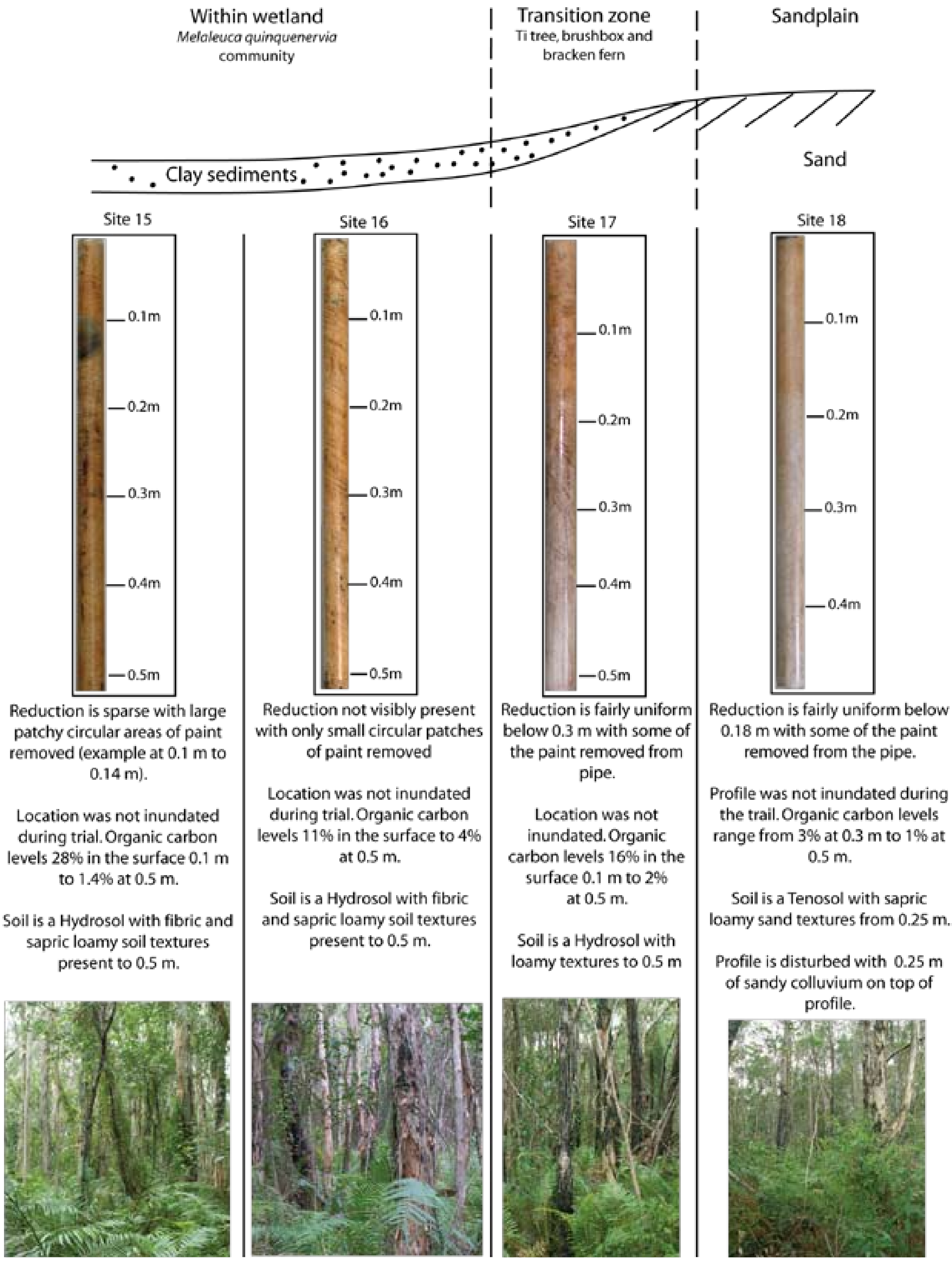


Figure 14. IRIS results for Bribie Island middle swamp crossing

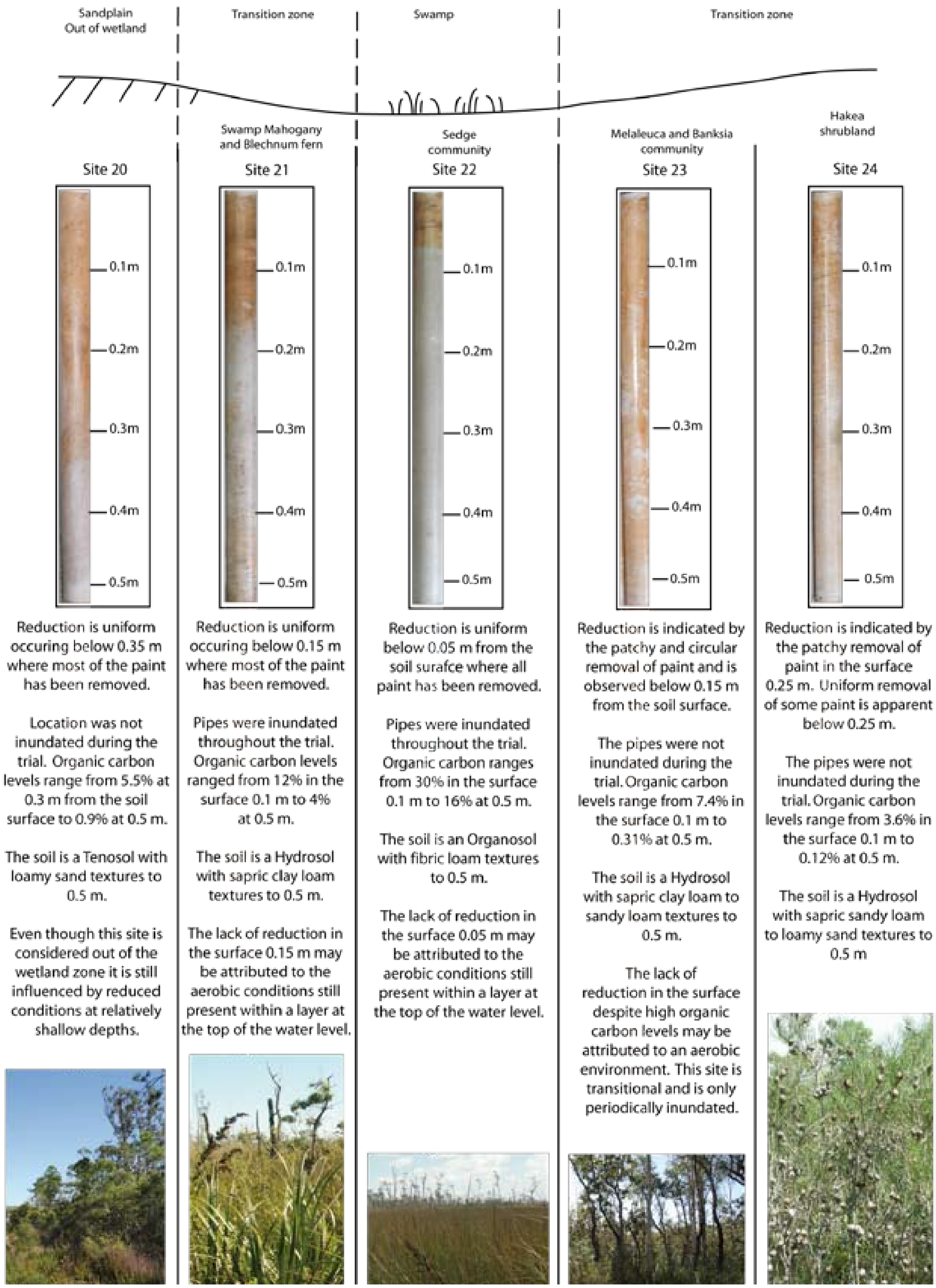
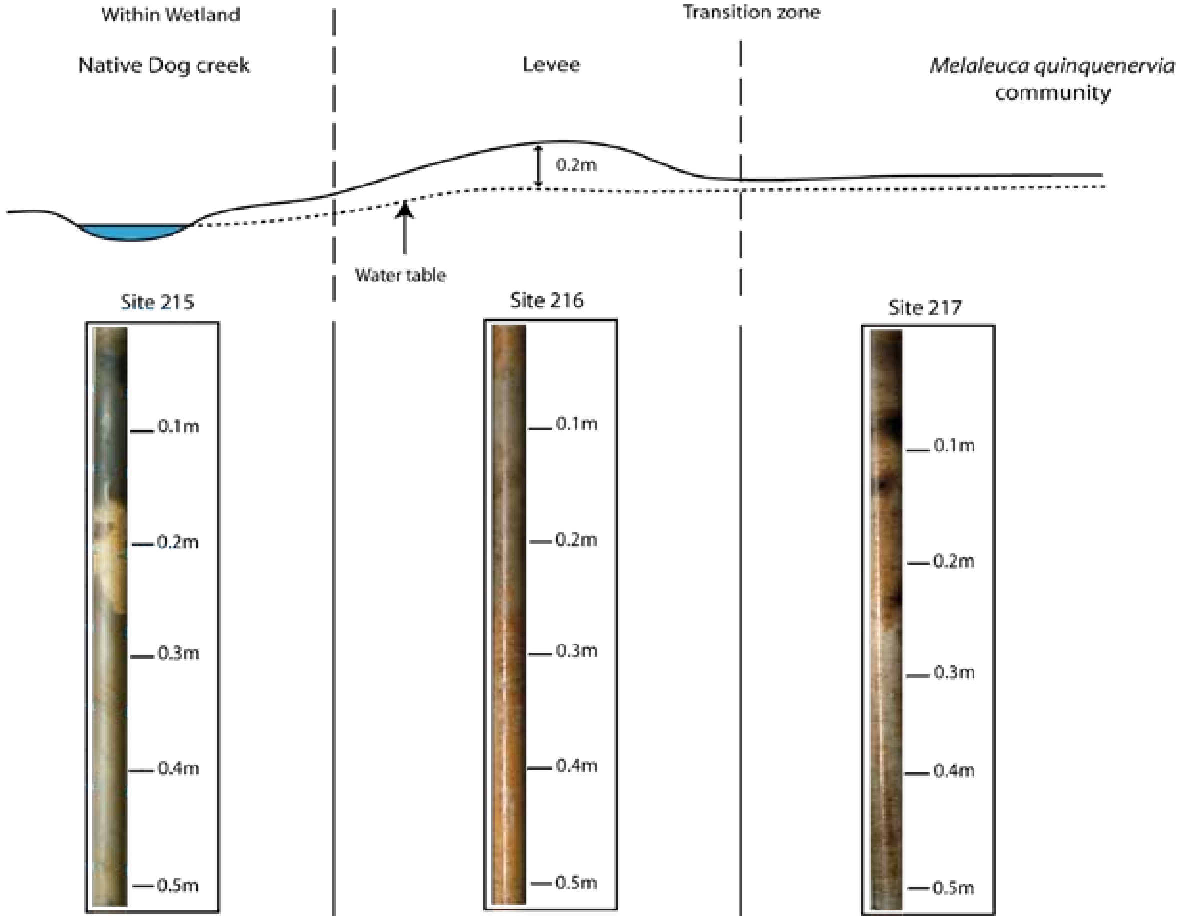


Figure 15. IRIS results for Carbrook Conservation Park



Reduction is uniform over majority of pipe with nearly all of the paint removed.

At the time of installation the water table was at 0.02 m and the pipe was inundated completly on removal. Organic carbon levels range from 28.2% in the surface 0.1 m to 3.15% at 0.5 m.

Soil is a Hydrosol with fibric and sapric loam to light clay textures to 0.5 m.

Acid sulfate materials were detected on installation and pipe is stained a prominant dark colour.

Reduction is uniform in a section between 0.05 m and 0.25 m. Below 0.25m removal of paint is patchy and circular.

At the time of installation the water table was at 0.2 m. Organic carbon levels range from 16.3% in the surface 0.1 m to 3.05% at 0.5 m.

Soil is a Hydrosol with sapric loam to heavy light clay textures to 0.5 m.

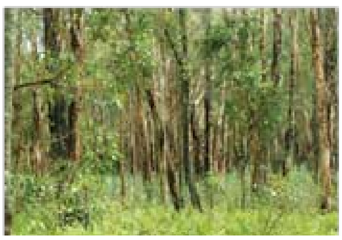
There is no evidence of dark stains as seen at site 215.

Reduction is uniform over majority of pipe with nearly all of the paint removed below 0.25 m.

At the time of installation the water table was at 0.05 m and there was visible surface water present on removal. Organic carbon levels range from 19.2% in the surface 0.1 m to 1.67% at 0.5 m.

Soil is a Hydrosol with fibric and sapric loam to light medium clay textures to 0.5 m.

Iron staining of the surrounding enviornment was visible on removal of pipes. Similar dark staining present in patches as seen at site 215.



4. Discussion

The most reliable way of determining a wetland boundary (wetland delineation) is by assessing current hydrological data to determine the depth and frequency of inundation or saturation of the soil profile. A variety of methods such as watertable wells and piezometers can be use to gather this data but they typically require long monitoring periods to develop accurate trends in water level. In most cases it is not practical to obtain such data, neither is there an abundance of this information currently available. In the absence of reliable watertable information, secondary measures of saturation frequency or soil morphological indicators, or the presence of wetland indicator species (hydrophytes or fauna) must be used to identify wetlands.

The following section discusses the outcomes from the indicator, monitoring and IRIS trials across Queensland. Considerations for using soil indicators and contextual information to support soil indicators for wetland identification in Queensland are also discussed.

Soil indicators in climatic regions

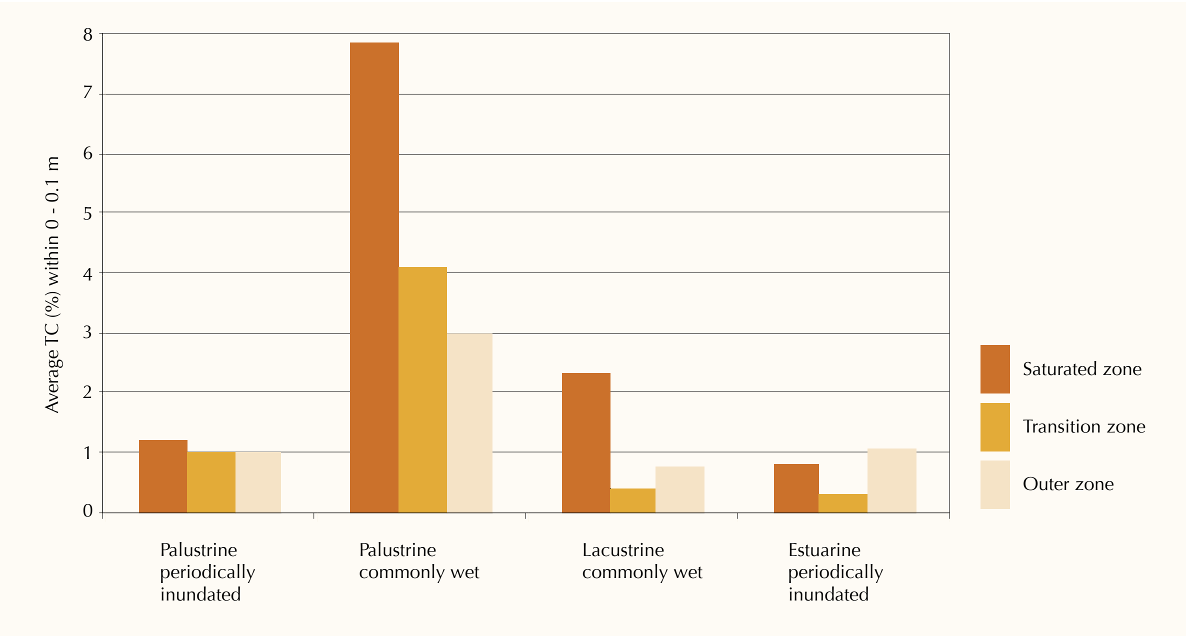
Tropical climatic region

Organic material was more commonly observed in wetlands that appeared permanently saturated. Fibric, sapric and streaked organic material was observed in wetlands sampled in this climatic region.

The average total carbon content for all sites sampled decreased moving from the saturated zone to the outer zone (Figure 16). There is no statistical evidence to support the use of TC(%) for wetland identification at a climatic region scale. However, there is scope to further refine the use of TC(%) for specific wetland groups, namely commonly wet, palustrine or lacustrine wetlands.

Mottling was not consistent between wetland groups or at sites along the transect. Mottling was observed in more than half the sites in the outer zone as a result of the hydropedological environment, which makes the use of mottling as an indicator of wetlands soil difficult. Mottling was observed in clay, sand and organic-dominated soil.

Figure 16. Average TC(%) across wetland groups in the tropical climatic region



Segregations were more commonly observed in the transition zone, which is consistent with the segregation formation being retarded by permanent saturation. Segregations were not present in sandy or organic-dominated soil.

Ferruginous root channel and pore linings were observed in loamy sand soil but not in sand or organic-dominated soil. As they were observed in all sites along the transect, this indicator is less reliable for wetland identification.

Sulfidic material was observed in estuarine wetlands, with sulfidic material detected by field observations and tests. Hydrogen sulfide gas was not detected at any sites.

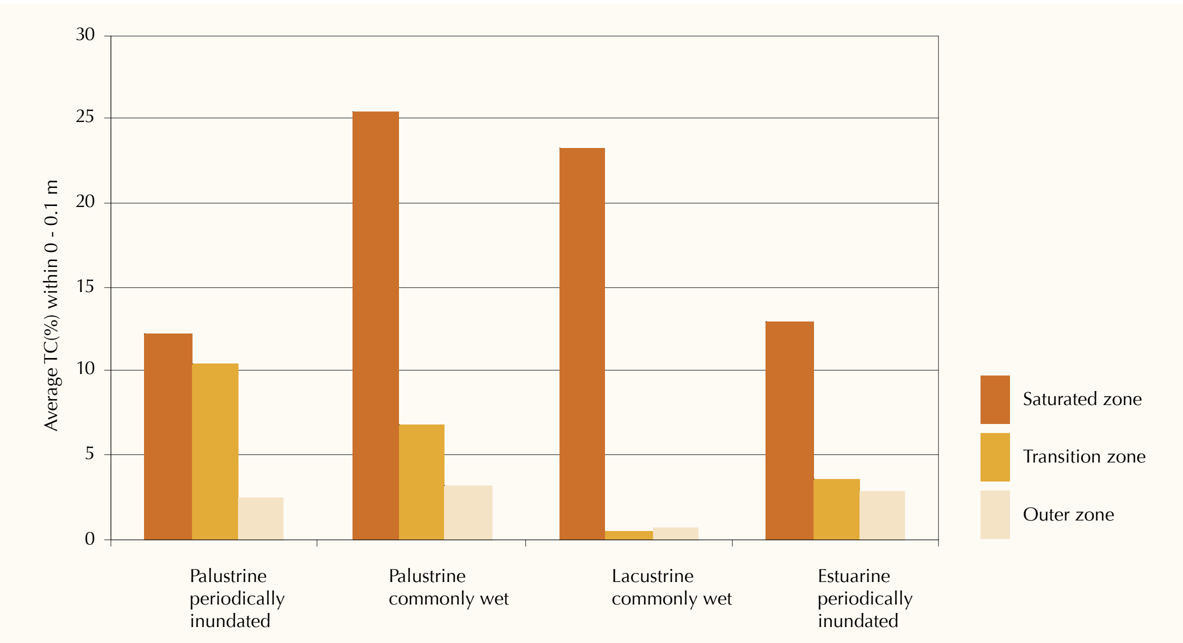
Soil matrix chroma values of 2 or less were observed in the majority of wetland types. A number of transects had low chroma values at sites outside the wetland suggesting that in this seasonally saturated environment it may be common to have non-wetland soil with low chroma within 0.3 m of the soil surface. No well defined trend for low soil chroma values was found.

Subtropical climatic region

Organic material was observed in the majority of wetlands sampled in the subtropical climatic region. Fibric and sapric material were recorded but sapric material was more commonly observed at sites in the transition zone. There was no streaked organic material recorded at any wetlands sampled. The decrease in observed organic material moving from the saturated zone to the outer zone was the most definitive indicator of the wetland boundary for the subtropical region.

There is a significant trend for increasing TC(%) in the surface 0–0.1 m moving from the outer zone to the saturated zone across all wetland groups in the subtropical climatic region (Figure 17). There is statistical evidence to support the use of TC(%) to identify wetland soil in this climatic region. Although wetlands with organic soil have significantly higher total carbon content than clay or sandy soil, when analysed separately the trend is similar for both organic and non-organic soil.

Figure 17. Average TC(%) across wetland groups in the sub-tropical climatic region



4. Discussion

Mottling was not observed in any organic soil. Clay soils were more likely to display mottling features, compared to sandy soils. One observation of mottles was made in sandy soil. Most clay soils presented mottling features at all sites along the transect.

Segregations were observed predominantly in wetlands that appeared to be seasonally inundated although segregations were recorded at all sites along the transect, with no broad trends to aid identification of the wetland boundary. Wetlands with organic or sandy soil did not have segregations present.

Ferruginous root channel and pore linings were not observed in organic soils. Some features were present in sandy soil but the majority were recorded in clay soil. These features were present in eight of nine clay wetlands sampled, and were observed at all sites along the transect.

In the majority of coastal wetlands influenced by seawater the presence of sulfidic material was observed. Sulfurous segregations (or yellow jarosite) were observed and hydrogen sulfide gas was detected. Sulfidic material was observed at sites in the saturated zone only.Soil matrix chroma was not a good indicator for wetland identification as the majority of wetlands sampled at all sites along the transect had chroma values of less than or equal to 2.

Semi-arid climatic region

Organic material was not recorded at any sites sampled, therefore it is not considered a good wetland soil indicator in the semi-arid region.

Lacustrine commonly wet wetlands were the only wetland group in the semi-arid climatic region with a statistically significant increase in average TC(%) moving into the wetland (Figure 18). It may be possible to determine a wetland soil from TC(%) with further sampling of this group.

Mottling was commonly recorded at all sites along the transect across all wetland groups, making this a difficult indicator to use for wetland identification. The majority of mottling features were present in clay soil. Mottling features observed in sandier soil appeared to be in areas that were permanently saturated.

Figure 18. Average TC(%) across wetland groups in the semi-arid climatic region

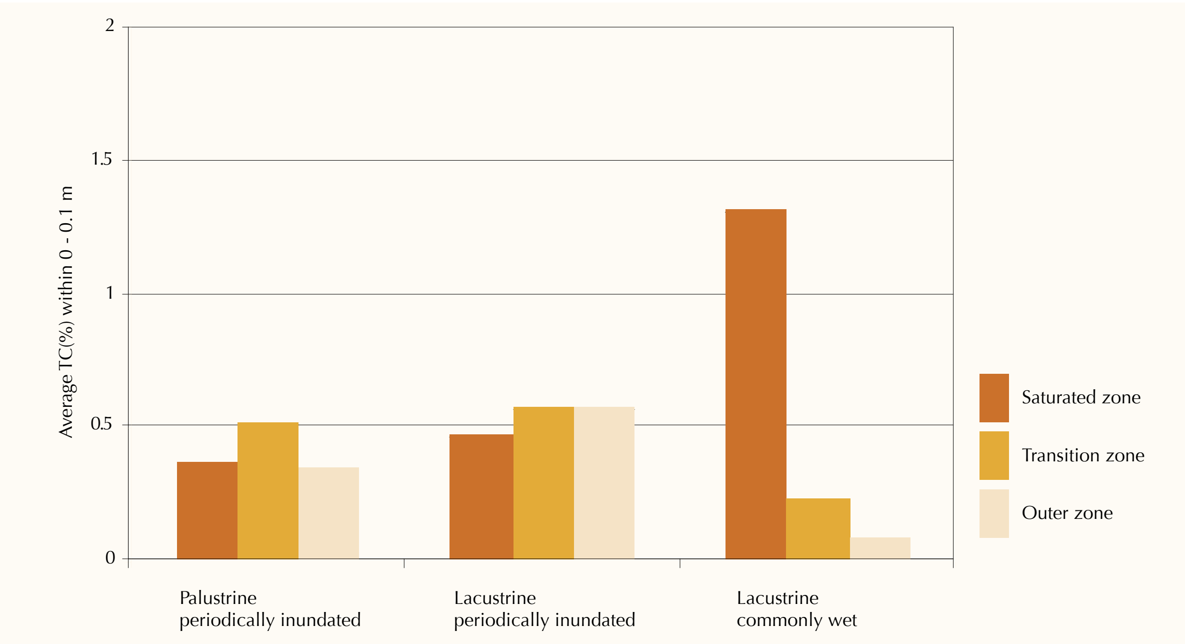


Figure 19. Percentage of sites sampled with soil matrix chroma values of 2 or less in the semi-arid region

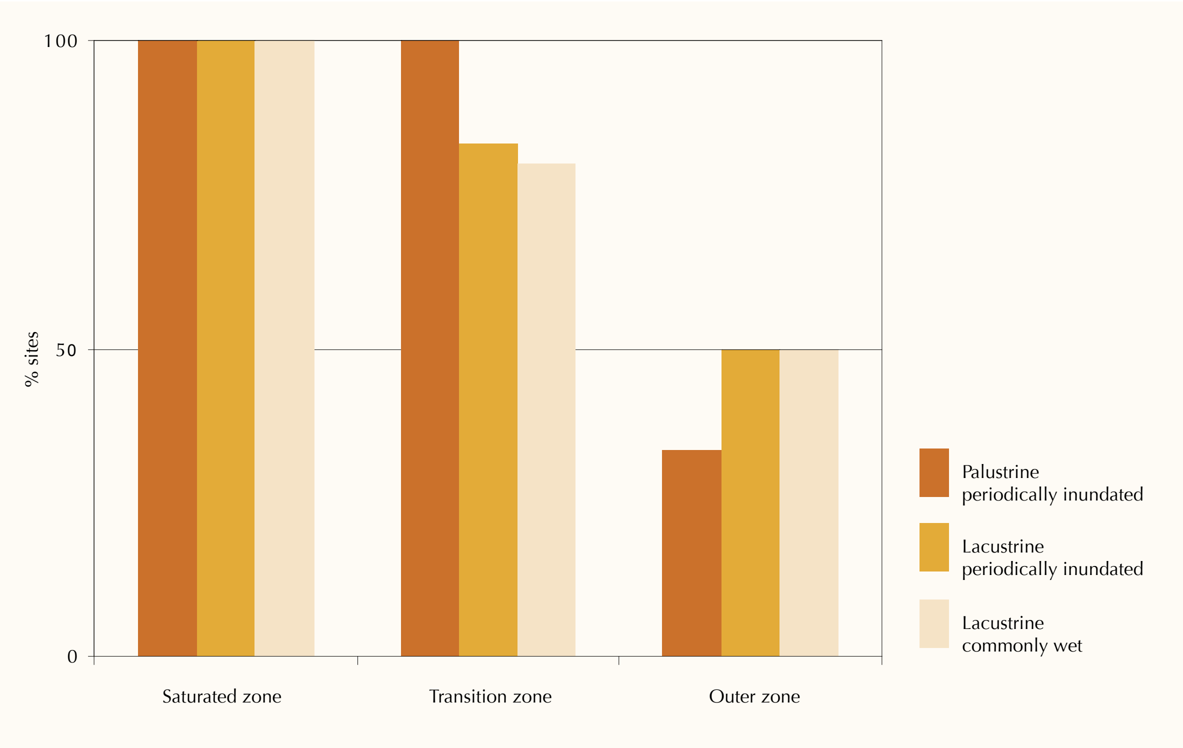
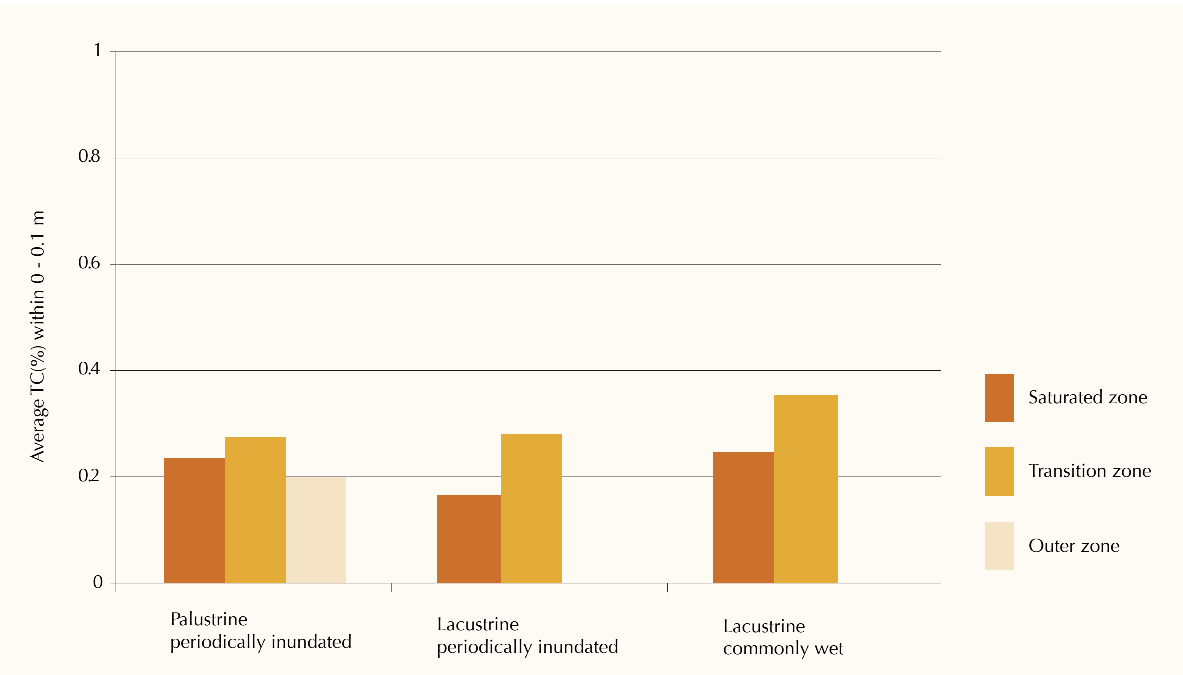


Figure 20. Average TC(%) across wetland groups in the arid climatic region (Outer zone site for lacustrine commonly wet and periodically inundated wetlands not sampled)



4. Discussion

There were no broad trends for segregations observed as they were recorded at all sites along the transect. Sulfidic material (confirmed by field peroxide and laboratory testing) was present in two permanent lake systems. The sulfidic material was recorded at sites in the saturated zone only.

In all wetland groups there was a distinct trend in the presence of depleted soil matrix chroma. All wetlands groups recorded increasing matrix chroma values moving out of the wetland, making this indicator one of the more useful for wetland identification in the semi-arid region (Figure 19).

Arid climatic region

Organic material was not observed at any sites sampled, therefore it is not considered a good indicator of wetland soil in the arid climatic region.

There was no distinct trend in average TC(%) at all wetlands sampled (Figure 20). There is little information to be gained by utilising average TC(%) for wetland identification in the arid climatic region. Mottles were observed at all sites along the transect across all wetland groups sampled. This suggests mottling is a poor wetland soil indicator for wetland identification in the arid region. All soils sampled were clay, therefore there was no comparison with sandy soils and whether they present mottling features in this climatic region.

No distinct trends in observation of segregations were apparent, limiting the use of this indicator for wetland identification in the arid region.

Ferruginous root channel and pore linings were not observed in the majority of wetlands sampled. This can be attributed to the wetlands being saturated so infrequently and to the lack of seasonal vegetation growth to form such features. Nearly all (8/9) wetlands sampled did not have ferruginous root channel and pore linings present.

There is a considerable evidence for the use of soil matrix chroma values for wetland identification in the arid region. Chroma values increased moving out of the wetland in the majority of wetland types sampled. Because of the lack of other soil features to distinguish the wetland boundary soil chroma may be the most useful to define the boundary of the wetland in the arid region accurately.

Considerations when using soil indicators for wetland identification in Queensland

The following section illustrates some considerations when applying soil indicators for wetland identification in Queensland. As this study focused on a statewide assessment, there will be situations where the recommended indicators for use may not apply at a particular wetland and it may be necessary to take other information into consideration for wetland identification.

As a result of the current study it is clear many soil indicators are suited to particular climatic regions, wetland and soil types. Indicators may also be indicative of a particular region and not reflective of a wetland soil (i.e. the mottled landscape of the tropical climatic region is a result of the hydropedological environment).

The following section outlines the current recommended wetland soil indicators for use in Queensland and presents conclusions made from the current study regarding the application of these indicators for wetland identification in Queensland.

Organic material

There were significant trends apparent in the presence of organic material between the different climatic regions. The presence of organic material is one of the more compelling indicators for wetland soils because of the predisposition to accumulate under wet conditions. Temperature, rainfall and solar radiation influence the amount of total carbon in the soil and the rate at which soil organic matter decomposes. Organic matter accumulation increases with increasing saturation and rainfall but decreases with increasing temperature (Peverill *et al.* 1999). The use of organic material (Figures 21 and 22) to identify wetland soils throughout Queensland is more relevant in subtropical environments where saturation favours slow decomposition of organic matter and temperatures allows for organic matter to accumulate. In the tropical environment rainfall and radiation inputs produce organic material; however, the higher temperatures may retard the accumulation of a large amount of soil organic matter in wetlands. Wetlands of the semi-arid and arid climatic zone do not naturally accumulate large amounts of organic matter. These drier environments generally have reduced seasonal plant growth with higher temperatures, which favour decomposition of organic material.

Streaked organic material is found in sandier soils when sapric/hemic organic material has coated the sand particles. The only observation of streaked organic matter in the current study was in two wetlands dominated by sandy soils, which appeared to be permanently saturated for most of the year. This leads to the conclusion that this indicator suits a specific wetland and soil type but would not be a commonly used indicator for wetland identification.

There is a requirement in the American classification system to have an organic material layer at least 0.2 m thick for it to be considered a wetland soil indicator (USDA 2006). In the Australian Soil and Land Survey Field Handbook (McDonald *et al.* 1990) it is noted that a P horizon (or peat horizon) is dominated by organic material as a result of saturated conditions. Because the formation of P horizons is dependent on prolonged saturation, its presence confirms a wetland soil regardless of how thick the horizon layer is.

Where there is a mineral soil that is appreciably organic but not dominated by organic material (i.e not a P horizon) these soils may be classified with a fibric or sapric qualifier (McDonald *et al.* 1990). In this case the thickness of the soil layer would be important for determining whether it is classified as a wetland soil. In the current study 19 sites had soil with fibric and sapric textures that were not part of a P horizon. Of those sites, 11 had a horizon thickness greater than 0.2 m. These 19 wetlands were in the tropical and subtropical climatic regions and consisted of a range of palustrine and lacustrine systems, periodically or permanently inundated. It is recommended that to classify as a wetland soil, a mineral soil layer with fibric or sapric textures must be at least 0.2 m in depth.

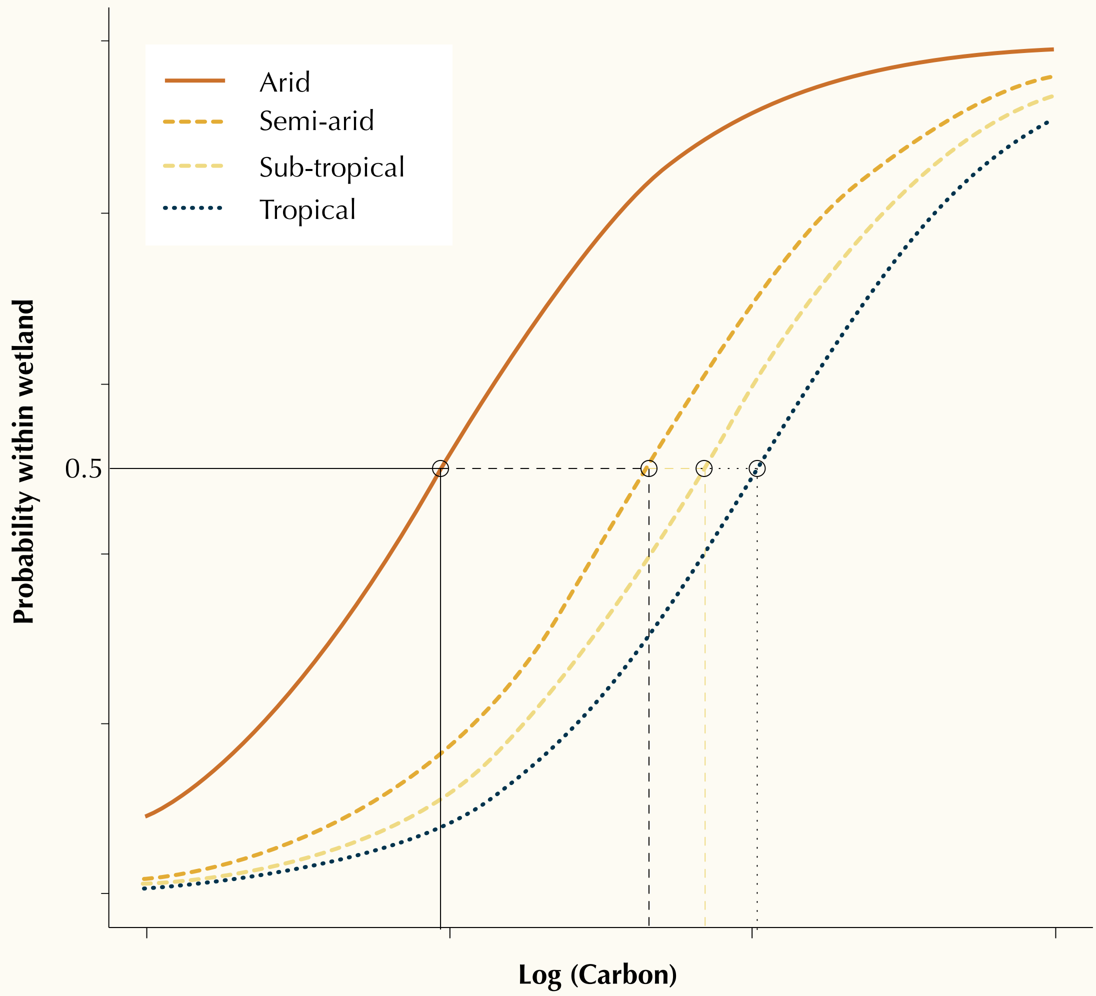
Soil total carbon content in the surface 0-0.1 m was a good indication of the wetland boundary in some climate regions and wetland groups. Total carbon levels in wetland soils varied significantly across climatic regions (Figure 8) precluding the use of TC(%) as a wetland soil identifier statewide. Results from this study suggest that a probability-based approach for TC(%) as a wetland indicator is more robust than a single-point figure.

Logistic regression was used to determine whether carbon content is a predictor for the probability of being either in or out of a wetland.
Results show there is a statistically significant increase in probability with increases in soil carbon and that the relationship is dependent on climatic region.The model also indicates that as a general trend, at any given soil total carbon level, the site had greater probability of being in a wetland in the arid climatic region followed by the semi-arid, the tropical and lastly the subtropical region.
Figure 23 is an example of the type of relationship that the logistic regression analysis could provide to aid wetland identification. To develop the relationship and provide a quantitative measure of soil carbon and wetland status there is a need for more site sampling, including replicates.

Figure 21. Fibric organic material from a wetland on North Stradbroke Island, south-east Queensland. Material extends to 0.6 m.

Figure 22. Sapric organic material from a wetland at Cape Flattery, Cape York Peninsula. Material extends to 0.5 m.

Figure 23. Example of preliminary trend from logistic regression analysis for total carbon content and climatic region



Mottles and segregations

Mottles

The presence of mottling is typically an indicator of poor drainage or water fluctuation throughout the soil profile. It is usually present in soil that has experienced intermittent periods of reduction and is one of the more easily identifiable indicators in wetland soil. However, mottling can persist in the environment from a single saturation event and may not reflect a current water regime. He *et al.* (2003) states that a saturation event of only 21 days was enough for reduced conditions to be achieved for a particular soil and for redox features to form. Without information relating to the current hydrologic regime it is difficult know if reduction indicators are the product of a current hydrologic regime or a relict one.

Soil may present mottling features that are a product of saturated soil through a capillary fringe effect from a lower ground watertable. Soil can develop redox features by saturation of the capillary fringes without meeting the saturation requirements of a wetland (Vepraskas 1998).

Mottles are largely formed by the oxidation and reduction of iron and manganese in the soil and therefore do not readily form in soil naturally low in these elements. A lack of iron and manganese is more common in coarser sandy soils (Dear and Svensson 2007).

Relating mottling features (Figure 25) to the current water regime is important for determining if these features are relict or contemporary. From the wetlands surveyed in this study no definitive trend was found for the presence of mottles in identifying a wetland. This was particularly apparent in large areas of the tropical climatic region where most of the landscape (not considered wetlands) is mottled from seasonal saturation. The use of mottles alone to determine the boundary of a wetland is misleading without information relating to a current hydrologic regime.

Segregations

Segregations develop in areas where air has penetrated the soil quickly in a saturated environment. Consequently they are not usually found in permanently saturated soil as it is essential for periodic wetting and drying to occur (Dear and Svensson 2007). This was clearly observed in the wetlands in the current study.

The focus for the current study was on segregations which were ferruginous or manganiferous in nature as these were the segregations outlined for wetland identification by Dear and Svensson (2007). However, segregations of gypsum, carbonate and salt were prevalent in arid to semi-arid wetlands in the current study. Tiner (1999) has stated that in climates where evaporation exceeds precipitation the accumulation of salts is associated with wetlands. Steinwand and Richardson (1989) found that gypsum concretions form along the transition zones of semi-permanent prairie pothole wetlands of the United States, and that this strongly correlated with the salinity of the wetland. This fringing of gypsum in the transition zone was recorded in large intermittently inundated closed-depression wetlands in arid and semi-arid environments in Queensland. This effect may be attributed to gypsum being leached out of profiles at sites in wetland areas subject to more frequent inundation. Where inundation is not frequent—i.e. at the fringe of the wetland, leaching does not occur and there is an accumulation of gypsum. In subtropical and tropical climatic regions there would be sufficient rainfall and inundation for gypsum to be leached from sites in the wetland and sites outside it.

There was no trend in observations of ferruginous or manganiferous segregations across wetland groups and climatic regions in the current study. Vepraskas (1998) observed that nodules and concretions, without other wetland soil indicators present, should be considered relict features. The use of segregations (as for mottles) by themselves for wetland identification is deceptive without information relating to a current hydrologic regime.

Soil colour

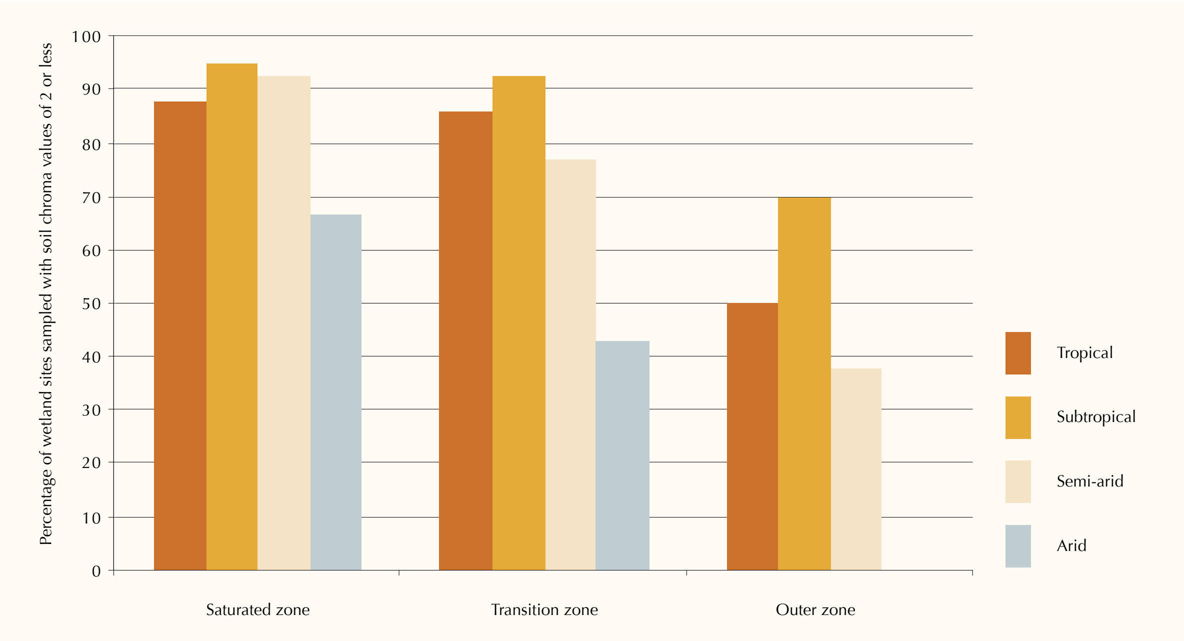
The presence of grey or gley colours, or low chroma (2 or less) in soil can indicate seasonally high watertables. Soil chroma decreases the longer soil is saturated and reduced (He *et al.* 2003). Grey and gley colours and soil with low chroma (2 or less) form following the reduction and removal of iron oxide coatings from individual mineral soil grains and are indicative of anaerobic conditions (Williams *et al.* 2001). However, this does not provide information relating to the duration of saturation or its frequency.

Soil chroma values were a useful indicator in the current study to identify wetland status. Typically chroma values decreased as sites moved into the wetland for all climatic regions and wetland groups (Figure 24).

This relationship was more pronounced in the arid and semi-arid regions, as many wetlands in the subtropical and tropical regions had low chroma values in sites in the outer zone. Vepraskas (1998) observed that where organic carbon is generally lower (<1%), chroma values of less than 2 suggest the area is subject to long periods of saturation. However, chroma values of 3 indicate significant periods of saturation without the level of reduction observed in other locations with higher organic carbon levels. This is true for the wetlands sampled in the semi-arid and arid region. Several wetlands in the arid zone that appeared to be saturated intermittently had chroma values of 3.

4. Discussion

Figure 24. Percentage of sites sampled with soil chroma values of 2 or less



In the arid and semi-arid regions soil chroma values may be one of the more prominent wetland soil indicators, given the general lack of other soil indicators observed in these regions.

Soil matrix chroma values were generally only useful in loamy or clay soils. Sandy soils sampled in this study had chroma values of 2 or less in sites in the outer zone. For soils dominated by sand textures, low chroma values alone are not considered good indicators of wetland soil without additional indicators such as organic material, redox features or ferruginous root channels and pore linings (Richardson and Vepraskas 2001).

Gley colours (matrix and mottles) were commonly located in permanently inundated wetlands throughout all climatic regions and are a reliable indicator of a reduced environment (Figure 25).

Ferruginous root channels and pore linings

The use of ferruginous root channel and pore linings is a good indicator of saturation events occurring (Tiner 1999). Ferruginous root channel linings provide reliable evidence of plant growth in a saturated environment, where the root has pushed oxygen into the saturated soil forming a coating of ferric iron around the root channel (Figure 25).

Mendelssohn *et al.* (1995) postulates that the presence of oxidised root channel linings coupled with the presence of an actual growing root suggests evidence of the current hydrologic regime, as the lining must have occurred in the lifespan of the plant.

Oxidised pore linings occur where oxygen has moved through pores in the soil matrix causing a coating of ferric iron to form. This can be a relict feature in soil and may again be misleading as a single indicator to aid wetland identification without information relating to the current hydrologic regime.

Acid sulfate soil material

Acid sulfate material is commonly thought to occur in coastal environments where seawater provides the source of sulfur for reduction. The presence of inland acid sulfate soil is well documented but less frequent.

Two readily identifiable indicators of sulfidic material used during this study were hydrogen sulfide gas (or rotten egg gas) and sulfurous segregations or yellow jarosite. Both indicators were detected in wetlands expected to have the presence of acid sulfate soils.

The presence of hydrogen sulfide gas is an indicator of a currently reduced environment (Richardson and Vepraskas 2001) and the observation of sulfurous segregations indicates that hydrogen sulfides are present.

A third indictor of sulfidic material, as outlined by Dear and Svensson (2007), is the detection of methane gas, which requires a minimum 24-hour assessment for accurate determination. During a single site visit this indicator is not easily identified and is therefore not recommended for common use in Queensland. The presence of organic ooze enriched with monosulfides, also called monosulfidic black ooze (MBO), is also a common feature of acid sulfate soils. Other non-soil indicators of acid sulfate soils are the presence of iron staining in the surrounding environment.

Soil–water interface

At the top of the soil–water interface a thin layer of red or orange soil colours may exist as evidence of the oxidation reactions occurring. This was observed at one site in a saline playa lake in the semi-arid region (Figure 25). Given the limited occurrence of this indicator it is not recommended as a primary wetland soil indicator but, if present, it provides a clear indication of the water-table depth.

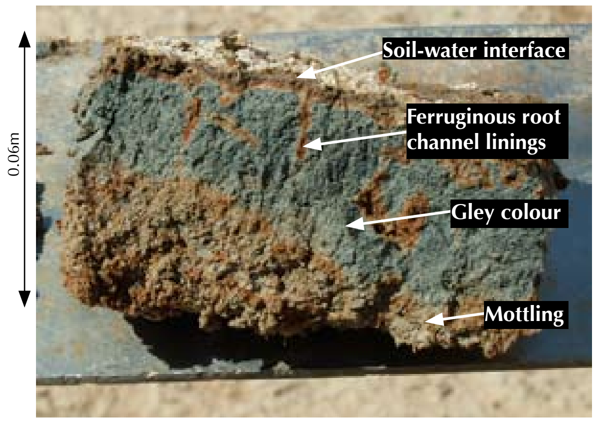


Figure 25. Presence of a soil–water interface, ferruginous root channel linings, gley colours and mottles from the soil surface of a lacustrine wetland in the semi-arid region.

Contextual information

Landform

Landform can help determine if areas are predisposed to saturation or ponding of surface water. McDonald *et al.* 1990 sets clear guidelines on the description of landform where attributes within a 20 m radius from the site are used. Landform attributes are described based upon slope, morphological type and name. A list of attributes to describe landform elements, as adapted from McDonald *et al.* (1990), that relate to wetlands, are included in Appendix 3. Landform is not indicative of a current hydrologic regime but can provide useful contextual information.

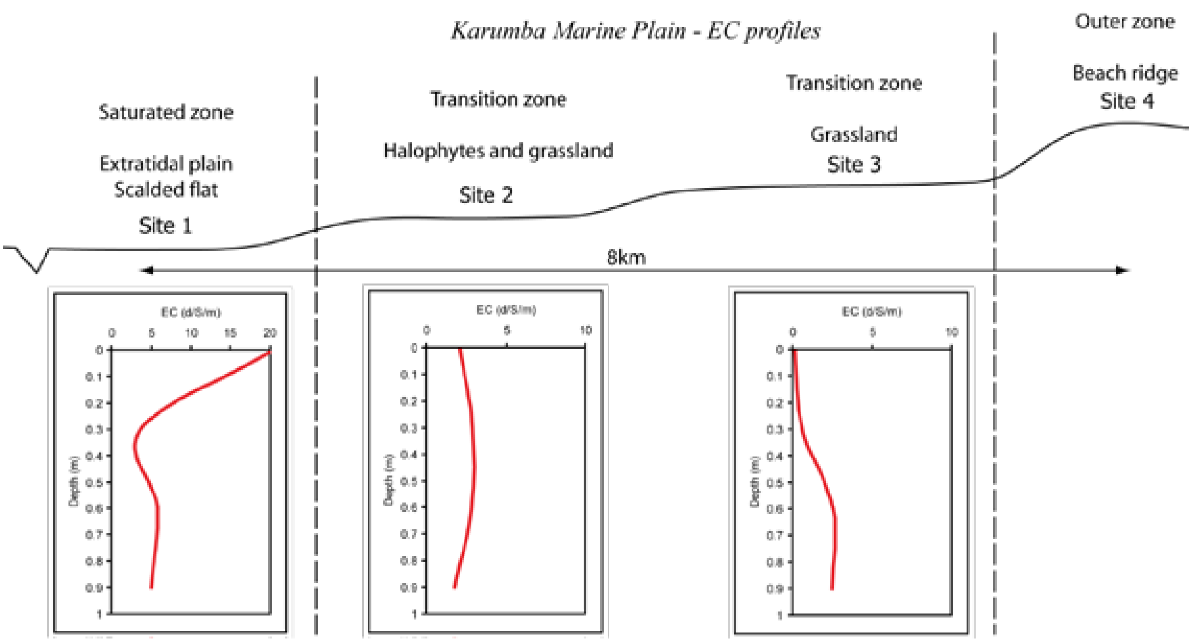
Salt profiles

The salt profiles observed during this study informed whether a wetland site was dominated by an evaporative or leached profile. Evaporative profiles have salts that accumulate towards and on the surface of the soil and leached-profile salts have moved down the soil profile. An example of this in the current study is a wetland on a marine plain near Karumba (Northern Gulf). The site in the wetland had an evaporative profile with a high concentration of salts at the surface and little leaching of salt, making this a hostile environment for vegetation growth. Moving out of the wetland into the transition zone salts were beginning to be leached down the soil profile with a lower concentration at the soil surface (Figure 26). Both profile types are indicative of different water regimes and provide interpretive information when describing wetland soil indicators.

Mottle and segregation boundaries

Mottle and segregation boundaries can help identify whether features are the product of contemporary or relict water regimes. Typically diffuse boundaries are considered contemporary features and sharp boundaries denote relict conditions in which features are no longer forming (Richardson and Vepraskas 2001).

Figure 26. Salt profiles of a wetland in the current study



This cannot be universally applied to all mottles and segregations because contemporary features with sharp boundaries were apparent in some wetlands sampled in the current study. Boundary conditions for segregations and mottles are difficult to interpret even for experienced soil scientists. This indicator may not be appropriate as a definitive indicator of either a relict or current hydrologic regime but may be more appropriate as contextual information to be utilised with other indicators.

Determining the current hydrologic regime

It is important to understand that soil features indicating saturated conditions need to be interpreted with regard to whether they are reflective of a current hydrologic regime or a relict one. In situations where indicators suggest further information is required about the current hydrologic regime to aid wetland identification, non-soil features may be used to provide this information. The following section describes the use of such features to determine whether hydrologic regime is current or relict for the purposes of wetland identification.

Microrelief

The microrelief most commonly associated with wetlands is hummocky microrelief, which includes debil debil and swamp hummocks.

Debil debil are small hummocks that rise above a planar surface. They are common in north Australian soils with impeded internal drainage and in areas of short seasonal ponding. Many observers consider them to be formed by biological activity (McDonald *et al.*1990).

Swamp hummocks are steep sided, rising above a flat surface. Hummocks are frequently occupied by trees and shrubs while the lower surface may be vegetation free or occupied by sedges or reeds. They are subject to prolonged seasonal flooding (McDonald *et al.* 1990).

The presence of hummocky microrelief is a positive indicator of the current hydrologic regime, as these are formed over time, rather than by one-off events. Sixteen sites in the current study (from 180) recorded the presence of hummocky microrelief. They were observed in wetlands in the tropical and subtropical climatic regions only, in palustrine and lacustrine systems and in wetlands that were both periodically inundated and commonly wet.

Figure 27. Flood-carried debris present at a site in the outer zone.

Figure 28. Example of floodmarks on trees in a palustrine wetland in the tropical climatic region. It appears the water level remains at approximately 0.4 m above ground for a period of time.

Floodmarks

Evidence of recently flooded areas via floodmarks can often be considered evidence of a current hydrologic regime. Floodmarks consist of water-carried debris, silt lines or water marks on trees and leaves. It is thought that water-carried debris and silt lines can be obtained from a one-off event and careful consideration must be used when applying this as a measure of the current hydrologic regime. This was apparent at a wetland in the current study where flood debris was visible at a site in the outer zone (Figure 27). This indicated the water level had reached that point at some time but there was no evidence from the soil indicators or the vegetation to suggest this site was considered a wetland.

Minimal research exists into the length of time for floodmarks (Figure 28) to form on trees and leaves. However, Tiner (1999) considers these floodmarks are common in wetlands that are predisposed to prolonged inundation and may be considered as an indicator of the current hydrologic regime.

If other wetland soil indicators are not present it is recommended that wetland vegetation species are used to determine the status of the wetland.

Algal mats

The presence of algal mats on the soil surface or algal or moss lines on trees can also indicate a ponding event; however, this does not identify the duration or frequency of the event.

Figure 29. Cryptogam surface for a palustrine wetland in the tropical climatic region.

4. Discussion

Two wetlands in the current study recorded the presence of a cryptogam surface. A cryptogam surface is a continuous crust of biologically stabilised soil material, usually due to algae, liverworts and mosses (McDonald *et al.* 1990). One of these sites was in the saturated zone and the other in a transition zone (Figure 29). Both were present in areas that appeared seasonally inundated.

Aerial roots

Aerial roots are an adaptation of plants to a water-logged environment. This adaptation occurs when initial roots die back from anoxia and other roots are forced to grow in positions that can access oxygen (Tiner 1999). Aerial roots are an indicator of the current hydrologic regime because this adaptation does not usually occur from a one-off event but over a period of time. Mangroves are a good example of plants adapted to a saturated environment through the growth of aerial roots.

Iron staining of surrounding environment

Iron staining is a by-product of the oxidation of acid sulfate soils. This leads to the formation of rust-coloured iron stains that coat the surrounding environment (Figure 30) and the formation of oily-looking bacterial surface water (NRW 2006). Iron staining is a non-soil indicator of acid sulfate soils and exists in environments where acid sulfate soils have been exposed to oxygen and are oxidising. This indicates the soil has been saturated or ponded at some point but consideration needs to be used when determining whether this reflects the current hydrologic regime.

Figure 30. Iron staining at an estuarine wetland in the tropical climatic region.

Water-table depth

Monitoring water-table depth for a period of time will provide the necessary information for determining wetland status. For soils to meet the requirements for wetland hydrology in the American wetland identification system a positive measure of watertable 0.3 m from the soil surface is required for a defined period (Vepraskas *et al*. 2004).
Any reliance on this indicator during a single site visit may be uncertain given fluctuations in water-table depth. In Queensland the time of year at which sites are sampled will have a direct effect on the presence of a watertable (Table 23). It is difficult to determine the duration of saturation from a single site inspection, especially in environments that lack strong seasonality and have variable rainfall.
In such cases expert opinion or local knowledge may be required (Isbell *et al.* 1997). In areas subject to highly variable rainfall, where some years may be significantly wetter than others, the direct presence of water may not be a reliable indicator of wetland status (Marnewecke and Kotze 1999).
This is particularly significant for wetlands in the arid and semi-arid regions of Queensland which are not influenced by seasonal rainfall.

Observing a watertable within 0.3 m of the soil surface is a good indication of wetland status but it is not definitive. A watertable needs to be observed for a period of time because the duration of saturation cannot be determined from a single site inspection. The exact period of time is not currently defined in Queensland. However, the lack of a watertable does not mean the soil is not saturated at some time, therefore it may be classed as a wetland.

Table 23. Summary of recordings of water-table depth of wetlands sampled across climatic regions.

Tropical	Watertable present within 0.3 m of the surface in wetlands that appeared to permanently inundated only Majority of wetlands sampled in the dry season
Subtropical	Watertable present within 0.3 m of the surface at sites in the wetland for the majority of wetlands sampled
Semi-arid	Majority of wetland sites sampled in wetter months No presence of a watertable recorded within 0.3 m of the surface for any wetlands sampled
Arid	No presence of a watertable recorded within 0.3 m of the surface for any wetlands sampled At the time of sampling the region was experiencing drought conditions

Monitoring trial

The accumulation of organic material was observed in swamps that were saturated (<0.3 m from the soil surface) for more than 32 per cent of the trial periods in both the subtropical and tropical climatic regions. However, this figure is ambiguous as it represents the lowest percentage of saturation in a swamp that had organic matter accumulation (Eubenangee transition zone). This is a location that has information for only half the year, mostly focused in the wet season. It is anticipated this figure would be greatly reduced when information is available on water levels in the dry season.

The transition zones in Bribie Island (middle swamp crossing) and Deepwater NP swamps also have significant organic matter accumulation but no data is available. It is anticipated these regions would have a lower saturation period, which would also reduce this figure.

There is good correlation between the formation of redox features (namely mottles and segregations) and the depth of a wet season watertable at Tam O'Shanter swamp (saturated zone and transition zone) and Eubenangee (transition zone only). This supports the theory by Richardson and Vepraskas (2001), who outline an approach to predicting a seasonal watertable without hydrologic data by using the presence of grey or gley mottles.

The depth at which these features occur marks the level of a seasonal watertable. However, there are considerations in using this method because it does not predict the duration or frequency of saturation and it assumes the water level rises no further than the depth indicated by mottling, although it may do so for short periods. The trial has shown that a saturation of five per cent or 17 days over a year (Tam O'Shanter transition zone) is sufficient for redox features to form and that these features are indicative of a wet season watertable.

There was a large difference between the rate at which water drains between swamps in the tropical and the subtropical climatic regions. Both swamps in the tropical climatic region had average drainage rates of 0.10 m per day and above, while the swamps in the subtropical climatic region had rates from 0.005–0.06 m per day.

Both wetlands in the subtropical climatic region are influenced by shallow groundwater systems in dune swales. This may slow drainage rates (even in the sandier soils) as the surface water comes into contact with the groundwater systems. The two swamps in the tropical climatic region are not influenced by groundwater interaction but the significantly higher rainfall (>4000 mm per year) promotes the formation of wetland features even with a much higher drainage rate.

The lack of data from six wetland sites in this trial has not allowed the full comparison between soil features and saturation across the range of wetlands monitored.

4. Discussion

However, the current results do highlight some significant points:

- The depths to which redox features (mottles and segregations) occur in the soil profile are indicative of a seasonal watertable in the wetlands monitored.
- Organic matter accumulation occurred in wetlands that were inundated, even for short periods of time (<6 days per year). No organic accumulation occurred in the wetlands where there was no inundation.

Indicator of Reduction In Soils (IRIS) trial

Reduced conditions were evident from the removal of paint at all three wetland sites trialled. Reduction was not necessarily uniform across the sites, with different patterns of paint removal observed—from complete and uniform removal of all or some of the paint to patchy, circular removal that was sporadic over the length of the pipes.

The pipes with complete removal of paint were in areas inundated throughout the trial and that had total carbon levels greater than 12 per cent.

These sites were in areas likely to remain permanently inundated and therefore subject to an environment that remains reduced. Areas where reduced conditions were indicated by patchy removal of paint were at sites that appeared periodically saturated throughout the year. These sites were in areas where reduced conditions may be intermittently present. To identify the full extent of the reduced environment, trials may have to be run over both wet and dry cycles throughout the year in these particular wetlands.

At the two sites in the permanently inundated dune swale system (Sites 21 and 22) there appeared to be a layer of aerated water that prevented the removal of paint from the top of the pipes. The pipe that had complete removal of paint from the surface (site 215) was in an area on a coastal plain where acid sulfate soils were observed on installation (hydrogen sulfide gas detected) and that was inundated throughout the trial. There appeared to be no aerated layer of water in this area, which suggests acid sulfate soils may contribute to, or be indicative of, a more strongly reduced environment.

The amount of reduction present (as indicated by the removal of paint) appeared correlated to the clay content of the soil. In soil with clay contents greater than 25 per cent there was less evidence of reduction (through the removal of paint) than at sites with sand or organic-dominated soils. This was apparent in areas subject to periodic inundation throughout the year and may be attributed to the reactions between clay and organic carbon, making organic carbon unavailable to reducing microbes. Clay can bind organic carbon making it unavailable to microbes physically through protection in smaller aggregates or through chemical binding (Hassink 1992; Van Veen and Kuikman 1990). If organic carbon is unavailable as an energy source for the microbes, essential to produce a reduced environment, it may explain the lack of reduction observed.

The lack of reduction at some periodically inundated wetland sites could also be attributed to the time the pipes were in the soil and the season in which the trial was conducted. Anaerobic conditions can vary in soils over different seasons and also during a season (Rabenhorst and Castenson 2005). Pipes that are not in the soil for enough time may have no removal of paint.

The 21-day test period was used by Castenson and Rabenhorst (2006) who conducted similar trials. Vepraskas *et al.* (2004) also determined that 21 days was the time required for reduced conditions to be produced after an inundation event but this was related to specific soil types defined by the US Soil Taxonomy (USDA 1999) as oxiaquic paleudults and typic albaqualfs. These soils roughly correlate to the Hydrosol order in the ASC (Isbell 2002) but may not reach the saturation requirement for a Hydrosol. Similar soils and climatic conditions may exist in the coastal swamps of southern New South Wales (Powell pers comm). Trials may need to be conducted over wet and dry cycles to determine the time required for an accurate indication of the reduced environment in periodically inundated wetlands.

Trials of the IRIS method showed promising results for indicating the depth to reduced conditions.

Further research in this area may allow the IRIS method to be used as an inexpensive tool providing accurate information on wetland status.

A few key areas of further research are to determine:

- the time necessary for pipes to be installed across wetlands that are periodically inundated, to provide an accurate representation of reducing conditions
- the effect of different soil textures on the amount and pattern of reduction that occurs
- the level of reduction (or amount of paint removal) required to enable classification as a wetland soil.

5. Key to wetland identification using soil indicators

This is the first statewide assessment of wetland soils in Queensland and a number of difficulties have been identified regarding the application of a single set of indicators across such a varied landscape. General trends are apparent for indicators identified across different soil types and climatic regions, as discussed in the Results section on page 19. Applying these indicators definitively requires more stringent evidence to accurately determine wetland boundaries using soil.

'Weights of evidence' is a term used in scientific literature and policies in the context of risk assessment, although there is no defined meaning for this term (Weed 2005). A weights-of-evidence-based approach for using wetland soil indicators is suggested to reduce the uncertainty of applying a single set of indicators across such a varied landscape.

When applying the key, where there is uncertainty with a particular indicator, other forms of evidence are required to definitively identify wetland soils. This is suggested as the most appropriate method for classifying wetland soils because many indicators can exist from relict hydrologic regimes and do not reflect the current environment. This would ensure that the best available information was used at any given time.

Rationale of the key

The key is split into three sections or parts (figure 31), each building on the evidence gained from the previous section. When enough evidence exists to determine if a soil is or is not a wetland soil, it is classified as such. Each section is hierarchical with the more reliable evidence used first and less conclusive information used in the later part of each section.
The three parts are:

- wetland soils
- wetland soil indicators
- landscape features

Figure 31. Rationale of the key

Part 1
Using the Australian Soil Classification the soil is defined as a wetland soil

↓

If there is insufficient evidence

↓

Part 2
Examine soil morphological features for wetland soil indicators

↓

If there is insufficient evidence

↓

Part 3
Interpret wetland soil indicators with landscape features

Part 1: Wetland soils

ASC Orders considered wetland soils

From the Australian Soil Classification (ASC) the only order that can be definitively called a wetland soil is an Organosol. The ASC defines an Organosol as:

Soils that are not regularly inundated by saline tidal waters and either:

> *Have more than 0.4 m of organic materials within the upper 0.8 m. The required thickness may either extend down from the surface or be taken cumulatively within the upper 0.8 m. or*
>
> *Have organic materials extending from the surface to a minimum depth of 0.1 m; these either directly overlie rock or other hard layers, partially weathered or decomposed rock or saprolite, or overlie fragmental material such as gravel, cobbles or stones in which the interstices are filled or partially filled with organic material. In some soils there may be layers of humose and/or melacic horizon material underlying the organic materials and overlying the substrate.*

The exceptions to an Organosol being unanimously identified as a wetland soil are Organosols present at higher altitudes that do not form under saturated conditions. These soils would not meet the saturation requirements for wetlands because their formation is predominantly based on the accumulation of organic material in low-temperature environments. These Organosols are unlikely to be found in Queensland.

ASC Orders and Suborders likely to be wetland soils

Hydrosols in the ASC are a range of permanently wet or seasonally wet soils and are defined as:

Soils other than Organosols, Podosols and Vertosols in which the greater part of the profile is saturated for at least 2–3 months in most years

Collectively defining all Hydrosols as wetland soils is difficult as the development of the order has not employed traditional methods of emphasising reducing conditions (Isbell 2002). Hydrosols may or may not experience reducing conditions during the period of saturation. The rationale used by Isbell (2002) for the Hydrosol order is that saturation affects soil properties regardless of whether or not reducing conditions are present. It is also difficult to identify redox features because they are not universally indicative of the duration of saturation or its frequency (He *et al.* 2003; Isbell *et al.* 1997). These factors do not support Hydrosols being exclusively classified as wetland soils without taking into account other evidence of a reduced environment.

Two other orders have an aquic component—Podosols and Vertosols. Aquic Podosols are defined by the ASC as soils with long-term (months) saturation of the B horizon with sufficient saturation present to create a reducing environment in the B horizon. The presence of an Aquic Podosol does not necessarily identify a wetland soil. For an Aquic Podosol to be a wetland soil the reducing conditions must be present within 0.3 m of the soil surface.

Aquic Vertosols are defined by the ASC as soils with stagnant water on the surface and/or saturation of the upper 0.5 m more or less continuously for prolonged periods (2–3 months) in most years. Evidence of wetness may be indicated by the presence of mottling or gley colours (Isbell 2002). Because this suborder requires evidence of reduced conditions if the depth at which these features are present is within 0.3 m of the soil surface, the soil would be identified as a wetland soil.

As Hydrosols, Aquic Podosols and Aquic Vertosols are not exclusively wetland soils, they require further interpretation of their morphology and wetland soil indicators to determine wetland status. Part 2 of the key should be used to identify if soils of these orders and suborders should be classified as wetland soils.

Horizon layers considered wetland soil indicators

Peat horizons (or P horizons) are defined by McDonald *et al.* (1990) in the Australian Soil and Land Survey Field Handbook as 'horizons dominated by organic materials in various stages of decomposition that have accumulated either under water or in conditions of excessive wetness'. Since the existence of such horizons is due to saturated conditions, they are good indications of a wetland environment.

5. Key to wetland identification using soil indicators

Part 2: Soil morphological features

Part 2 of the key is used to determine if the wetland soil indicators present are adequate to ascertain if a soil is a wetland soil. Soil features and considerations for their use are discussed in the Discussion section on page 54.

Some wetland soil indicators such as organic material, the presence of acid sulfate soil and gleyed matrix colours provide more compelling evidence to determine wetland status and can be used independently in classifying wetland soils. Other indicators require additional information to determine wetland status because identifying reducing conditions is difficult. The presence of many reducing features such as mottles and segregations is not unanimously indicative of the frequency and duration of a saturation period (Isbell *et al.* 1997). It is also not known whether these features are considered contemporary or relict without having current hydrologic data. For the purposes of this key redox features include mottles, segregations (iron and manganese), ferruginous root channel and pore linings, and decreasing soil matrix chroma.

Part 3: Landscape features

To determine if a soil is a wetland soil some wetland-landscape features that are indicative of a current hydrologic regime may need to be used.

These non-soil indicators are discussed in detail in the Determining the current hydrological regime on page 64 and are highlighted in Table 24. The use of landscape features will be more prevalent in arid, semi-arid and tropical regions where soil indicators, which require further interpretation, are common and there is an increased reliance on the use of redox features alone.

The key to wetland identification using soil indicators is summarised in Figure 32.

When applied to wetland locations sampled in the current study the key is accurate in correctly identifying wetland soils for more than 80 per cent of wetlands. The key is more accurate in identifying wetland soils in the saturated zone where wetland soil features are more pronounced.

In areas that are periodically or intermittently inundated—i.e. transition zone sites or ephemeral wetland locations, there is a reliance on redox features and landscape information alone to determine wetland status. If landscape features are not present to determine a current hydrologic regime there is insufficient evidence to identify a wetland soil using the key.

Figure 32. Key to wetland identification using soil indicators

Part 1: Wetland soils	
1. Is the soil an Organosol in the Australian Soil Classfication*?	
Yes	within wetland
No	Go to 2
2. Does a P horizon occur within 0.3m of the soil surface**?	
Yes	within wetland
No	Go to 3
Part 2: Wetland soil indicators	
3. Which climatic region is the site in?	
Tropical/Equatorial	Go to 4
Subtropical	Go to 4
Semi-arid	Go to 5
Arid	Go to 5
4. Are organic materials present within 0.3m of the soil surface and is the thickness of organic materials layer at least 0.2m?	
Yes	within wetland
No	Go to 5
5. Is there evidence of the acid sulfate soils within 0.3m of the soil surface?	
Yes	within wetland
No	Go to 6
6. Is there evidence of gleyed soil matrix colours in a horizon starting within 0.3m of the soil surface?	
Yes	within wetland
No	Go to 7
7. Are redox features present within 0.3m of the soil surface?	
Yes	Go to 8
No	Not a wetland soil
Part 3: Landscape features	
8. Do the surrounding landscape features provide supporting evidence of a current hydrologic regime?	
Yes	within wetland
No	Insufficient evidence to identify a wetland soil

* Isbell (2002)

** P horizon as defined by McDonald *et al* (1990)

6. Key findings and recommendations

The wetland soil indicators trialled during this project were adapted from wetland identification techniques developed in other parts of the world that do not take into account the unique landscapes, climate and wetland groups represented across Queensland. These findings, from the statewide assessment of soil indicators, advance the knowledge of wetland soil across Queensland.

Soil indicators that form in wetlands are affected by the climatic region, wetland system and the duration and frequency of inundation. The indicators identified by the current study (Table 24) and applied in the key (Figure 32), provide a solid foundation for wetland soil information in Queensland. Several of the indicators identified require further analysis and consideration if they are to be definitively used for wetland identification.

The use of redox features in wetlands subject to periodic inundation does not accurately identify wetland status. These features rely on the identification of the current hydrologic regime and are better suited to areas subject to permanent or seasonal inundation. Further research is necessary to refine the use of redox soil indicators as a single attribute for determining wetland status.

Soil total carbon content in the surface 0–0.1 m was a good indication of the wetland in some climate regions and wetland groups. Total carbon levels in wetland soils varied too significantly across climatic regions to use a single TC(%) to identify a wetland soil.

Results from this study suggest that a probability-based approach for TC(%) as a wetland indicator is more robust than a single-point figure. It proved difficult to identify wetlands using soil features alone for wetlands in a highly seasonal environment.

The soil indicators may only be present in the areas that are constantly inundated or saturated. The areas inundated during the wet season appear to lack the period of saturation required for anaerobic or reduced conditions to occur and for soil indicators to form. This was apparent at several wetlands sampled in the current study.

Landscape features are required for accurate mapping of periodically inundated wetlands in arid and semi-arid environments.

Soil matrix chroma was the only wetland soil indicator identified that could aid wetland identification across many wetland groups in these regions. Given the overall lack of other soil features identified, decreasing soil matrix chroma may be one of the more powerful indicators for wetland identification. Further research is necessary to determine the minimum thickness of a layer within 0.3 m of the soil surface that has chroma values less than or equal to 2 to apply this indicator definitively in the arid and semi-arid regions.

The episodic nature of wetlands in the semi-arid and arid environments does not allow ferrous segregations to readily form. Other forms of segregations (like salt, gypsum and carbonate) for these particular wetlands, may aid wetland boundary identification. This is dependent on site-specific chemistry, parent material and landform. Further research will be required for the development of this trend.

The time required for a watertable to rise within 0.3 m of the soil surface and thus be classed as a wetland is not defined. For this indicator to be used as a definitive measure of wetland status there is a need to determine this period.

This study used single site inspections to determine wetland status. Given Queensland's highly variable rainfall it may be impossible to assess a water regime based on soil indicators from a single site inspection, a fact also noted by Dear and Svensson (2007) and Isbell *et al.* (1997). To obtain accurate soil information to determine wetland status it may be necessary to conduct site inspections in ephemeral and periodically inundated wetlands over several wet and dry periods.

The applicability of these indicators at fine scales is difficult to determine. This study was conducted at a scale to determine variation in the indicators across a large area and to develop the trends in wetland soil indicators across Queensland.

For fine-scale assessments the use of these indicators over small distances (i.e. tens of metres) to determine the wetland boundary would not be accurate. Further research is required to refine the indicators for use over small distances. In some high-risk coastal wetlands, where a high level of precision is necessary, further research will be required.

Table 24 Soil indicators for the identification of Queensland wetlands

Indicator	Recommendation	Comment
Organic material	Recommended	Only relevant in tropical and subtropical environments
Streaked organic matter	Recommended	Only observed in specific wetlands (sandy soils, commonly wet). Would only be relevant in the tropical and subtropical environments
Gleyed matrix	Recommended	Easily identified in the field across all wetland groups and climatic regions
Decreasing matrix chroma	Recommended	More apparent in wetlands in the semi-arid and arid climatic regions. Not reliable in sandy soils without additional information
Mottles	Recommended	Easily identified in the field but, to be used for wetland identification, needs to be taken into context with evidence of a current hydrologic regime. More prevalent in clay soils
Segregations	Recommended	Easily identified in the field but, to be utilised for wetland identification, needs to be taken into context with evidence of a current hydrologic regime
Soil–water interface	Recommended	Only observed in one wetland in current study but, if present, provides reliable evidence of water-table depth
Ferruginous root channel and pore linings	Recommended	Easily identified in the field across all wetland groups and climatic regions
Hydrogen sulfide gas	Recommended	Easily detected in the field and indicates a reduced environment
Microrelief	Recommended	Hummock microrelief a good indication of current hydrologic regime
Aerial roots	Recommended	Good indicator of a current hydrologic regime
Sulfidic material	Recommended	Easily identified in the field and indicative of the presence of acid sulfate soils
Mottle and segregation boundaries	Not recommended	Difficult to interpret; may provide limited contextual information
Total carbon content	Not recommended	Is suited for use in particular wetland groups but further research necessary to enable use of total carbon to define a wetland boundary definitively
Redox potential	Not recommended	Expensive and time consuming to measure
Ferrous iron detection	Not recommended	Can be a time-consuming and inaccurate test
Particle size analysis	Not recommended	Field texture is sufficient
Soil oxygen	Not recommended	Expensive and time consuming to measure
Methane gas	Not recommended	Requires a minimum 24-hour assessment
Salt profile	Contextual	Indicative of an evaporative or leached soil profile

6. Key findings and recommendations

Indicator	Recommendation	Comment
Landform	Contextual	Provides information on whether a site is predisposed to saturated conditions
Cation exchange capacity	Contextual	Provides no indication of the wetland boundary but is useful contextual information
Floodmarks	Contextual	Indicates recent inundation event but can be a one-off occurrence and not reflective of current hydrologic regime
Algal mats	Contextual	Can be an indicator of a current hydrologic regime but more information required to determine wetland status
Groundwater depth	Contextual	If observed within 0.3 m of soil surface a good indication of wetland status but needs to be observed over a period of time, which is not currently defined in Queensland
Iron staining	Contextual	Indicates presence of sulfidic material but may not reflect current hydrologic regime
pH	Contextual	Provides no indication of the wetland boundary but is useful contextual information

The definition of 'upper layers' of the soil profile or the depth to which soil indicators must be present for classification as a wetland soil was defined as 0.3 m from the soil surface. As this analysis has been conducted at such a broad scale (statewide) it is likely that many wetlands across Queensland may not present any wetland soil indicators or will have indicators below 0.3 m only. In these cases other contextual information such as vegetation, landform and microrelief should be taken into account to determine wetland status.

The current monitoring trial provided good correlation between the presence of redox features (mottles and segregations) indicating the depth to a seasonal high-watertable. However, this is limited to specific climatic regions and wetland groups and further investigation will be required if these features are to be utilised alone for an accurate representation of watertable depth.

Use of the IRIS method to determine the depth at which anaerobic conditions are present in wetland soil has shown promising results in the south-east Queensland trials. Further research to refine this inexpensive technique for Queensland conditions will provide a further tool to aid wetland identification in Queensland.

Given the limited timeframe for this study and the variation commonly observed in wetlands, the recommended soil indicators and key (Figure 32) should be considered a first approximation, with the indicators to be refined and updated over coming years. There will always be exceptions with wetland and soil types that were not sampled in this study that do not fit the current key.

A basic knowledge of soil–landscape functions, with soil survey techniques, is necessary for accurate wetland identification to be made using these indicators. As the knowledge of wetland soils in Queensland increases the indicators will need to be refined and updated as necessary. The recommended indicators used in the current key are a reflection of the analyses performed and knowledge gained to date. As further research on wetland soils in Queensland is conducted, indicators not currently recommended may become more useful for wetland identification.

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APPENDIX 1: Soil indicators for wetland identification

Dear and Svensson (2007)

Indicator	Description
Organic material	Partially decomposed or decomposed plant material (e.g. fibric, hemic or sapric peat); has a thick layer of decomposing plant material on the surface, or has a dark soil layer
Streaked organic matter	Soil is sandy and has dark stains or dark streaks of organic material (decomposed plant material attached to the soil particles) in the upper soil layers
Gleyed matrix	A gleyed matrix (bluish-grey or grey colour below the surface) that occupies 60% or more of a layer starting within 0.3 m of the soil surface
Redox depletions	Bodies of low chroma (2 or less) having a value of 4 or more where Fe and/or Mn have been removed or when both the oxides and clay have been removed from the matrix. The redox depletions may be referred to as iron depletions or manganese depletions
Decreasing matrix chroma, mottle hue and chroma	Matrix chroma steadily decreases when moving from dry to wet soil conditions. Mottle hue and chroma initially increase, but decrease as the soil become increasingly wet
Mottles	The presence of more than one soil colour within a horizon. Mottling occurs as blotches or streaks of subdominant colour throughout the matrix colour. Overall mottle abundance initially increases then steadily decreases as the soil becomes increasingly wet. Soils that are predominantly grey with brown or red mottles are often waterlogged for a longer period than those that are yellow or brown with grey mottles. Soils with only a few grey mottles near the surface are not usually wet enough for the soil to be identified as hydromorphic. The higher the percentage of brighter mottles the more dry oxidising conditions predominate.
Segregations	Nodules and concretions, two specific forms of segregations, are suspected to form when air penetrates soil quickly, perhaps in an area of the wet matrix containing Fe (II) and Mn (II)
Mottle and segregation boundaries	Contemporary and recent hydric soil morphologies have diffuse boundaries, with relict hydric features having sharp boundaries
Soil–water interface	A thin layer of oxidised soil present at the surface of the soil–water interface via the presence of a red–orange colour in the oxidised soil
Oxidised rhizosphere	Oxygen excess to the roots' requirements diffuses into the surrounding soil, forming deposits of oxidised iron along small roots
Pore linings	Oxidised pore linings can be found in reduced soils and can be evidence of a reduced matrix where oxygen enters the pores and oxidises the ferrous iron around the pores
Groundwatertable depth	Present ≤0.30 m from the surface

Indicator	Description
Redox potential	The electrical potential of a system to acquire or give up electrons (Brady and Weil 1996). Redox potential <175mv at pH 7
Ferrous iron detection	Chemical test using the alpha-alpha-Dipyridyl method that indicates the presence of reduced iron (FeII)
pH	pH is not an indicator that can be used to verify the presence/absence of hydromorphic soil. However, it can provide useful interpretive information
Cation exchange capacity	Cation exchange capacity is not an indicator that can be used to verify the presence/absence of hydromorphic soil. However, it can provide useful interpretive information
Particle size analysis	Particle size analysis can provide useful interpretive information
Soil oxygen	≤5 ppm
Hydrogen sulfide	Rotten-egg gas odour detected within the upper 0.3 m of the soil profile
Methane gas	Methane detected in the field
Pyrite present	This compound is stable under reducing conditions and can be detected using a field hydrogen peroxide test
Salt profile	The salt profile is not an indicator that can be used to verify the presence or absence of hydromorphic soil. However, it can provide useful interpretive information.

APPENDIX 2: Wetland location list

No.	Wetland	Location	Coordinates (GDA 94)			Soil type (in wetland)	Wetland type
			Easting	Northing	Zone		
1	Tam O'Shanter NP (licuala palm swamp)	North Queensland	401523	8020261	55	Clay	Coastal and sub-coastal non-floodplain tree swamps—palm
2	Lakefield NP drainage depression	Cape York Peninsula	240302	8305267	55	Clay	Coastal and sub-coastal floodplain tree swamp (melaleuca and eucalyptus spp.)
3	Lakefield NP oxbow swamp	Cape York Peninsula	188696	8358929	55	Clay	Coastal and sub-coastal floodplain grass, sedge herb swamp
4	Lakefield NP coastal plain	Cape York Peninsula	820524	8379886	54	Clay	Coastal and sub-coastal floodplain grass, sedge, herb swamp
5	Ferricrete swamp	Cape York Peninsula	690147	8564589	54	Clay	Coastal and sub-coastal non-floodplain tree swamp (melaleuca and eucalyptus spp.)
6	Archer River swamp	Cape York Peninsula	708199	8517362	54	Clay	Coastal and sub-coastal non-floodplain tree swamp (melaleuca and eucalyptus spp.)
7	Edward River Landscape	Cape York Peninsula	672941	8360737	54	Sand	Coastal and sub-coastal floodplain tree swamp (melaleuca and eucalyptus spp.)
8	Double Lagoon	Gulf Plains	521504	8089239	54	Clay	Coastal and sub-coastal floodplain tree swamp (melaleuca and eucalyptus spp.)
9	Staaten River floodplain	Gulf Plains	609922	8161864	54	Clay	Coastal and sub-coastal floodplain tree swamp (melaleuca and eucalyptus spp.)
10	Melaleuca citrolens chain of pools	Gulf Plains	605282	8144009	54	Clay	Coastal and sub-coastal non-floodplain tree swamp (melaleuca and eucalyptus spp.)
11	Smithbourne Gilbert Aggregation (2 locations)	Gulf Plains	525099	8105469	54	Clay	Coastal and sub-coastal floodplain grass, sedge, herb swamp
			571044	8093117	54		

12	Melaleuca viridiflora drainage depressions (3 locations)	Gulf Plains	518955	8067857	54	Clay	Coastal and sub-coastal floodplain tree swamp (melaleuca and eucalyptus spp.)
			516802	8055928	54		
			540667	8015854	54		
13	Karumba dune swale	Gulf Plains	484157	8068147	54	Clay	Coastal and sub-coastal non-floodplain grass, sedge, herb swamp
14	Eubenangee Swamp (northern transect)	North Queensland	391468	8074891	55	Organic	Coastal and sub-coastal floodplain grass, sedge, herb swamp
15	Eubenangee Swamp (southern transect)	North Queensland	391059	8070725	55	Organic	Coastal and sub-coastal floodplain grass, sedge, herb swamp
16	Lakefield NP lagoon	Cape York Peninsula	213046	8318121	55	Clay	Coastal and sub-coastal floodplain grass, sedge, herb swamp
17	12 Mile waterhole	Gulf Plains	517101	8061992	54	Sand	Coastal and sub-coastal floodplain grass, sedge, herb swamp
18	Cape Flattery	Cape York Peninsula	303501	8334545	55	Sand	Coastal and sub-coastal non-floodplain grass, sedge, herb swamp
19	Cape Flattery	Cape York Peninsula	304687	8331878	55	Sand	Coastal and sub-coastal non-floodplain sand lake—window
20	Normanton Marine Plain	Gulf Plains	510382	8047265	54	Clay	Supratidal flat
21	Karumba Marine Plain	Gulf Plains	503400	8072305	54	Clay	Supratidal flat
22	Bribie Island (lower swamp crossing)	South-east Queensland	512707	7011849	56	Clay	Coastal and sub-coastal non-floodplain tree swamp (melaleuca and eucalyptus spp)
23	Goorganga Plain freshwater swamp	Central Queensland	671010	7740993	55	Clay	Coastal and sub-coastal floodplain tree swamp (melaleuca and eucalyptus spp)
24	Condamine floodplain	South-west Queensland	369173	6913924	56	Clay	Coastal and sub-coastal floodplain tree swamp (melaleuca and eucalyptus spp)
25	Goondiwindi floodplain	South-west Queensland	219625	6840567	56	Clay	Coastal and sub coastal floodplain tree swamp (melaleuca and eucalyptus spp)
26	Carbrook Conservation Park	South-east Queensland	526726	6937382	56	Clay	Coastal and sub-coastal floodplain tree swamp (melaleuca and eucalyptus spp)

27	Bribie Island (middle swamp crossing)	South-east Queensland	512520	7017727	56	Organic	Coastal and sub-coastal non-floodplain grass, sedge herb swamp
28	Goorganga Plain lagoon	Central Queensland	671374	7741337	55	Clay	Coastal and sub-coastal floodplain grass, sedge, herb swamp
29	Brown Lake overflow swamp	South-east Queensland	543372	6957621	56	Organic	Coastal and sub-coastal non-floodplain grass, sedge, herb swamp
30	18 Mile swamp	South-east Queensland	549118	6955932	56	Organic	Coastal and sub-coastal non-floodplain grass, sedge, herb swamp
31	Wivenhoe Dam	South-east Queensland	459066	6976369	56	Clay	No type—artificial wetland
32	Brown Lake	South-east Queensland	542628	6958706	56	Organic	Coastal and sub-coastal non-floodplain sand lake—perched
33	Goorganga Plain mangrove swamp	Central Queensland	671548	7741062	55	Clay	No type—intertidal and supratidal flat
34	Bollon Road claypan	South-west Queensland	459799	6902968	55	Clay	Semi-arid floodplain swamp
35	Wyandra claypan	South-west Queensland	461432	6971081	55	Clay	Semi-arid floodplain swamp
36	Currawinya claypan	South-west Queensland	282304	6829783	55	Clay	Semi-arid floodplain swamp
37	Birch Lagoon	South-west Queensland	655065	6881637	55	Clay	Semi-arid floodplain lake
38	Lake Munya	South-west Queensland	652302	6890133	55	Clay	Semi-arid floodplain lake
39	Murrawondah (lake 1)	South-west Queensland	408600	6897441	55	Clay	Semi-arid floodplain lake
40	Murrawondah (lake 2)	South-west Queensland	406613	6893775	55	Clay	Semi-arid floodplain lake
41	Lake Dartmouth	South-west Queensland	333345	7118063	55	Clay	Semi-arid floodplain lake

42	Lake Kapoonyee	South-west Queensland	238642	6809242	55	Clay	Semi-arid floodplain lake
43	Lake Wyara	South-west Queensland	230071	6817384	55	Clay	Semi-arid saline lake
44	Lake Numulla	South-west Queensland	236184	6816422	55	Clay	Semi-arid floodplain lake
45	Lake Wombah	South-west Queensland	287027	6794351	55	Clay	Semi-arid floodplain lake
46	Lake Bindegolly	South-west Queensland	223107	6892408	55	Clay	Semi-arid floodplain lake
47	Durrie Station	Channel Country	425048	7161188	54	Clay	Arid floodplain swamp
48	Eyre Creek floodplain	Channel Country	363416	7243978	54	Clay	Arid floodplain swamp
49	Cooper Creek floodplain	Channel Country	656936	7108217	54	Clay	Arid floodplain swamp
50	Lake Nappernicia	Channel Country	306212	7134101	54	Clay	Arid non-floodplain swamp
51	Arid zone closed depression	Channel Country	360264	7229015	54	Clay	Arid floodplain swamp
52	Bedourie Swamp	Channel Country	344327	7322410	54	Clay	Arid floodplain swamp
53	Lake Machattie	Channel Country	383062	7252396	54	Clay	Arid floodplain lake
54	Lake Mipia area	Channel Country	358800	7241364	54	Clay	Arid floodplain lake
55	Lake Didichie	Channel Country	427605	7150124	54	Clay	Arid floodplain lake

APPENDIX 3: Landform element descriptions associated with wetlands

Adapted from McDonald *et al.*1990

Morphological types associated with wetlands

F—Flat

V—Open depression

D—Closed depression

L—Lower slope

M—Mid-slope

U—Upper slope

S—Simple slope

Slope percentages

Symbol	Slope class	Degrees (%)[3]
LE	Level	0.6
VG	Very gently inclined	1
GE	Gently Inclined	6

Name

Backplain (BKP): large flat resulting from aggregation by over-bank stream flow at some distance from the stream channel and in some cases biological peat accumulation often characterised by a high watertable and the presence of swamps or lakes

Blowout (BOU): usually small, open or closed depression excavated by the wind

Crater (CRA): steep to precipitous closed depression excavated by explosions due to volcanism, human action or the impact of extraterrestrial object

Dam (DAM): ridge built up by human activity to close a depression

Doline (DOL): steep-sided closed depression eroded by solution directed towards an underground drainage way, or by collapse consequent to such solution. A typical element of a Karst landform pattern

Drainage depression (DDE): level to gently inclined, long narrow, shallow open depression with smoothly concave cross section rising to moderately inclined side slopes, eroded or aggregated by sheet wash

Estuary (EST): stream channel close to its junction with sea or lake where the action of channelled stream flow is modified by tides and waves. The width typically increases downstream

Fan (FAN): large gently inclined to level element with radial slope lines inclined away from a point, resulting from aggradations or occasionally from erosion by channelled, often braided, stream flow, or possible sheet flow

Flood out (FLD): flat inclined radially away from a point on the margin or at the end of a stream channel, aggraded by over-bank stream flow or by channel stream flow associated with channels developed in the over-bank flow; part of a covered plain landform pattern

Footslope (FOO): moderately to very gently inclined waning lower slope resulting from aggradations or erosion by sheet flow, earth flow or creep

Gully (GUL): open depression with short, precipitous walls and moderately inclined to very gently inclined floor or small stream channel, eroded by channelled stream flow and consequent collapse and water-aided movement

Intertidal flat (ITF): see tidal flat

Lagoon (LAG): closed depression filled with water that is typically salt or brackish, bounded at least in part by forms aggraded or built up by waves or reef-building organisms

Lake (LAK): large water-filled closed depression

3 Approximate average slope values from McDonald *et al.* 1998

Levee (LEV): very long, very low nearly level sinuous ridge immediately adjacent to a stream channel, built up by over-bank flow

Lunette (LUN): elongated, gently curved low ridge built up by wind on the margin of a playa, typically with a moderate, wave-modified slope towards the playa and a gentle over-slope

Maar (MAA): level-floored commonly water-filled closed depression with a nearly circular rim, excavated by volcanism

Oxbow (OXB): long curved, commonly water-filled closed depression eroded by channelled stream flow but closed as a result of aggradations by channelled or over-bank stream flow during the formation of a meander landform pattern. The floor of an oxbow may be more or less aggraded by over-bank stream flow, wind and biological peat accumulation

Pediment (PED): large gently inclined to level (less than 1%) waning lower slope with slope lines inclined in a single direction, or somewhat convergent or divergent, eroded or sometimes slightly aggraded by sheet flow. It is underlain by bedrock

Pit (PIT): closed depression excavated by human activity

Plain (PLA): large very gently inclined or level element of unspecified geomorphologic agent or mode of activity

Playa (PLY): large shallow level-floored closed depression intermittently water filled but mainly dry due to evaporation; bounded as a rule by flat aggraded by sheet flow and channelled stream flow

Prior stream (PST): long generally sinuous low ridge built up from materials originally deposited by stream flow along the line of a former stream channel. The landform element may include a depression marking the old stream bed and relict levees

Scald (SCD): flat, bare of vegetation, from which soil has been eroded or excavated by surface wash or wind

Scroll (SCR): long curved very low ridge built up by channelled stream flow and left relict by channel migration

Scroll plain (SRP): large flat resulting from aggradation by channelled stream flow as a stream migrates from side to side

Stream bed (STB): linear, generally sinuous open depression forming the bottom of a stream channel, eroded and locally excavated, aggraded or built up by channelled stream flow

Stream channel (STC): linear, generally sinuous open depression, in parts eroded, excavated, built up and aggraded by stream channelled flow

Supratidal flat (STF): see tidal flat

Swale (SWL):

i) linear, level-floored open depression excavated by wind, or left relict between ridges built up by wind or waves or built up to a lesser height than them

ii) long curved open depression left relict between scrolls built up by channelled stream blow

Swamp (SWP): almost-level closed or almost-closed depression with a seasonal or permanent watertable at or above the surface, commonly aggraded by over-bank stream flow and sometime biological peat accumulation

Terrace flat (TEF): small flat aggraded or eroded by channelled or over-bank stream flow, standing above a scarp and no longer frequently inundated; a former valley flat or part of a former floodplain

Tidal creek (TDC): intermittently water-filled open depression in parts eroded, excavated, built up and aggraded by channelled tide-water flow

Tidal flat (TDF): large flat subject to inundation by water that is usually salt or brackish aggraded by tides. An intertidal flat (ITF) is frequently inundated; a supratidal flat (STF) is seldom inundated

APPENDIX 4: Synthesis of ferrihydrite paint

Martin C. Rabenhorst (2006)

1. Dissolve 16g of anhydrous $FeCl_3$ in 0.5 L of distilled water (approximately 0.2 M) in a 2 L beaker. Add a magnetic stir bar and place on a magnetic stirrer. The initial pH of this solution will be approximately 1.6. While stirring, monitor the pH as you add approximately 370 ml of 1M KOH until you reach a pH of 12 (use pH buffers of 7 and 10 (or higher) to standardise the pH meter rather than 4 and 7). At around pH 4, the Fe oxides will begin to precipitate rapidly and the suspension will become very thick. You will need to speed up the stir bar and continue to adjust it to maintain a stirred suspension. Continue adding the KOH until the pH reaches 12.0, adding it more slowly and carefully as you approach the final pH. Allow the suspension to stand for approximately 30 minutes, then restart the stirring and check the pH. If it has dropped below 12.0, add additional KOH drop-wise to bring it back to the target pH. The total volume of suspension should be approximately 900 ml.

2. Transfer the suspension equally into four 250 ml nalgene bottles and centrifuge at approximately 1000 rpm for 5 min to concentrate the Fe oxides. Discard the supernatant. Transfer the contents of the four tubes into two 250 ml tubes and centrifuge wash the precipitated Fe oxide two times with distilled water, discarding the supernatant each time.

3. After the third centrifugation, re-suspend the Fe oxides with distilled water and transfer to dialysis tubing. Place the dialysis tubing into basins filled with distilled water and replace the water at approximately six hourly intervals during the first day and then at approximately 12 hourly intervals for a total of three days. Transfer the Fe oxides from the dialysis tubing to a nalgene storage bottle and keep in the dark. The suspension should be suitable for painting IRIS tubes approximately seven days after the initial synthesis of the Fe oxides (this will vary based upon a number of factors including laboratory and storage temperature).

4. To get the paint to the right consistency, place the paint in a 250 ml centrifuge bottle and centrifuge at approximately 1000 to 1500 rpm for approximately five minutes. After centrifugation, decant the supernatant so there is approximately the same volume of supernatant as the volume of the Fe oxide ‘cake’ at the bottom of the bottle (see figure). Then thoroughly re-suspend the Fe oxide and the paint should be at approximately the correct consistency for painting tubes.

5. Paint is applied to the tubes (½ inch schedule 40 PVC that has been cleaned with acetone to remove ink and lightly sanded with very fine sandpaper) using a 2 inch foam brush while the tube is spun using a cordless drill (typically we use 60 cm tubes and paint the lower 50 cm). Before painting a large number of tubes, be sure to test the paint by painting one or two prepared PVC IRIS tubes and allowing the paint to dry overnight. If the paint on the tubes is resistant to abrasion (does not rub off easily on your fingers) then proceed to paint and prepare IRIS tubes.

6. Once the paint has been tested it should be stored in the refrigerator to minimise mineralogical alteration over time (Rabenhorst and Burch, 2006). Approximate shelf life when stored cold (refrigerated) is a couple of months. Tubes that have been painted have a long shelf life (a year or perhaps even up to several years), as long as they are kept dry.

APPENDIX 5: Organic material

(Isbell 2002)

These are plant-derived organic accumulations that are either:

1. saturated with water for long periods or are artificially drained and excluding live plant tissue: (i) have 18% or more organic carbon[4] if the mineral fraction is 60% or more clay; (ii) have 12% or more organic carbon if the mineral fraction has no clay; or (iii) have a proportional content of organic carbon between 12 and 18% if the clay content of the mineral fraction is between zero and 60%; or

2. saturated with water for no more than a few days and have 20% or more organic carbon.

Peat is described as:

Fibric peat: undecomposed or weakly decomposed organic material; plant remains are distinct and identifiable; yields clear to weakly turbid water; no peat escapes between fingers

Hemic peat: moderately to well decomposed organic material; plant remains recognisable but may be rather indistinct and difficult to identify; yields strongly turbid to muddy water; amount of peat escaping through the fingers ranges from none to up to one third; residue is pasty

Sapric peat: strongly to completely decomposed organic material; plant remains indistinct to unrecognisable; amounts ranging from about half to all escape between fingers; any residue is almost entirely resistant remains such as root fibres and wood

4 Walkley-Black x 1.3 or a total combustable method (Rayment and Higginson 1992, Methods 6A1 or 6B2)

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