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Cover picture: Soil texturing

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Summary

In 2008, the Ord Irrigation Expansion Project was approved by the Western Australian Government to develop irrigated agriculture on the Weaber Plain (Goomig), which is located north-east of the existing 14 000 ha Ord River Irrigation Area (ORIA), 30 km from Kununurra. Construction of a new irrigation water supply channel connecting the Weaber Plain to the existing ORIA, and the final period of irrigation design, environmental management and related approval processes, began in 2009.

As part of the environmental planning and approvals process, the WA Government was required to prepare a groundwater management plan and a hydrodynamic plan. These plans were to address potential issues of salinity and water quality that might result from developing the proposed farmlands and to specifically address new hazard mapping derived from SkyTEM airborne electromagnetics (AEM) data. The Weaber Plain groundwater modelling report identified several options to manage watertables and salinity risk (KBR 2010). However, both studies identified that the existing groundwater data was inadequate for evaluating risk and quantifying the impact of options to manage shallow watertables and salinity; that soil and subsoil data was limited; and that downstream impacts required further evaluation.

As a result, the Department of Agriculture and Food, Western Australia (DAFWA) was requested to lead an investigative program to support a second phase of modelling. The project was divided into five components: two addressing deficiencies related to groundwater, two relating to soils and subsoils, and one addressing surface and groundwater quality aspects. This report summarises the two soil assessment components of the project.

The prime objective of this assessment was to distinguish areas of Cununurra and Aquitaine clay and to collect baseline information on soil structure, potential soil salinity hazard, and soil drainage prior to agricultural development. This objective involved characterising the soil profile to a depth of 2–4 m, including the substrate, and the saturated hydraulic conductivity.

The soil profiles and substrates are described across the main soil, landform, geology and vegetation units determined from previous survey data and more recent airborne electromagnetic (AEM) mapping. One hundred and sixty backhoe pits were excavated along 12 transects to expose the substrate (C horizon) below the cracking clay horizon. The soil profile and morphology were characterised at each site and infiltration tests using a constant head permeameter were conducted within each map unit as well as for a range of soil texture classes within the substrate.

The use of existing soil–vegetation boundaries overlain with AEM mapping and the excavation of deep soil pits to the substrate proved to be an efficient method of strategically locating contrasting soils and substrates. Results indicate that the AEM data is positively correlated to field electrical conductivity (EC) measurements and substrate clay content. Soils with medium to heavy clay substrates are usually less well drained and have relatively high levels of boron, chloride, and exchangeable sodium percentage at 100 and 200 cm depth compared to soils with coarser-textured substrates.

In general, areas of typical Cununurra clay had relatively low inherent EC and friable self-mulching topsoils that have developed on coarse to medium textured substrates (sand to fine sandy clay loam). In contrast, areas of Aquitaine clay are subject to more run-on and frequent inundation; they have relatively high subsoil EC and have formed on medium clay to medium-heavy clay substrates.

Soil pit sampling helped locate and verify the position of a paleo-drainage system determined by AEM and deep drilling. Saturated hydraulic conductivity tests carried out on soil substrate at 50 sites indicate that substrate permeability is generally higher in areas of Cununurra clay, particularly over the paleo-drainage system.

Areas dominated by Cununurra clay (map units 1 and 1/5b) and by the less saline variants of Aquitaine clay (map units 5bls and 5als) have a moderate to high capability for horticultural development. Areas containing the soil complexes, Cununurra/Aquitaine clay intergrades and the better drained areas of Aquitaine clay (map units 1/5bms, 5b and 9c) present moderate limitations to sustainable horticultural development that can be addressed with careful management. Areas of Aquitaine clay (map unit 5a) generally have a low capability for horticultural development, however they can be used for moderately salt-tolerant crops provided the groundwater depth is kept below 2 m.

1. Introduction

In 2008, the Ord Irrigation Expansion Project was approved by the Western Australian Government to develop irrigated agriculture on the Weaber Plain (Goomig[1]). The Weaber Plain is located north-east of the existing 14 000 ha Ord River Irrigation Area, 30 km from Kununurra (Figure 1). Construction of the M2 supply channel connecting the Ord River Irrigation Area (ORIA) and Weaber Plain, and the final period of irrigation design, environmental management and related approval processes began later in 2009.

In late 2009, the Department of Agriculture and Food, Western Australia (DAFWA), with partners Kellogg Brown and Root Pty Ltd (KBR), undertook to deliver a groundwater management plan and contribute to the completion of a hydrodynamic plan to ensure sustainable development of the project area. The requirement for these plans had been established by the Environmental Protection Authority as part of the process of evaluating the project.

In preparing the groundwater management plan, KBR (2010) noted that some of the existing groundwater data was inadequate for the purpose of substantiating modelled options to manage shallow watertables and salinity; that soils data was limited; and that downstream impacts required further evaluation to support improved farm design and the environmental approval process.

To fill the identified gap in soils data, the characterisation of Weaber Plain soil and subsoil needed to be improved and the soil and subsoil chemistry of the proposed farmlands area needed investigation. This report details the results of the soils assessment, which builds on existing soil mapping of the proposed Weaber Plain farmlands (WPF) and provides additional information on the permeability of the substrate.

Previous soil mapping of the WPF shows the area to be dominated by two major soils families that have contrasting physical and chemical characteristics and, consequently, differing horticultural capabilities (Dixon 1996). The Cununurra clays are commonly very dark greyish brown to dark brown, self-mulching cracking clays, while the Aquitaine soils are dark grey, mottled, coarse-structured clays that are subject to relatively long periods of inundation and are prone to salinity.

After 30 years of irrigation development within the ORIA, it is now apparent that the Cununurra and Aquitaine soils are not homogeneous in their characteristics. In particular, soil self-mulching properties, drainage and salinity hazard can be variable within soil map units.

In 2008, the Ord Irrigation Co-operative and the Ord Catchment Reference Group commissioned an airborne electromagnetic (AEM) survey of the ORIA and WPF to better quantify potential salinity risks (Lawrie et al. 2010). AEM mapping highlighted areas of high regolith electrical conductivity (salinity) within the established irrigation precinct and areas of salinity hazard in the WPF. Areas of inherently high salinity were generally associated with Aquitaine soils, although anomalies are apparent in both the Aquitaine and Cununurra soil units.

Reassessing the soil–vegetation mapping with AEM is imperative prior to developing new horticultural areas and could be an important tool in developing a soil capability model for horticulture within the WPF and adjoining areas.

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[1] Goomig is the Indigenous locality name for the Pincombe Range area.

Other DAFWA Resource Management Technical Reports (RMTR) detail the results of the other identified gaps:

- RMTR 366: Weaber Plain hydrogeology: preliminary results (George et al. 2011)
- RMTR 367: Weaber Plain aquifer test results (Paul et al. 2011)
- RMTR 368: Hydrochemistry of the Ivanhoe and Weaber Plains (Lillicrap et al. in press)
- RMTR 370: Surface water characteristics of the Weaber Plain and Lower Keep River Catchments (Bennett & George in press).

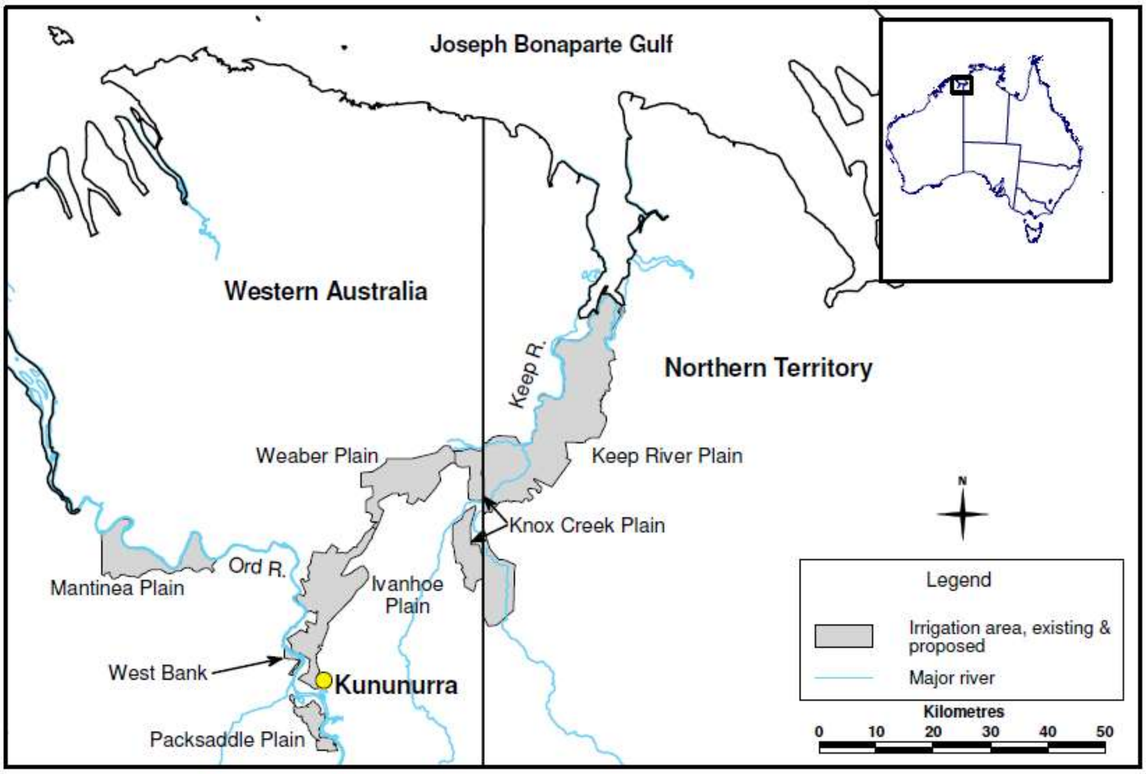

Figure 1 Study area locality map

2. Geology and physiography

The Weaber Plain farmlands (WPF) are found on a relict alluvial plain bordered by the Weaber and Pincombe Ranges and extends from Cave Spring Gap to Border Creek. The alluvial plain consists of fluvial sand, gravel and clay derived from ferruginised sandstones, siltstones, limestone and volcanic rocks of Cambrian to Proterozoic Ages (Figure 2).

AEM interpretations indicate sand and gravel sediments associated with alluvial fans and ancient drainage channels of the Ord River (Apps et al. 2009). The main channel extends from Cave Spring Gap, meanders south of Brown Ridge and deviates north-east between Sorby Hills and Border Creek. Run-off from the surrounding ranges and hills results in seasonal flooding and inundation. Prolonged inundation is associated with footslopes and depressions, especially along meandering flow lines associated with Border Creek in the Point Spring area.

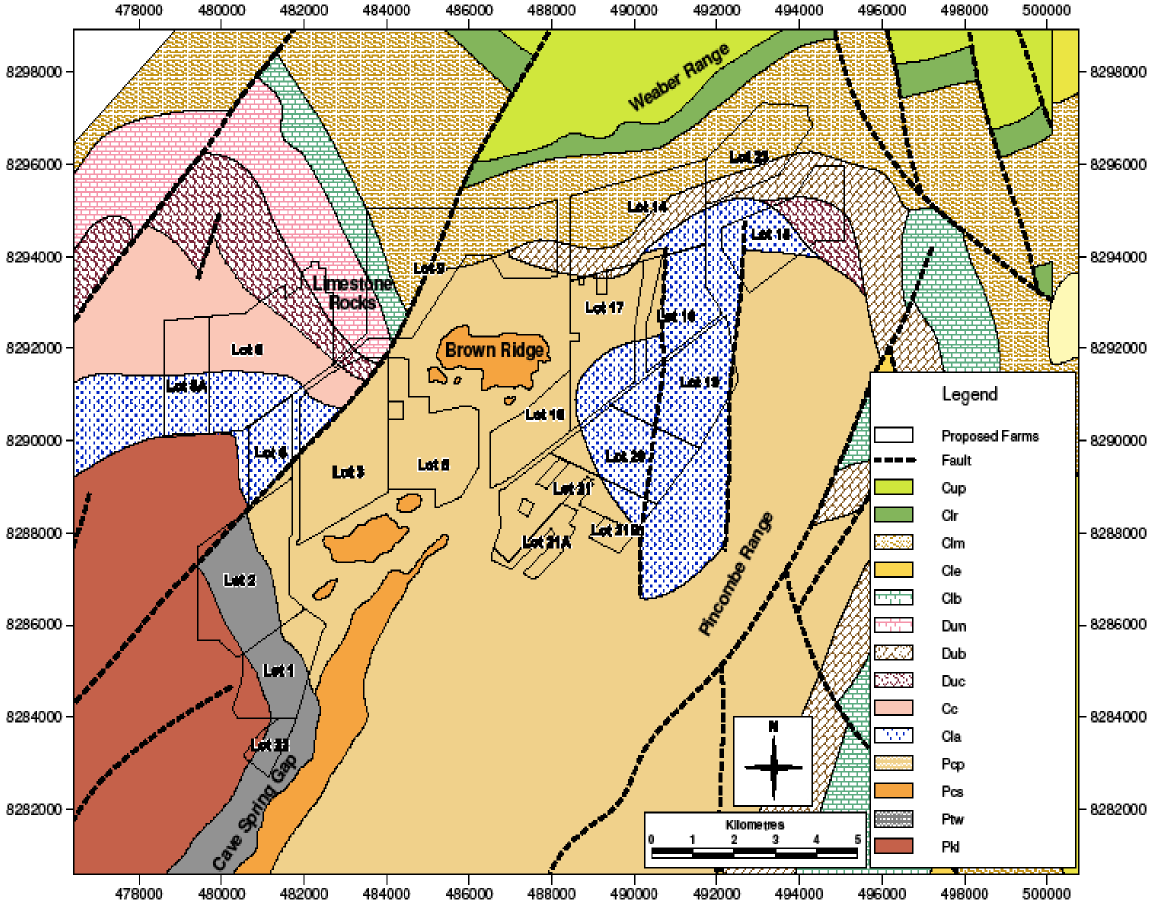

Figure 2 **Regional geology (based on Laurie et al. 2010). Refer to Table 1 for details on geological units**

Table 1 **Weaber Plains geological units**

Era	Period	Group	Formation	Unit
Paleozoic	Carboniferous	Wadeye	Point Spring Sandstone	Cup
		Weaber	Burvill	Clr
			Milligans	Clm
		Langfield	Enga Sandstone	Cle
			Burt Range	Clb
	Devonian	Ningbing	Ningbing—undifferentiated	Dun
			Buttons	Dub
		Cockatoo	Cockatoo—undifferentiated	Duc
	Cambrian	Carlton	Carlton—undifferentiated	Cc
		Goose Hill	Antrim Plateau Volcanics	Cla
Proterozoic	Early to middle Proterozoic	Carr Boyd	Pincombe	Pcp
			Stonewall Sandstone	Pcs
	Early Proterozoic	Bastion	Wyndham Shale	Ptw
		Kimberley	King Leopold Sandstone	Pkl

3. Previous studies

George Burvill first examined the soils surrounding Kununurra in detail in 1944 (Burvill 1991). He also mapped Carlton Reach Plain and described the Cununurra clay (Burvill 1991). The Carlton Reach Plain (now referred to as Ivanhoe Plain) lies directly to the south-west of the Weaber Plain. The Ivanhoe Plain and adjacent Packsaddle Plain were developed for horticulture in 1962 and Aldrick et al. (1990) remapped both areas in 1977.

Aldrick and Moody (1977) mapped the Lower Weaber and Keep River Plains, lying to the east of the WPF in the Northern Territory. Here they recognised Burvill's 'flooded' Cununurra clays as a separate soil family, which was named Aquitaine.

In 1977, the soils of the Weaber Plain were surveyed by Dixon (1996) using aerial photography and free survey methods. About 150 soil profile descriptions support the production of a map that covers the Weaber Plain and northern Knox Creek Plain. All these sites have been entered into DAFWA's soil profile database, though most lack a geo-reference.

On the Weaber Plain, Dixon's soil map units mainly conform to the common map unit key proposed by Aldrick et al. (1990). Dixon recognised the Cununurra and Aquitaine clays as the main soil families on the Weaber Plain. The Cununurra clays are well structured, with self-mulching (fine granular to sub-angular blocky structure) topsoils. Cununurra clays are less prone to salt accumulation and relatively better drained than the coarse-structured Aquitaine clays. The delineation of these soils is important to crop selection and drainage management.

In 1994, Schoknecht and Grose (1996), who identified similar soils and vegetation communities within the framework developed by Aldrick and Dixon, mapped the soils of the Knox Creek Plain.

Apps et al. (2009) provided SkyTEM coverage (AEM) of the Weaber Plain based on 200 m transects. This data provides an interpretation of soil/regolith conductivity at various depth slices over the ORIA (Figure 4). Areas of low conductivity are commonly associated with coarse-textured sediments, while high conductivity is usually associated with deep clayey sediments. The soil conductivity patterns indicate that there is not a clear correlation between the nature of the regolith and existing soil mapping.

4. Methods

4.1 Soil survey

Fieldwork was conducted on 15–24 June and 7–17 July 2010. One hundred and sixty backhoe pits were excavated along predetermined transects for soil profile descriptions and permeability tests. The pits were dug 2–3 m deep to the C horizon substrate below the cracking clay layer (Figure 3).

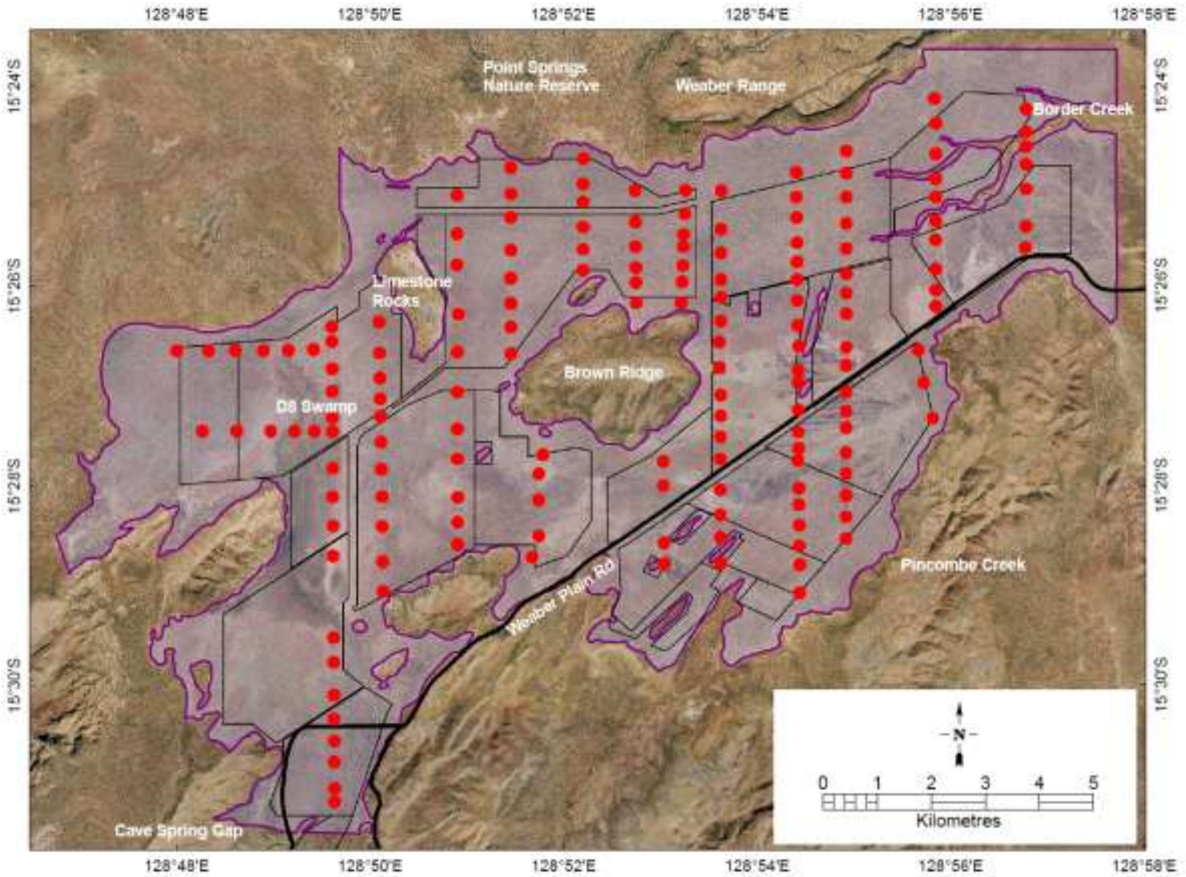

Figure 3 **Study area and backhoe pit locations (red dots)**

Information used to determine the transect layout and positioning of the backhoe pits included:

- the soil mapping of Dixon (1996)
- Carlton and Kununurra high-resolution aerial photography, flown in 2005, which indicates the major landforms and vegetation complexes in more detail than existing Ord Valley vegetation mapping (2009) held by Geoscience Australia
- SkyTEM data identifying areas of contrasting ground electromagnetics (Lawrie et al. 2010)
- geotechnical investigations carried out by Golders Associates (2010), which included soil texture and depth of the strata along the proposed irrigation channels. This information provided a reference to the range of substrate characteristics that can be encountered within the irrigation blocks.

Most transects are positioned perpendicular to the drainage system and intersect the major soil–vegetation units defined by Dixon (1996). Transects also dissected likely areas of the coarse-textured substrate (paleo-drainage system) identified by Golders Associates (2010), to define drainage pathways or permeable substrates.

In the course of the survey it was realised that deeper pits were required at some sites, particularly along the northern boundary adjacent to Border Creek, to better define the relationship between the soil type and AEM data. In these situations pits were excavated to the watertable or a maximum depth of 4 m.

The locations of the backhoe pits were recorded using a standard geographic positioning system (Garmin GPS76) set to GDA94 datum. Site descriptions use the terminology of McDonald and Isbell (2009). Data recorded in the survey included:

- vegetation structure and dominant species
- landform features
- soil colour, using the Munsell Colour Chart (Munsell Colour Company 1975)
- soil texture, described by hand texturing
- soil structure
- the presence of gravel and segregations
- soil pH, using a field pH kit (Raupach & Tucker 1959)
- soil salinity, using a pocket electrical conductivity (EC) meter
- soil horizon depth
- topsoil consistency.

A Geonics EM38 (electrical conductivity meter) was used to measure soil conductivity at each site, to correlate field $EC_{1:5}$ with airborne electromagnetics and subsequent soil analyses.

Topsoils (0–20 cm) were sampled at all sites. In addition, 74 soil profiles were sampled within the following depth ranges, which usually fall within soil horizons: 0–20 cm, 80–120 cm and 200–220 cm.

Substrate samples (180–220 cm) were collected to relate soil physical and chemical characteristics with soil hydraulic conductivity.

A qualitative test for soil strength was conducted in the field using dry aggregates to determine whether there was a correlation between soil physical and chemical characteristics.

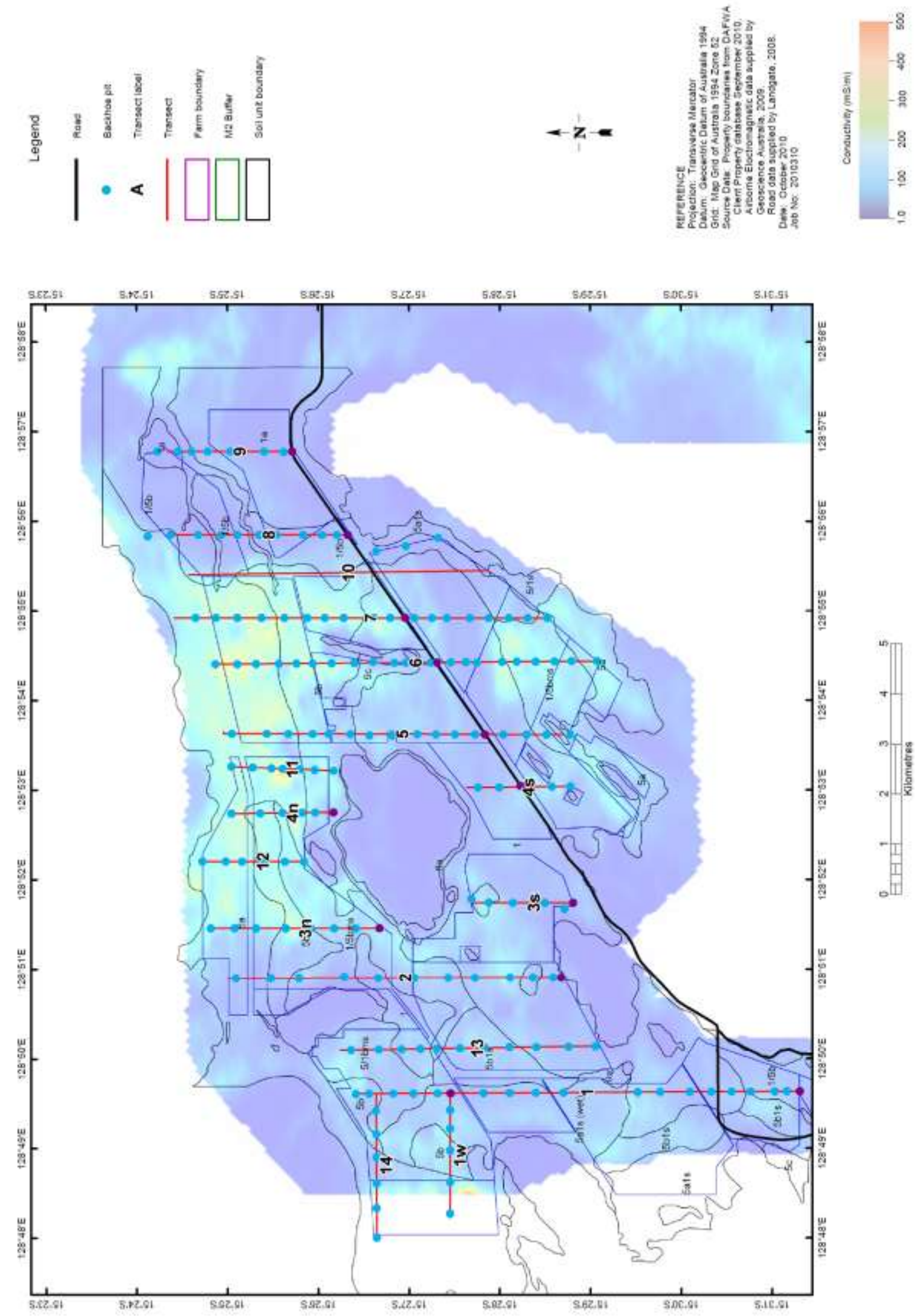

Figure 4 **AEM 0–4 m depth slice**

Soil analyses included:

- soil particle size (gravel, coarse sand, fine sand, silt and clay)
- Emerson tests on dispersion and slaking
- exchangeable cations, including cation exchange capacity (CEC) and exchangeable sodium percentage (ESP)
- pH in water (H_2O) and calcium chloride ($CaCl_2$) solution (1:5)
- electrical conductivity EC1:5 (mS/m)
- electrical conductivity from a saturated extract ECse (mS/m)
- chloride
- organic carbon
- total nitrogen
- total phosphorus and extractable bicarbonate
- calcium carbonate ($CaCO_3$ %)
- sulfur
- trace elements (copper, iron, manganese, zinc)
- boron.

Soil analyses were conducted by CSBP Laboratories, Perth.

Average site observation density within the WPF is about one site to every 50 ha. This observation density is adequate for a 1:50 000 scale survey using large-scale, coloured aerial photography (McKenzie et al. 2008). Coupled with the AEM spatial mapping and the mapping by Dixon (1996), mapping scale meets the requirements of semi-detailed class surveys for irrigation implementation.

4.2 Saturated hydraulic conductivity

As a measure of saturated hydraulic conductivity (KSat), soil permeability tests were conducted on substrate layers at 50 sites using a modified Talsma tube (constant head well permeameter) developed by Nash et al. (1986). The permeability testing technique follows procedures initially outlined by Talsma and Hallam (1980).

Field procedures and analyses are described in DAFWA's field techniques manual (Department of Agriculture 1991).

Certain procedures were modified for this survey:

- a permeameter hole (radius 35 mm) was augered within the backhoe pit, typically within the substrate at a depth of 200–250 cm
- substrate horizons were generally moderately moist to dry, resulting in minimal smearing to the auger hole after wire brushing. In horizons that were moist, the soil face was picked with a broad spatula in preference to wire brushing as it resulted in less smearing and sealing. Wire brushing was considered unnecessary on massive or weakly structured substrates, particularly where ped cracks were evident
- infiltration tests used Ord M2 channel water

- permeameter tests ceased once soil infiltration rates reached a steady state, which varied between 20 and 120 minutes, depending on the substrate texture and structure. Representative sites were pre-wet for 24 hours to determine whether soil moisture content prior to KSat testing had an influence on results. In fact, there was little change in KSat between pre-wetted and non pre-wetted tests on weakly structured or massive substrates. Tests were generally non-problematic, apart from excessive slumping within some massive sandy clay loam or fine sandy clay substrates. On occasion, it was necessary to remove sludge from the auger holes and restart tests.

5. Soils

The most common soils within the WPF are the Cununurra clays and Aquitaine clays. Both are very dark greyish brown, dark brown or dark grey cracking clays that exhibit self-mulching topsoils to some degree. The soils are classified as black, brown and grey Vertosols in the Australian Classification (Isbell 2002), with grey Vertosols being more common. They were described as occurring in the WPF by Dixon (1996) and in adjoining areas have been described by Aldrick and Moody (1977), Aldrick et al. (1990), and Schoknecht and Grose (1996).

These surveys generally defined the upper 120–160 cm of the soil profile from auger holes or coring tubes, although a limited number of soil profile descriptions extended to 200–350 cm. Soil colour, soil mottling, soil pH and the presence of carbonate and gypsum were typically the main criteria used to describe the soil profile. Generally, characteristics of the deeper soil substrate (C horizon) were not included in the soil classification or development of the map units.

The AEM data indicated that soil electrical conductivity varied widely within the soil–vegetation map units defined by Dixon (1996). To evaluate the AEM data, this assessment characterised soil substrates at 200–300 cm and conducted saturated hydraulic conductivity tests to better define these map units.

Topsoil colour was not a good indicator of soil phases or soil family. Aldrick (1977) observed that ‘soil colour was frequently difficult to assess’ and that ‘colour hues varied with soil moisture’. Within the Cununurra clay, topsoil and subsoil colour usually ranged from very dark greyish brown (2.5Y–10YR 3/2) to dark greyish brown (2.5Y–10YR4/2), while browner phases ranged between 2.5Y–10YR 3/3 and 4/3. Faint yellow-brown mottles may also be evident along root channels within the upper 0–10 cm. Similar soil colours were associated with the Aquitaine clay, although hues of 2.5Y were more common; in the wet depressions, hues of 5Y were encountered and yellow, brown and grey mottles were more distinct.

The Cununurra clays within the WPF mostly grade between the normal phase and leached phases described by Aldrick et al. (1990). Field pH tests and soil analyses indicate the topsoil pH range is 6.5 to 7.5 (Appendix A). Soil pH becomes alkaline (8.0–8.5) in the top 20–40 cm; more commonly below 30 cm, where very few to few (less than 2–10 per cent) carbonate nodules may be encountered and slight to moderate effervescence is evident after reaction with acid. The Cununurra alkaline phase and soils with alkaline, calcareous topsoils (soils within soil map units 9c) were encountered but were not as common as implied in mapping by Dixon (1996).

Topsoil horizons generally exhibit strong, medium to coarse, sub-angular blocky to angular structure with rough and smooth ped fabric. As the topsoil becomes more desiccated, soil peds break down to finer granular and/or polyhedral aggregates that typify a self-mulching surface condition.

Both Cununurra and Aquitaine clays exhibit self-mulching topsoils, although field observations indicate that finer aggregates of the Cununurra clay are usually less hard and develop more quickly. Chemical analyses indicate only minor differences between the Cununurra and Aquitaine clay topsoil horizons (Appendix A). However, Cununurra clay topsoils usually contain 10 per cent less clay and proportionally more sand than the Aquitaine clays. This relationship persists within subsoil horizons, albeit the difference is reduced to about 5–10 per cent.

The main cracking clay layer (B horizon) usually extends from 30 to 120–160 cm and is commonly medium-heavy clay. Both Cununurra and Aquitaine clays exhibit strong, medium to coarse, angular blocky, platy or lenticular structure and shiny, smooth ped fabric, referred to as slickensides (Figure 5).

Figure 5 **Tree root is centred on the BC horizon and extends into the brown C horizon. Slickensides (shiny ped surfaces) are clearly evident in the B horizon**

Slickensides—smooth slip surfaces which form along shear planes resulting from shrink-swell movement—are a diagnostic feature of Vertosols. Shrink-swell and soil expansion properties are also characterised by wavy heave lines and domed subsoil structures. In the moderately moist state, pedal cracks are distinct throughout the soil horizon and few cracks extend into the substrate (C horizon).

Very few to few carbonate nodules and fine, iron-manganese concretions are evident in the cracking clay layer. Soft carbonate segregations are extremely rare in the upper 100 cm. However, soil below 30–40 cm usually exhibits a slight to moderate effervescence with acid (1 Molar HCl), indicating the subsoil is moderately calcareous.

A transition layer (BC horizon) is usually evident between the cracking clay (B horizon) and the weakly structured or massive substrate (C horizon). Position of the transition layer within the profile is influenced by the clay content, mineralogy and overburden pressure. BC horizons are deeper within Aquitaine clays because of the higher percentage of montmorillonite clay, which allows for greater soil expansion to overcome overburden pressure.

The BC horizon has an amalgamation of B and C horizon colours, a thickness of usually 20–30 cm and is associated with bio-turbidation processes (insect pupae casts, termite galleries, in-filled root channels and live roots can be encountered).

The lower B horizon and upper BC horizon (zone of less soil cracking) act as a throttle to unsaturated flow where soil–water movement is reduced to a matrix flow that is conducive to the retention of more base cations and total salts. BC horizons contain more carbonate segregations, and within the Aquitaine clays these horizons also exhibit up to 5–10 per cent lenticular gypsum crystals or nests of needle-shaped gypsum crystals. Gypsum crystals are rarely encountered in the Cununurra clays (also noted by Burvill 1944). The absence or rarity of gypsum within Cununurra clay (normal phase) supports the general finding that these soils are relatively better drained. The presence of gypsum in Aquitaine clay is variable, with less gypsum associated with soils bordering the Pincombe Range. Aquitaine clays containing appreciable amounts of gypsum were encountered in areas bordering the Weaber Range, particularly near Point Springs.

BC horizons usually exhibit weak to moderate, sub-angular blocky or angular blocky structure and a rough and smooth ped fabric. Soil structure is usually better developed in the Aquitaine soils and slickensides may extend into the C horizon if subsoil texture is medium-heavy to heavy clay.

The C horizons in both Cununurra and Aquitaine soils are commonly brown to strong brown (7.5YR 4/4–4/6). Cununurra clays occasionally exhibit redder hues (5YR 4/4–4/6) while Aquitaine clays grade to dark yellowish brown (10YR 4/4–4/6), particularly in swampy areas. Clay content decreases within the C horizon in most soils, apart from the more saline Aquitaine clays. A few carbonate segregations are usually evident, but are usually less common compared to the B and BC horizons.

The soil map in Appendix C is based on the mapping of Dixon (1996), modified to indicate variations in soil EC that were determined from field tests, soil analyses and estimated EC from the AEM. These modifications have resulted in the amalgamation of some map units. In particular, map units 9a and 9c were incorporated into map unit 1 or 1/5bms if alkaline soil types were not commonly encountered within the specified areas. Also, map units 5at and 5bt, which were defined mainly on species composition, were incorporated into 1/5bms, 5a or 5b on the basis of vegetation and soil EC. The map unit descriptions follow, including a summary of the associated vegetation and indicator species.

Note: A general realignment of Dixon's map unit boundaries was necessary, as the original mapping used aerial photography overlays. Rectification of the mapping resulted in warping of the original linework by 100–200 m in some areas.

5.1 Soil map legend

Cununurra clay, normal and leached phase (map unit 1)

This unit is associated with broad plains.

- complex of Cununurra normal and leached phases
- topsoils are very dark greyish brown cracking clays with medium to coarse, sub-angular blocky structure breaking to fine to medium, angular blocky or granular structure
- moderate to strongly developed self-mulching topsoil with a firm to very firm consistency when dry
- reddish brown substrates at 120–160 cm. Substrate horizons are massive and earthy with soil textures in the range of sand to light-medium clay
- light, sandy clay loam substrates are common within the paleo-drainage line
- non-saline to slightly saline subsoils at 200 cm
- vegetation is grassland or very open shrub land with emergent *Bauhinia cunninghamii* and subdominant *Vachellia* sp. (formerly *Acacia bidwillii*). *Terminalia volucris* and *Atalaya hemiglauca* are minor associated species. *Sorghum australiense* may form uniform, dense stands devoid of emergent species. *S. australiense* and *B. cunninghamii* are generally absent in areas of moderate to high subsoil salinity and *Bauhinia* is rarely encountered in wet areas.

Cununurra clay, alkaline phase (map unit 9c)

This unit is usually adjacent to or within map unit 1.

- soils are similar to Cununurra clay (normal phase) although some topsoils may be more alkaline and exhibit more pedogenic carbonate in the subsoil horizons.
- vegetation is similar to map unit 1 with *Carissa lanceolata* and *Grewia retusifolia* indicating alkaline soils.

Cununurra clay, wet phase (map unit 1/5b)

This unit is similar to map unit 1, although vegetation indicates the unit is wetter (that is, it may be inundated or subject to more run-on).

- topsoils are very dark greyish brown to greyish brown cracking clays with medium to coarse, sub-angular blocky structure breaking to fine to medium, angular blocky or granular structure
- self-mulching topsoils have a firm to very strong consistency when dry
- subsoil BC horizons at 120–160 cm exhibit massive, earthy or weak to moderate, angular blocky structure
- substrate soil texture is generally fine sandy clay loam to light-medium clay and non-saline to slightly saline at 200 cm
- vegetation is open woodland or woodland with *Eucalyptus microtheca, Exoecaria parvifolia, Vachellia* sp., *T. volucris* and *Atalaya hemiglauca*. Understorey may include *Sorghum australiense, S. stipoideum, Sesbania* spp., *Panicum decompositum, Ophiuros exaltatus, Themeda triandra* and *Aristida latifolia*. *Bauhinia cunninghamii* is not encountered or is rare.

Cununurra clay, wet phase/moderately saline (map unit 1/5bms)

This unit represents a Cununurra/Aquitaine complex, in which soil types grade between Cununurra and Aquitaine clay. It also contains inclusions of Cununurra alkaline phase soils (9c).

- unit has better external and internal drainage than map unit 5b
- topsoils are very dark greyish brown, greyish brown and dark brown cracking clays, medium to coarse, sub-angular blocky structure breaking to fine to medium, angular blocky or granular structure
- self-mulching topsoils are moderately developed with a very firm to very strong consistency when dry
- substrates present at 140–160 cm are usually fine sandy clay to medium clays that exhibit massive or weakly developed, angular blocky structure
- substrates are usually moderately saline at 200 cm
- vegetation is shrub land to very open woodland with *Eucalyptus microtheca, E. parvifolia, Vachellia* sp., *Terminalia volucris* (common) and *Atalaya hemiglauca* (not common). Stunted *Cathormion umbellatum* may be present. Understorey includes *Panicum decompositum, Ophiuros exaltatus, Themeda triandra, Aristida latifolia*. *Bauhinia cunninghamii* is not dominant and often appears stunted or as a shrub form. *Sorghum australiense* is absent.

Aquitaine clay (map unit 5a)

This unit is found in broad, low-lying areas bordering hilly terrain. Flooding and inundation may persist for long periods during the wet season.

- topsoils are very dark greyish brown, greyish brown and sometimes grade to olive-brown with depth. Yellow-brown or reddish yellow mottling is usually evident within the topsoil and the soil profile usually has a yellow-grey hue compared to the Cununurra clays
- topsoils exhibit a cloddy or medium to coarse, sub-angular blocky structure that breaks to medium, sub-angular blocky or granular structure
- self-mulching is weak to moderate while soil consistency is strong to very strong when dry
- substrates are present at 140–180 cm and soil texture is medium to medium-heavy clay
- substrates usually exhibit a strong, medium to coarse lenticular or angular blocky structure with common smooth and shiny clay skins (slickensides)
- typically has moderate to highly saline subsoils with localised areas being extremely saline
- gypsum is usually evident within the subsoil and highly saline subsoils usually exhibit large (5–10 mm) gypsum crystals
- vegetation is woodland or open woodland dominated by *Eucalyptus microtheca* and *E. parvifolia* with an understorey of *Ophiuros exaltatus*. Secondary associated species include *Terminalia volucris* or *T. platyptera* (tall species), *Cathormion umbellatum* (tree), *Atalaya hemiglauca* (rare), *Panicum decompositum*, *Sesbania* spp., *Themeda triandra*, *Aristida latifolia, Wedelia* spp. and *Bauhinia cunninghamii*. *Sorghum australiense* is absent.

Aquitaine clay (map unit 5als)

This unit is similar to map unit 5a, although AEM indicates low conductivities.

- drilling confirms the presence of sand or gravel substrates
- vegetation is woodland or open woodland dominated by *Eucalyptus microtheca* and *E. parvifolia* with an understorey of *Ophiuros exaltatus* and/or *Sorghum australiense*. Secondary associated species include *Terminalia volucris* or *T. platyptera* (tall species), *Vachellia* sp., *Cathormion umbellatum* (rare), *Atalaya hemiglauca*, *Panicum decompositum*, *Sesbania* spp., *Themeda triandra*, *Aristida latifolia* and *Wedelia* spp. *Bauhinia cunninghamii* may be present but rare.

Aquitaine clay (map unit 5als, wet)

This unit is similar to map unit 5als. This unit defines the surface expression of seepage from the D8 drain.

- subsoils are usually non-saline and substrates commonly have soil textures of fine sandy clay or coarser
- vegetation is similar to unit 5als but is now denuded by heavy grazing. Presence of *Melaleuca* spp. and absence of *Bauhinia cunninghamii* indicate wet conditions.

Aquitaine clay (map unit 5b)

This unit is similar to unit 5a but better drained and subject to shorter periods of inundation.

- vegetation, particularly grasses, is less luxuriant and is likely to hay off earlier compared to areas of map unit 5a
- topsoils are very dark greyish brown, greyish brown and sometimes grade to olive-brown with depth. Yellow-brown or reddish yellow mottling is usually evident within the topsoil and the soil profile usually has a yellow-grey hue compared to the Cununurra clays
- topsoils exhibit a cloddy or medium to coarse, sub-angular blocky structure that breaks to medium, sub-angular blocky or granular structure
- self-mulching surface condition is weak to moderately developed, with a very firm to very strong consistency when dry
- substrate soil texture is fine sandy clay to medium clay
- substrates at 140–160 cm exhibit a massive or moderately strong, medium to coarse, lenticular or angular blocky structure
- moderately to highly saline subsoils at 200 cm
- gypsum is usually evident within the subsoil
- vegetation is shrub land to woodland but generally more open than unit 5a with *Eucalyptus microtheca*, *E. Parvifolia, Terminalia volucris, Atalaya hemiglauca* (not common) and stunted *Cathormion umbellatum*. Understorey includes *Panicum decompositum, Ophiuros exaltatus* (usually dominant), *Themeda triandra* and *Aristida latifolia*. *Bauhinia cunninghamii* is rarely encountered and *Sorghum australiense* is absent.

Aquitaine clay (map unit 5bls)

This unit is similar to unit 5b, although subsoils are generally less saline.

- substrate soil texture is usually fine sandy clay to light-medium clay
- substrates at 140–160 cm exhibit a massive or weak to moderately developed, angular blocky structure
- slight to moderate saline subsoils at 200 cm
- gypsum is not common in the subsoil
- soils within this unit are underlain by sand or gravel sequences
- vegetation is similar to unit 5als.

Aquitaine clay (map unit 5c)

This unit is similar to unit 5a but subject to prolonged waterlogging and inundation.

- shallow bedrock may be encountered
- vegetation is similar to unit 5a but with sedges common in the understorey.

Complex (map units 8a and 8b)

These units are associated with footslopes bordering hilly terrain.

- areas are subject to run-off
- soils include sands, duplex soils and cracking clays
- vegetation is variable woodland or open woodland. May include *Eucalyptus microtheca, Corymbia bella, C. confertiflora, E. bigalerita, E. parvifolia* with an understorey of *Ophiuros exaltatus* and/or *Sorghum australiense*. Secondary associated species include *Terminalia volucris* or *T. platyptera* (tall species), *Vachellia* sp., *Panicum decompositum, Sesbania* spp., *Themeda triandra*, *Aristida latifolia* and *Wedelia* spp. *Bauhinia cunninghamii* may be present but rare.

6. Soil formation

In 1944, Burvill (1991) considered the 'black soils' or cracking clay soils of the Carlton Reach Plain (including the Weaber Plain) had developed over deep alluvial sediments whereby lacustrine mud was laid down from ponded floodwaters during a time of higher sea level. Later surveys by Gunn (1969) and Aldrick and Moody (1977) consider the soils were formed from alluvial sediments with in-situ geochemical alteration. The Ord River drainage system comprises alluvial sediments derived from a wide range of rock types, including sandstone, shales, limestone and basalts. Sediment from these parent materials is commonly alkaline and rich in calcium and magnesium. In a semi-arid tropical climate (contrasting wet and dry season), these constituents are conducive to the formation of base saturated clays (Mayers & Willett 1981).

Mineralogical analysis of the Cununurra and Aquitaine clays shows that montmorillonite is the dominant constituent with secondary quartz, kaolin, illite and mica (Dixon 1996). In general, the cracking clay horizon (B horizon) contains 10 per cent more clay and 10 per cent more montmorillonite relative to the C horizon.

The cracking clay B horizon usually extends to a depth of 120 to 160 cm across the Weaber, Ivanhoe and Keep Plains. Aquitaine clays usually have deeper BC horizons with a diffuse boundary to the C horizon, compared to Cununurra clay, in which the boundary is shallower and gradual, especially where the substrate is coarser textured. Cununurra clays with light-medium clay, cracking clay horizons have corresponding sandy loam to clay loam C horizons. In contrast, Aquitaine clay topsoils are usually medium to heavy clays that overlie medium clay subsoil (Appendix A, Table A1). This textural relationship between the B and C horizons suggests that soil formation has resulted mainly from in situ processes.

The higher proportion of clay associated with Aquitaine soils could be attributed to an influx of fine sediment, as areas of Aquitaine clay are associated with drainage depressions that are subject to run-on from adjacent hills. Satellite imagery and field observations in this assessment indicate that Aquitaine clay (map unit 5a) supports actively growing grasslands under open woodland for an additional 1–2 months after grasslands have hayed-off on Cununurra clay. Prolonged moist conditions would promote both geochemical and biological processes.

Black land crabs (*Holthuisana* sp.) form mounded burrows on cracking clays after the wet season. More conspicuous is the presence of termite mounds that can be common on the WPF. Termite mounds can contain 10–30 per cent more clay and higher concentrations of organic matter, base cations and total salts than surrounding soils (Lobry de Bruyn & Conacher 1995; Adekayode & Ogunkoya 2009).

Biological processes may also contribute to the formation or transformation of clay. Jouquet et al. (2002) tested the hypothesis of clay transformation under laboratory conditions where they identified the presence of new, smectite-rich, illite-smectite minerals in termite chambers and concluded that termite saliva directly or indirectly, through stimulating micro-fauna or flora, altered clay minerals.

7. Substrate saturated hydraulic conductivity

Sustainable irrigation and drainage management on the Weaber Plain will depend on managers having detailed knowledge of variations in permeability of the cracking clay soils and substrate sediments. The development of localised soil salinity and rising groundwater within the ORIA is the result of excessive through-flow via channel leakage and inappropriate irrigation practices on permeable soils (O'Boy et al. 2001).

The permeability of the cracking clay is bi-modal and dependent on the soil moisture status. In the dry state, water infiltration rates are excessive through the numerous cracks until the clay wets up and swells. Unlike most soils, cracking clays wet up from the top of the weakly structured or massive BC horizon, which is less permeable and acts as a throttle to through-flow. That is, water flow through the vertical cracks is restricted at the top of the BC horizon and cracks gradually close upwards. Unsaturated hydraulic conductivity of 1–5 m per day (m/d) within the dry cracking clay layer can be reduced to a saturated hydraulic conductivity (KSat) of less than 10 mm/d once the clay has swelled after wetting.

The time required to wet up and saturate the soil profile depends on the permeability of the substrate layer. Non-expansive substrates and coarse sediments with moderate to high saturated hydraulic conductivities (sand, loam, silts and gravels) would not be major barriers to through-flow, so that cracking clay layers would take longer to wet up and attain low saturated hydraulic conductivity under matrix flow (soil pore flow). In comparison, soil profiles with medium to heavy clay substrates (Aquitaine clay) are likely to wet up rapidly and remain moist for longer periods, particularly once cleared for annual horticulture.

Figure 6 provides estimates of substrate saturated hydraulic conductivity based on 48 substrate tests (see Appendix B) correlated to substrate soil texture and AEM mapping. The yellow and red areas represent the areal extent of medium and coarse-textured sediments respectively, associated with the main paleo-drainage system. Medium-textured sediments (loams to silty clay loams) have saturated hydraulic conductivity estimates of 0.4 m/d, while coarse-textured sediments (sand to sandy loams) have estimates of 0.8 m/d.

Areas outside the paleo-drainage system have highly variable saturated hydraulic conductivity values (mean KSat of 0.04 m/d) as substrate textures range from sandy clay loam to medium-heavy clay. Substrate saturated hydraulic conductivity values range within the typical estimates for soil texture and structure (Hazelton & Murphy 2007).

Several KSat tests on pre-wet (24 hour) cracking clay horizons recorded a range of 0.01–0.04 m/d. As a reference, KSat tests were conducted on Cununurra clay (normal phase), light-medium clay topsoils. Two sites adjacent to recently flooded irrigation furrows at DAFWA's Frank Wise Institute had KSat values of 0.08 and 0.19 m/d. Ponding tests carried out on similar soils by Kinhill Pty Ltd (1999) and Chapman (1982) recorded rates ranging from 0.01 to 0.47 m/d, while George (1983) mentions values of less than 0.001–0.08 m/d. Similarly, work on irrigated sodic cracking clays in Queensland recorded ponded infiltration rates of 0.002–0.01 m/d (Shaw et al. 1994).

Chapman (1982) postulates that high infiltration rates may be associated with highly pervious substrates (sandy loam) that maintain through-flow for longer periods via preferred pathways such as old root channels and structural cracks (slickensides). Observations from the current assessment support this view. In particular, cracks associated with slickensides were still evident in moist Aquitaine clay subsoils during excavation. In addition, low EC values within Cununurra clay (normal phase) occur where substrates have medium to coarse textures.

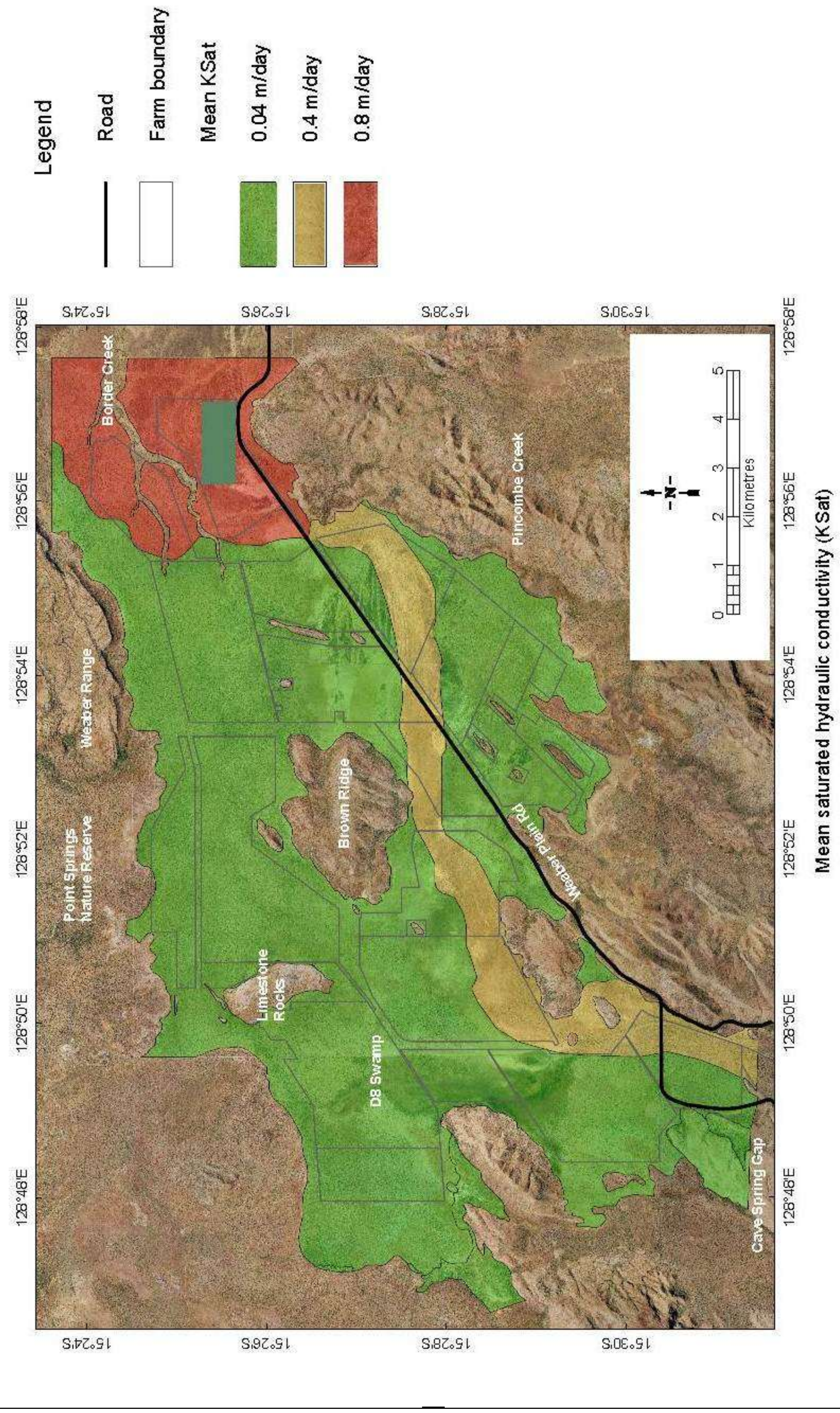

Figure 6 **Substrate saturated hydraulic conductivity (m/d)**

8. Soil analysis

Appendix A contains the average values of selected analytical data for each map unit. The results are grouped in three depth intervals (0–20 cm, 80–120 cm, 180–220 cm) that correspond to the A, B and C horizons respectively.

Generally, topsoil horizons have similar chemical characteristics across map units, apart from slightly elevated electrical conductivity (saturated extract), EC_{se}, and about 10 per cent more clay within Aquitaine soils.

Topsoil pH values range between 6.5 and 7.5, with lower values associated with Cununurra clay, normal phase. Field tests recorded mean pH values of 6.0 to 6.5 within the self-mulching layer (0–10 cm).

Aldrick and Moody (1977) note that salt levels gradually increase with depth and that a salt bulge often manifests at 110–130 cm. The current assessment, and results from Schoknecht and Grose (1996), confirm that salt levels increase with depth. Aquitaine clays generally have an increasing salinity trend with depth. A decline in salinity within the deeper subsoil only applies to Cununurra clays (map unit 1 and 1/5b), which have better drained substrates.

Soil analyses confirm AEM estimates of low salt storage within Cununurra clays while slight to high salt levels are associated with Aquitaine clay map units. Mean EC_{se} values are in the range of 360–460 mS/m at 80–120 cm and 690–920 mS/m at 180–220 cm, with the highest values occurring in map unit 5a. All topsoils contain low soil boron, while moderate to high boron levels (3.9–6.2 mg/kg) are found in subsoil horizons within map units 5a and 5b.

Soil sulfur content, used as a surrogate for gypsum, supports field observations that gypsum is commonly associated with Aquitaine clays and particularly soils with high EC_{se}. Gypsum content is generally lower in the better drained Cununurra clays.

All soils within the main map units have high base status and cation exchange capacity, which is consistent with a clay mineralogy dominated by montmorillonite (Appendix A, Table A2). Aquitaine clays have slightly higher cation exchange capacity because of a higher clay percentage. Exchangeable sodium percentage (ESP) is higher within Aquitaine clay subsoils, although both Cununurra and Aquitaine clays are sodic. Cununurra clay subsoils have an ESP of about 10, which decreases to 6 within the substrate. Aquitaine clays have subsoil ESP ranging from 9 to 15 and values also decline slightly with depth. Cununurra and Aquitaine clay exchangeable cation values are comparable with data for Ivanhoe and Knox Creek Plains; however, virgin Aquitaine clay on the Ivanhoe Plain commonly has higher topsoil and subsoil ESP (George 1983).

Electrochemical Stability Index (ESI), derived from $EC_{1:5}$/ESP, is used to rate soil structural stability and potential for soil dispersion. ESI is a useful predictor on cultivated cracking clay soils in Queensland and New South Wales (Hulugalle & Finlay 2003). However in the current assessment, topsoil ESI values did not indicate any correlation with soil type.

Analysis of soil chemical and physical data, together with observations of soil profile morphology, suggest that Cununurra and Aquitaine clays within the WPF are similar to soils within the Ivanhoe and Knox Creek Plains. The mean depth of the dark cracking clay horizon (depth of soil formation) is 150 cm throughout the ORIA. Although earlier surveys identified variations in topsoil pH that resulted in the development of soil phases, actual variability in topsoil pH may be greater within than between map units (Aldrick et al. 1990). The hypothesis by Aldrick et al. of older and younger provinces based on pedogenic development (differences in topsoil clay content and topsoil pH) is challenged by this assessment. The regional differences can be attributed to localised external and internal drainage affected by topography, run-on and substrate texture.

9. Development potential

Results from this assessment indicate that soils of the WPF are generally similar in both physical and chemical characteristics to soils within the ORIA and adjoining Knox Creek Plain.

Horticulture in the ORIA has developed over the past 30 years, with management of groundwater and soil salinity a major focus, particularly in the last five years. Developers of the WPF will be confronted with similar management challenges; however most limitations can be managed. AEM mapping and field verification have identified the main areas prone to salinity and poor drainage, and areas with severe limitations have been excluded from the WPF.

The study of salinity and sodicity on the Ivanhoe Plain by George (1983) and the review of soil sodicity for cracking clay soils in Queensland by Shaw et al. (1994), consider these soil limitations as manageable, especially with good quality irrigation water. George (1983) noted a reduction in subsoil salinity and ESP in both Cununurra and Aquitaine clays after development. Within the WPF, low subsoil EC and ESP values recorded within map unit 5als is evidence of reduced subsoil sodium levels following more than a decade of leaching from the D8 tail drain. Shaw et al. (1994) show that productive horticulture is practised on cracking clays with higher subsoil ESP values in Queensland's Emerald area, using water of similar quality to that of the Ord. These two studies both note that swelling montmorillonitic soils have a reduced sensitivity to sodium, and subsoil clays must be strongly sodic (ESP greater than 20) before clay instability problems develop.

The development and management of irrigation networks and drainage channels require careful consideration, particularly over permeable substrates within the paleo-drainage system. Infiltration testing from this assessment has highlighted extremes in subsoil saturated hydraulic conductivity.

Sustainable horticultural development within the WPF will hinge on irrigation management systems that schedule irrigation to actual crop requirements to minimise through-flow.

Areas dominated by Cununurra clay (map units 1 and 1/5b) and less saline variants of Aquitaine clay (map units 5bls and 5als) have a moderate to high capability for horticultural development. Soils within these map units are likely to have better drained substrates and are therefore suited to a broad range of annual and perennial crops.

Areas containing the soil complexes, Cununurra/Aquitaine clay intergrades, and better drained areas of Aquitaine clay (map units 1/5bms, 5b and 9c) present moderate limitations to sustainable horticultural development that can be addressed with careful management. Note that map unit 9c contains alkaline cracking clays that are associated with zinc deficiency.

Areas of Aquitaine clay (map unit 5a) generally have a low to moderate capability for horticultural development. Aquitaine clay has been successfully cropped for rice as well as moderately salt-tolerant crops such as cotton, sugar cane, sorghum and maize, provided the groundwater is kept below 2 m (Ali & Salama 2003).

Table 2 provides a summary of map unit suitability for flood irrigation.

Table 2 **Suitability of map units for flood irrigation**

Map unit	Suitability	Limitations
1	suitable	Suitable for a broad range of annual and perennial crops. Potentially high through-flow under rice. Consider trickle irrigation in areas with moderate to high KSat substrates.
1/5b	suitable	Suitable for a broad range of annual crops and perennial crops tolerant of slight subsoil salinity and subsoil waterlogging.
1/5bms	suitable	Suitable for a broad range of annual crops.
5b	suitable	Suitable for slight to moderately salt-tolerant annual crops.
5bls	suitable	Suitable for a broad range of annual crops.
5a	suitable	Suitable for moderately salt-tolerant annual crops.
5als	suitable	Suitable for a broad range of annual crops and perennial crops tolerant of subsoil waterlogging.
5als (wet)	suitable	Suitable for a broad range of annual crops and perennial crops tolerant of subsoil waterlogging.
5c	unsuitable	Subject to prolonged waterlogging and run-on.
9c	suitable	Suitable for annual crops provided soil alkalinity and zinc deficiency is managed.
8a	unsuitable	Variable soils subject to run-on.
8b	unsuitable	Variable soils subject to run-on.

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Appendix A Results of soil analyses

Table A1 **Average values of selected analytical data for each map unit**

Depth (cm)		Cununurra clay	Cununurra clay – wet	Cununurra clay – wet, moderately saline	Aquitaine clay	Aquitaine clay – low EM conductivity	Aquitaine clay – better drained	Aquitaine clay – less saline subsoil	Cununurra clay – alkaline
		(1)	**(1/5b)**	**(1/5bms)**	**(5a)**	**(5als)**	**(5b)**	**(5bls)**	**(9c)**
Soil pH									
0–20	av*	6.9	6.6	7.0	7.0	7.3	7.0	7.8	6.6
80–120	av	8.7	8.9	8.6	8.5	8.2	8.4		9.1
180–220	av	8.4	8.3	8.5	8.1	8.6	8.2	8.8	8.7
0–20	sd*	0.4	0.4	0.5	0.7	0.2	0.3	0.1	0.3
80–120	sd	0.2	0.1	0.1	0.3	0.1	0.4		
180–220	sd	0.5	0.1	0.3	0.2	0.2	0.3		
Soil EC $_{1:5}$ (mS/m)									
0–20	av	3.9	2.1	2.9	5.5	4.2	3.7	3.9	3.9
80–120	av	23.2	19.1	51.7	98.0	14.4	74.7		22.8
180–220	av	20.6	14.3	93.2	242.6	49.0	136.9	17.0	59.6
0–20	sd	2.2	0.8	1.2	9.3	1.0	1.8	1.2	1.9
80–120	sd	21.3	3.8	39.1	71.8	5.6	45.7		
180–220	sd	14.0	9.0	100.5	111.3	97.4	116.8		
Soil EC$_{se}$ (mS/m)									
0–20	av	17	10	13	25	17	16	16	0.14
80–120	av	104	81	264	462	36	363		132
180–220	av	150	143	596	918	214	689	57	550
0–20	sd	21	4	6	30	5	7	2	5
80–120	sd	110	50	195	318	5	200		
180–220	sd	125	82	355	338	437	392		
Soil boron (mg/kg)									
0–20	av	0.4	0.4	0.4	0.6	0.4	0.5	0.5	0.3
80–120	av	2.2	3.3	4.5	6.2	1.7	4.9		2.4
180–220	av	1.0	0.8	2.8	6.2	1.8	3.9	4.1	1.3
0–20	sd	0.1	0.0	0.2	0.7	0.0	0.1	0.1	0.0
80–120	sd	1.1	0.8	1.6	2.6	0.8	1.4		
180–220	sd	0.4	0.4	1.7	2.3	1.5	2.6		

(continued next page)

Table A1 (*cont*) **Average values of selected analytical data for each map unit**

Depth (cm)		**Cununurra clay**	**Cununurra clay – wet**	**Cununurra clay – wet, moderately saline**	**Aquitaine clay**	**Aquitaine clay – low EM conductivity**	**Aquitaine clay – better drained**	**Aquitaine clay – less saline subsoil**	**Cununurra clay – alkaline**
		(1)	**(1/5b)**	**(1/5bms)**	**(5a)**	**(5als)**	**(5b)**	**(5bls)**	**(9c)**
Soil sulfur concentration (mg/kg)									
0–20	av	1.2	1.1	1.1	3.3	2.1	1.3	1.1	1.2
80–120	av	17.4	2.4	75.0	199.6	3.3	101.9		5.6
180–220	av	12.2	21.8	601.1	1089.3	103.5	497.0	10.5	81.9
0–20	sd	1.0	0.6	0.8	4.6	1.0	0.9	0.4	0.6
80–120	sd	49.1	1.4	77.9	196.5	1.7	78.3		
180–220	sd	20.0	24.3	934.1	1027.3	261.3	531.2		
Soil clay content									
0–20	av	53	57	60	64	57	63	60	50
80–120	av	55	62	59	65	56	62		58
180–220	av	39	25	37	46	35	50	47	28
0–20	sd	5	4	6	6	6	5	8	1
80–120	sd	5	6	5	8	6	5		
180–220	sd	12	4	15	17	15	15		
Soil ESP content									
0–20	av	1.2	0.6	1.9	1.5	0.5	1.0	0.6	0.8
80–120	av	9.0	9.4	13.2	13.4	3.2	14.8		17.0
180–220	av	9.1	10.2	10.1	10.2	6.7	8.6	15.2	19.6
0–20	sd	3.0	0.4	5.4	3.1	0.1	0.7	0.2	0.4
80–120	sd	5.6	2.3	2.3	5.5	4.7	2.5		
180–220	sd	6.4	2.8	6.5	5.6	6.5	6.2		
Soil chloride concentration (mg/kg)									
0–20	av	5.6	2.2	3.1	12.5	1.5	4.7	2.2	2.0
80–120	av	92.9	65.3	307.9	578.4	5.5	502.7		134.4
180–220	av	173.9	136.9	490.9	896.0	233.0	659.1		705.0
0–20	sd	6.0	1.9	4.1	43.0	1.6	7.1	2.3	1.4
80–120	sd	196.0	91.7	240.6	414.0	3.4	301.7		
180–220	sd	195.4	119.2	310.2	597.1	635.4	397.4		
Number of samples analysed									
0–20		41	10	22	33	7	23	3	3
80–120		19	3	12	21	6	11		1
180–220		17	3	13	23	8	16	1	1

* av = average; sd = standard deviation

Table A2 **Calcium carbonate and exchangeable cations**

Map unit	Depth (cm)	No. of samples	$CaCO_3$ %	Ex Ca meq/100g	Ex K meq/100g	Ex Mg meq/100g	Ex Na meq/ 100g	Ca/Mg ratio	ECEC meq/ 100g	ESP %
1	0–20	41	0.2	17.8	0.7	12.4	0.3	1.5	31.3	1.2
	80–120	17	0.8	16.4	0.6	13.2	3.0	1.3	33.2	9.0
	160–200	18	0.9	11.4	0.5	8.0	1.7	1.4	21.7	8.9
1/5b	0–20	10	0.2	14.8	0.7	12.6	0.2	1.2	28.3	0.7
	80–120	3	0. 8	15.6	0.8	16.3	3.4	1.0	36.0	9.5
	160–200	3	0.4	7.2	0.3	6.7	1.6	1.1	15.8	10.2
1/5bms	0–20	21	0.2	16.4	0.9	15.6	0.4	1.1	33.2	2.0
	80–120	12	0.7	13.3	0.7	16.4	4.7	0.8	35.1	13.3
	160–200	13	1.1	15.1	0.5	9.8	2.3	1.5	27.7	10.2
5a	0–20	33	0.3	22.1	1.1	14.4	0.5	1.6	38.1	1.6
	80–120	22	0.6	16.2	1.0	15.2	4.9	1.1	37.3	13.5
	160–200	22	1.2	24.2	1.0	14.5	3.9	2.0	43.6	10.4
5als (wet)	0–20	7	0.2	19.4	0.7	13.0	0.2	1.5	33.3	0.6
	80–120	6	0.7	17.8	0.6	15.2	1.1	1.2	34.7	3.3
	160–200	8	0.9	8.9	0.6	8.5	1.5	1.4	19.6	6.8
5b	0–20	22	0.2	18.7	0.9	15.7	0.3	1.2	35.8	0.9
	80–120	10	0.5	12.0	0.8	14.4	4.8	0.8	32.1	15.2
	160–200	15	1.4	18.8	0.8	12.5	2.7	1.5	34.7	9.1
5bls	0–20	3	0.3	24.9	1.2	18.1	0.3	1.4	44.5	0.6
	160–200	1		14.5	0.7	13.2	5.2	33.5		
9c	0–20	3	0.3	12.8	0.6	12.3	0.2	1.0	25.8	0.8
	80–120	1	0.7	12.1	0.4	12.9	5.2	0.9	30.6	17.1
	160–200	1	0.4	6.0	0.3	6.5	3.1	0.9	16.0	19.6

Appendix B Saturated Hydraulic Conductivity

Table B1 **Saturated hydraulic conductivity**

Site number	Eastings	Northings	K-Sat (m/day)	Soil texture	Depth (cm)
10	481427	8292208	0.02	FSCL	240
11	481429	8291797	0.05	LSCL	240
15	481444	8289308	0.04	FSCL	240
17	481457	8287242	0.08	ZC	260
20	483746	8288959	0.45	SCL	320
22	483743	8289834	0.06	FSCL	240
25	483753	8291771	0.06	MC	230
27	483760	8293216	0.02	MC	230
33	485243	8289779	0.41	ZC	350
35	485322	8290623	0.21	LMC	Surface
38	484731	8293418	0.08	FSCL	230
45	487558	8288986	0.07	MC	230
47	487542	8290491	0.37	ZL	350
49	487042	8293801	0.04	LMC	280
53	487021	8295506	0.03	MHC	Surface
53	487021	8295506	0.03	MC	330
55	488596	8289095	0.08	MHC	240
58	488600	8290545	0.19	MHC	100
59	488601	8290956	0.02	SCL	200
61	488603	8291722	0.03	LMC	150
64	488607	8293094	0.06	LMC	150
69	488612	8294786	0.08	MC	200
79	490040	8291037	0.10	LC	230
80	490037	8291448	0.05	FSCL	230
81	490033	8291952	0.02	FSCL	230
86	490018	8293855	0.13	MHC	230
91	490002	8295833	0.06	MHC	230
93	490922	8289478	0.02	LMC	230
97	490923	8291120	2.10	CL	330
106	490927	8294895	0.16	MC	300
109	490928	8296236	0.07	MC	200
110	492580	8293363	0.01	LC	220
112	492581	8294047	0.28	CL	230
117	492583	8296181	2.14	LSCL	200
120	494237	8294448	0.03	MHC	Surface
120	494237	8294448	0.76	LSCL	260
130	481469	8285334	0.02	C	260
131	481471	8284950	0.06	SL	260
133	481475	8284212	0.36	ZL	230
135	487891	8293814	0.04	MHC	230
137	487916	8294467	0.04	MC	230
140	487957	8295505	0.03	MC	260
146	486066	8296094	0.08	LMC	260

Site number	Eastings	Northings	K-Sat (m/day)	Soil texture	Depth (cm)
148	482364	8288644	0.38	ZCL	350
149	482354	8289301	0.02	LMC	260
150	482362	8289865	0.23	MHC	Surface
150	482362	8289865	0.05	MHC	60
150	482362	8289865	0.06	LC	220
154	482317	8291653	0.09	ZC	320
156	482304	8292501	0.07	FSCL	260
157	482295	8293076	0.03	MHC	350
160	480622	8292552	0.11	ZCL	260

Texture	
FSCL	Fine Sandy Clay Loam
MC	Medium Clay
C	Clay
LC	Light Clay
ZL	Silty Loam
MHC	Medium Heavy Clay
LMC	Light Medium Clay
SL	Sandy Loam
LSCL	Light Sandy Clay Loam
ZC	Silty Clay
ZCL	Silty Clay Loam
CL	Clay Loam
SCL	Sandy Clay Loam

GPS coordinates in UTM GDA 94, Zone 52

Appendix C
Weaber Plain Soils