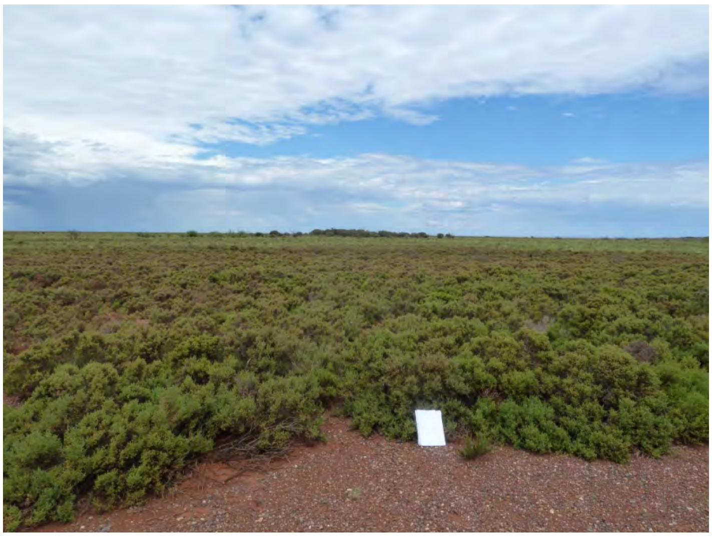
Fortescue Marsh: Synthesis of eco-hydrological knowledge

Final Report (Updated 2013)



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Executive Summary

The Fortescue Marsh is the largest ephemeral wetland in the Pilbara, with multiple conservation values of regional and national significance. Proposed expansions to the Fortescue Metals Group (Fortescue) Chichester Operations have the potential to affect the values of the marsh and surrounding areas, due to modified watertables (*i.e.* drawdown and mounding) and disrupted surface water regimes.

Since the commencement of mining of the Chichester iron ore deposits in 2008, Fortescue has commissioned a range of studies relating to the ecohydrology of the Fortescue Marsh. These studies have collectively addressed landforms and soil profiles, surface hydrology, groundwater systems, vegetation types and distribution, and samphire vegetation water use and eco-physiology. This report:

- provides a consolidated summary of knowledge gained from these studies;
- describes a conceptual ecohydrological model of the Fortescue marsh fringe south of the Christmas Creek LoM Project area; and
- discusses the prediction of potential indirect impacts to the Fortescue Marsh and fringing areas resulting from modified hydrology.

Major findings and conclusions

Supported by empirical evidence from multiple studies, the Fortescue Marsh conceptual ecohydrological model indicates that the water balance dynamics of the marsh are principally controlled by surface water inflows from the greater marsh catchment, as dictated by episodic flooding events. The flood events replenish a shallow aquifer system in the Tertiary sediments beneath the marsh, which is gradually depleted by direct surface evaporation and evapotranspiration by the fringing vegetation communities. In periods of prolonged drought, the shallow watertable reaches a pseudo-steady state set by the evaporation extinction depth in the lowest parts of the marsh basin. The fringing vegetation is dominated by samphire communities which exhibit zonal species distribution patterns influenced by soil water and salinity dynamics, depth to watertables and flooding frequency.

The Christmas Creek LoM Expansion Project is predicted to cause drawdown of up to 3 m in the shallow aquifer near the marsh fringe, in association with dewatering of the Marra Mamba orebody aquifer. Fortescue has evaluated the potential effects of this amount of drawdown on the fringing samphire communities dominated by *Tecticornia indica* subsp. *bidens*, which occur with the span of the drawdown footprint. A vertical 2-dimensional variably-saturated model (HYDRUS) was used to simulate soil water dynamics and plant water uptake by samphire vegetation on the fringe of the Fortescue Marsh. In combination with empirical observations, in particular the demonstrated ability of *T. indica* subsp. *bidens* to tolerate drought and other stressors, the findings of the modelling study suggest that the ecological water requirements of the fringing samphire communities are wholly or predominantly met by surface inputs. The findings provide confidence that the predicted drawdown will not significantly affect samphire survival and health. Other potential groundwater system impacts associated with the Christmas Creek LoM Expansion Project water management strategy, such as injection mounding and water quality changes, are also not predicted to be significant.

Mining and infrastructure development associated with the Christmas Creek LoM Expansion Project will disturb the surface flow regime north of the Fortescue Marsh, within a zone of relatively stable channel systems occasionally separated by sheetflow areas. The divergent channel drainage network downstream from these areas will remain largely unaffected by mining disturbances. Assuming effective implementation of the Fortescue Chichester Operations Surface Water Management Plan, minimal disruption to the downstream flow regime at the marsh fringe is expected. Where changes to the flow regimes of individual drainage outlets occur, these are predicted to be modest and will not significantly affect the ecological water requirements of the Fortescue Marsh samphire communities.

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1 Introduction

Fortescue Metals Group (Fortescue) operates the Cloudbreak and Christmas Creek north of the Fortescue Marsh, in the central Pilbara region of Western Australia. These mines are collectively referred to as the Chichester Operations.

The Fortescue Marsh is the largest ephemeral wetland in the Pilbara, with multiple conservation values of regional and national significance. Proposed expansions to the Chichester Operations have the potential to affect the values of the marsh and surrounding areas, due to modified watertables (*i.e.* drawdown and mounding) and disrupted surface water regimes. To predict the potential environmental impacts of these activities, and develop strategies to avoid and minimise environmental harm, it is necessary to have an understanding of the marsh ecohydrology.

Equinox Environmental Pty Ltd (Equinox) has assisted Fortescue with the coordination of research activities relating to the ecohydrology of the Fortescue Marsh since 2010. These studies and investigations have collectively addressed:

1. landform and soil profiles
2. surface hydrology
3. groundwater systems
4. vegetation types and distribution
5. vegetation water use and eco-physiology
6. measurement and modelling of ecohydrological processes.

This report provides a consolidated summary of knowledge gained from these studies, and discusses the prediction of potential indirect impacts to the Fortescue Marsh and fringing areas resulting from modified hydrology. This is an updated version of the original project report submitted to Fortescue in December 2012.

This report supports the environmental impact assessment (EIA) process associated with the proposed Christmas Creek Life-of-Mine (LoM) Expansion Project, and more generally informs Fortescue's environmental management and monitoring approaches.

1.1 Report structure

This document is structured as follows:

Section 2 provides a summary of the environmental setting and key values of the Fortescue Marsh. This includes information summarised from various study reports (hydrogeology, hydrology, landform/soil profile investigations, ecological surveys) augmented by field observations made by Equinox.

Section 3 describes the current environmental management framework for the Fortescue Marsh, including Environmental Protection Authority (EPA) management objectives set out in EPA (2013) and a discussion of relevant principles applied by the EPA in recent project assessments.

Section 4 describes the key findings of targeted studies and investigations undertaken by Fortescue in collaboration with research partners, which have contributed to the current understanding of the marsh eco-hydrology.

Section 5 describes eco-hydrological modeling undertaken by Fortescue, which integrates the various knowledge sources to provide a consolidated understanding of the eco-hydrological functioning of the marsh. This includes a conceptual ecohydrological model and a 2D numerical model of the unsaturated zone near the northern fringe of the Fortescue Marsh.

Section 6 provides a preliminary assessment of potential impacts on the ecohydrology of the Fortescue Marsh associated with the Christmas Creek LOM Expansion Project, as informed by the aforementioned studies. Potential approaches for impact mitigation and management are discussed. Consideration is also given to the potential for cumulative impacts associated with other mining projects in the vicinity of the marsh.

Section 7 provides a brief summary of the key findings and conclusions.

2 Fortescue Marsh overview

2.1 Location and physical description

The Fortescue Marsh forms an extensive ephemeral wetland in the central Pilbara Region, situated in the floor of a broad valley that separates the Hamersley Range (>1000 m AHD) to the south and the Chichester Range (>500 m AHD) to the north (Figure 1). It is approximately 100 km long and 3 to 12 km wide, occupies an area of approximately 1000 km^2, and lies at an elevation of about 400 m to 405 m AHD.

The marsh is defined by zone of confined drainage in the middle reaches of the Fortescue River, which flows into the marsh from the east. The Goodiadarrie Hills form the confining feature at the western end of the marsh (≈410 m AHD at marsh outlet), which ostensibly has not been overtopped by flood waters for at least 50 years (DEC 2007; Gilbert & Associates 2009). Drainage westwards to the lower Fortescue drainage system is therefore expected to be very infrequent and contingent on extreme flooding events.

The ecophysiographic boundary of the marsh is not clearly defined in the literature, but approximately corresponds with the lower margins of the Fortescue valley subject to episodic flood inundation. The boundary is generally discernible on the basis of topography (roughly 406 to 408 m AHD) and the occurrence of samphire dominated vegetation communities. The Marsh land system described by van Vreeswyk *et al.* (2004) is a working approximation of the ecophysiographic boundary for broad scale assessment purposes.

2.2 Climate

The climate in the Fortescue Marsh locality is described as desert: hot (persistently dry) under the modified Köppen classification system (Stern *et al.* 2000). It is characterised by hot humid summers and relatively cooler, drier winters.

Records from the Bureau of Meteorology (BOM) Marillana weather station[1] located ≈20 km south of the central marsh (Figure 1) provide an indication of the rainfall regime (BOM 2011). Long-term, mean annual rainfall is approximately 310 mm, but is highly

[1] BOM Station Number 5009

variable between years and over longer time scales. Annual potential evaporation is estimated to be 3200 mm to 3600 mm, and annual average evaporation of 2500 mm has been reported (Fellman *et al.* 2011). With the exception of infrequent cyclonic rain events, evaporation exceeds rainfall in all months of the year.

Higher than average rainfall has occurred since the mid-1990s, with a corresponding increase in the number of significant daily rainfall events outlined as follows:

Size of daily rainfall event	No. of events 1936 - 1995[2]	No. of events 1995 - present[3]
>20 mm	184	83
>50 mm	40	21
>100 mm	5	5

2.3 Geology

The Fortescue Marsh is located in the Hamersley Basin, a late Archaean to early Proterozoic (2765-2470 Ma) depositional basin up to several kilometers thick overlying granite-greenstone basement rocks (Thorne & Tyler 1997). The stratigraphic sequence of the Hamersley Basin includes the following major geological formations:

Youngest ↓

Turee Group: comprising (in descending order) the Kazput Formation, Koolbye Formation, and Kungarra Formation

Hamersley Group: comprising (in descending order) the Boolgeeda Iron Formation, Woongarra Rhyolite, Weeli Wolli Formation, Brockman Iron Formation, Mount Sylvia Formation and Mount McRae Shale, Wittenoom Formation, and Marra Mamba Iron Formation.

Fortescue Group: comprising (in descending order) the Jeerinah Formation, Bunjinah Formation and Maddina Basalt, Pyradie Formation, Boongal Formation, Hardey Formation, and Mount Roe Basalt.

Granite-greenstone basement: estimated to have formed between 3500 and 2800 Ma.

Oldest

[2] Including 4,974 days of missing data
[3] Including 812 days of missing data

At a sub-regional scale, the original sedimentary surface has been heavily eroded, dissected and laterised since the late Mesozoic era. A variety of partly consolidated Tertiary materials are associated with valley fill deposits including cemented colluvium (Czc), alluvium (Czn) and calcrete (Czk). Residual lateritic deposits (Czr and Czl) are also recognised. More recent Quaternary deposits are typically comprised of unconsolidated silt, sand and gravel in various proportions depending on local formation processes.

The Hamersley Range includes outcropping of the Weeli Wolli Formation (PLHj) and Brockman Iron Formation (PLHb) (Figure 2; mapping codes described in Appendix 1). The Weeli Wolli Formation includes jaspilite, shale and chert, and also hosts significant doleritic sills (PLHt). The Brockman Iron Formation contains various BIF, shale and chert bands.

The Chichester Range includes outcropping of the Marra Mamba Iron and Wittenoom Formations on the southern slopes, and Fortescue Group members of the Jeerinah Formation further north (Figure 2). Major rock types include chert, basalt, shale, BIF, mudstone, dolomite and thin-bedded meta-sandstone. Mineralisation in the Fortescue Christmas Creek project area is confined to the Nammuldi Member of the Marra Mamba Formation, where it is overlain and concealed below Tertiary deposits (Fortescue 2012a). A weathered hardcap generally overlies the orebody. Further south the Marra Mamba Formation is overlain by a sequence of Quaternary and Tertiary deposits generally referred to as Tertiary Detritals. Moving further south again towards and beyond the marsh boundary, the Marra Mamba Formation dips below the dolomitic Wittenoom Formation. In this vicinity zones of re-precipitated calcium carbonate and silica occur near the base of the Tertiary Detritals, referred to as the Oakover formation. A generalised stratigraphic profile of the Christmas Creek locality is provided in Figure 3.

Alluvial and colluvial sequences associated with the Fortescue Valley between the ranges are indicatively greater than 100 m thick in and adjacent to the Fortescue Marsh, with sequences up to 70 m thick recorded north of the marsh boundary (Fortescue 2012a). The marsh fringe areas are commonly associated with calcrete exposures (Czk), which are likely to have formed under evaporitic conditions combined with fluctuating groundwater levels. These are most extensive and developed on the southern side of the marsh. A detailed discussion of calcrete formation in alluvial fans and valley environments is provided by Wright (2007). Groundwater calcretes often exhibit varying degrees of silicification, reflecting the influence of saline groundwater and silica precipitation/displacement of calcium carbonate. Chert breccia exposures (Czz) occur at the Goodiadarrie Hills (western end of marsh) and also south of the marsh near Coondiner Pool (773000E; 7484000N).

2.4 Hydrology

2.4.1 Catchment

The Fortescue River is Western Australia's third longest river, spanning a distance of 760 km from its headwaters near the Ophthalmia Range, near Newman, to the Indian Ocean outfall near Mardie Station (DEC 2009). The Fortescue Marsh represents the terminus of the Upper Fortescue catchment, which includes an area of approximately 29,300 km^2 (Worley Parsons 2012). In addition to the Fortescue River in the east, numerous creeks discharge to the marsh from the flanks of the Hamersley and Chichester ranges. The physiographic marsh land surface spans an area of approximately 85,000 to 100,000 hectares (i.e. ≈3% of the Upper Fortescue Catchment).

Following significant rainfall events, direct rainfall and catchment runoff contributes to widespread inundation of the marsh flats. The zone of potential inundation is up to approximately 100 km long and 30 km wide (EPA 2013). Following smaller events, isolated pools form on the marsh opposite the main drainage inlets (Aquaterra 2005). The large events typically occur during the period December to April, in the order of two to three times per decade. In contrast the period May to November typically has low rainfall and significant runoff events during this time are uncommon.

The Upper Fortescue Catchment has putatively been affected by the construction of the Ophthalmia Dam in 1981 (Payne & Mitchell 1999; Elith & Bidwell 2004). The dam is located approximately 100 km upstream from Roy Hill and was built to supply water to the town of Newman and nearby mining operations. It captures water from three of the 15 major tributaries of the Fortescue River, intercepting long term median inflows of about 30 GL (Payne & Mitchell 1999). The dam does not prevent large flows from reaching downstream areas (Florentine 1999; Astron 2010), but has been implicated in reducing flow volumes, peak flows, flooded width and frequency of flooding on the downstream floodplain (Payne & Mitchell 1999). Prior to 2000 it appears to have prevented medium sized flows, which would have had a recurrence interval of one to three years pre-construction of the dam. A more recent assessment in 2010 included the finding "*Over the past 28 years, Ophthalmia Dam has overflowed, every 2.3 years on average, via a spillway*" (Astron 2010).

The influence of the dam on the downstream flow regime diminishes with distance towards Roy Hill. Reductions in medium sized flows have been linked to vegetation stress (in particular in *E. camaldulensis* var. *refulgens* and *E. victrix* woodlands) upstream of the marsh. Payne & Mitchell (1999) made the following assessment in their report "*possible long term effects on the Marsh land system further downstream (west of Roy Hill homestead) are unknown. The survey team saw no clear cut evidence of an effect on this system at this stage, although there appears to be some areas of the system that have not been flooded for a few years*". BHP Billiton Iron Ore (BHPBIO) maintains an ongoing tree health monitoring program in riparian areas downstream from the dam.

Worley Parsons (2012) describe a recently completed a Fortescue Marsh catchment water balance study, using a daily water balance model to evaluate the effect of the Christmas Creek LoM Expansion Project on water volumes reaching the marsh. Sub-catchment delineation (35 sub-catchments) was undertaken using topographic information from Shuttle Radar Topographic Mission (SRTM) data. Calibration of the model was achieved using data from a limited number of stream flow gauging stations in the catchment, and marsh storage volumes derived from Fortescue's LIDAR dataset and satellite imagery. The model was run for the period spanning 01/12/1984 to 30/04/2011. Groundwater interactions with the marsh were assumed to be insignificant, consistent with Fortescue's hydrogeological conceptualisation of the marsh (refer to Section 2.5). Based on the outputs from this model, the average volume of water entering the Marsh over this period was 260 GL per year. Direct rainfall accounted for about 10% of this volume, and the East Fortescue Catchment contributed approximately 50% of the inflows. The Chichester Ranges catchment area (comprising six sub-catchments) was estimated to contribute approximately 17% of the total water input on average, but 9% to 32% of the total water input for individual inflow events. Although subject to data input limitations (principally minimal gauging station data) the model results give an indication of the dynamics and relative importance of catchment inflows (in particular the Fortescue River) to the overall marsh water balance.

2.4.2 Wetland type

There are 40 major types of wetlands in Australia, as defined using a modified version of the international Ramsar Classification System for Wetland Type (Environment Australia 2001). The main elements of this classification system include wetland size, water salinity, geomorphology, seasonality and vegetation structure. The Fortescue Marsh purportedly includes two wetland types:

- **Type B4:** Riverine floodplains; includes river flats, flooded river basins, seasonally flooded grassland, savanna and palm savanna; and
- **Type B6:** Seasonal/intermittent freshwater lakes (>8 ha), floodplain lakes.

Surface water expression is intermittent across the majority of the marsh, and is generally considered to be formed by episodic flood events (surface flows) rather than surface groundwater expression. Flooding events contribute to a shallow aquifer system beneath the marsh, with ponding slowly dissipating through the processes of seepage and evaporation (Worley Parsons 2012).

2.4.3 Chichester drainage networks

Catchments draining the southern flanks of the Chichester Range have formed a series of floodplains, alluvial fans and sheet flow zones that form a band of low relief between the range and the Fortescue Marsh (Worley Parsons 2012). Surface flows only occur during, and for relatively short periods after, significant rainfall. The upland areas drain into a series of relatively well defined, parallel drainage channels. The larger channels can be up to 50 m wide with defined banks and flat gravelly/cobbled beds, and are usually devoid of vegetation due to bed load movement during flood events. These channels effectively define a relatively stable transfer zone between the Chichester range uplands and deposition zones further downstream. Fortescue's Chichester mining areas coincide with the lower reaches of these channels.

Near the base of the hills, relictual alluvial fan formations are dissected by the channels, which both diverge and coalesce. Some of the broad inter-channel areas with low relief support banded mulga vegetation, particularly to the west of the existing Christmas Creek mining areas. These are considered to be localised sheetflow areas.

Further south, the land flattens out further and the channels become narrower and more divergent, with zones of channel avulsion and anabranching. The banded vegetation areas tend to pinch out back into the distributary drainage network, several kilometers north of the marsh boundary. The channels in this zone are ostensibly less stable than those upstream, with variable channel widths and depths superimposed on overall downstream size decreases. Floodway widths generally increase. The flowlines, including floodway spillovers and splays, are generally well vegetated relative to the surrounding stony mantled plains. Defined flow lines persist into the marsh, where they further distribute into splay channels and marsh playas.

Backhoe pit excavations undertaken by Fortescue in the lowland Chichester drainage tracts (depositional zone) have consistently found cobble layers overlain by 1 to 2.5 meters of fine-grained floodplain sediments (Figure 4). This suggests that many of the drainage lines are relictual higher energy channels, which in more recent geological time have been in-filled with sediments in a lower energy environment. The in-filled channel incisions are likely to have relatively good soil water holding capacity in comparison with the surrounding landscape, which is consistent with the pronounced boundaries between relatively dense mulga vegetation on the drainage tracts and the sparsely vegetated shrublands in the inter-drainage areas (Figure 5). Gypsum crystals were observed in the deep cobble layers in some of the pits, indicating that persistent saturation of these layers has occurred in the past.

Examples of drainage features near the northern side of the marsh observed by Equinox are presented in Figure 5 (photographs from April/May 2012 all looking approximately south; aerial photograph captured in April 2012):

- Plate 1 shows a narrow drainage line within the marsh lined by couch grass, and holding water in connection with down gradient floodwaters.
- Plate 2 shows a narrow incised channel within a wider, anabranching floodway tract located about 600 m north of the marsh boundary.
- Plate 3 shows the same channel as Plate 2 but 300 m further downstream. Note the sandy deposits in the channel, contrasting with heavy textured bank soils.
- Plate 4 shows shallow, anabranching flowlines within a wider floodway tract; near the edge of the marsh ecophysiographic boundary.
- Plate 5 shows the edge of a zone of shallow anabranching flowlines, within a wider floodway tract.

- Plate 6 shows a well vegetated drainage tract in the background, with a stony mantled and sparsely vegetated inter-drainage area in the foreground that is typical near the marsh in the Fortescue Christmas Creek LoM Expansion Project area.
- Plate 7 shows a 1.5 m wide channel downstream from a small, historical pastoral dam structure, located about 1.6 km north of the marsh boundary. This channel may have been historically influenced by avulsion near the dam inlet.
- Plate 8 shows a 3 m wide, flat bedded channel within a wider, anabranching floodway tract located about 4 km north of the marsh boundary. Mature mulga fringes the channel.

2.5 Groundwater systems

Groundwater flow in the Christmas Creek area is strongly controlled by stratigraphy and topography, and is often enhanced along faults and discontinuities (Fortescue 2012a). Groundwater levels adjacent to the Fortescue Marsh are a subdued reflection of the topography, such that depth to groundwater tends to increase with distance upslope from the marsh.

The major hydrostratigraphic units, in their approximate vertical sequence, are summarised as follows (Fortescue 2012a):

- Tertiary Detritals (alluvium and colluvium) – variable hydraulic conductivity and storativity as influenced by depositional heterogeneity, substrate geology and particle size distribution. Aquifers within the Tertiary depositional sequence are semi-confined to unconfined. The Fortescue Marsh has an associated shallow aquifer that overlies Tertiary clay layers and extends into areas surrounding the marsh. Fortescue bore records show that watertables at the edge of the marsh fluctuate in the order of 2 to 3 m under natural conditions, and are responsive to significant rainfall events. However, the response of shallow watertables to rainfall rapidly diminish moving further north from the marsh boundary.
- Tertiary Detritals (clay) - thick, low permeability clay layers are prominent in the deeper profile near the Fortescue Marsh. These overlie the Oakover Formation, and at their northern extent onlap the Marra Mamba Formation. These layers are believed to impede vertical water transfer between the surficial and deeper groundwater systems.

- Tertiary Detritals (Oakover Formation) – high permeability calcretes and silcretes, in a layer up to 20 m thick. Overlies the Marra Mamba Formation, including some areas of mineralisation, at its northern extent. Overlies the Wittenoom Formation further south near the Fortescue Marsh. Poorly developed or absent to the east, towards the Roy Hill deposit.
- Orebody aquifer (mineralised Nammuldi Member) - a semi-continuous brackish aquifer of relatively high hydraulic conductivity and storativity, with groundwater flow in a south-westerly direction towards the Fortescue Valley. Unconfined to partially confined near the Chichester Range, and partially confined to confined in the south where overlain by Tertiary clay layers. The aquifer is bound to the north by the outcropping of the underlying Roy Hill Shale Member and to the south by the lower permeability, unmineralised Nammuldi Member.
- Non-mineralised Nammuldi Member – relatively low permeability chert and BIF, with enhanced permeability along faults.
- Wittenoom Formation – a generally confining layer of massive, crystalline dolomite. More permeable zones associated with faulting may have developed. Weathering has resulted in the formation of a clay-dominated zone in the upper profile with low permeability.
- Jeerinah Formation – mudstone and chert associated with the Roy Hill Shale, generally thought to have low transmissivity. There are zones of relatively enhanced hydraulic conductivities associated with structures, faults zones and weathering.

Groundwater is brackish near the Chichester Range, grading to saline with depth and proximity to the hypersaline Fortescue Marsh basin. The density contrast between saline groundwater and fresher groundwater leads to a wedge-shaped transitional zone beneath the fresher groundwater in the aquifers flanking the Chichester Range. The transition zone is heterogeneous, with more saline zones often aligned with structural lineaments and other preferential flow paths.

Connectivity relationships between the key hydrostratigraphic units have been evaluated by Fortescue hydrogeologists and are summarised as follows (Fortescue 2012a):

- Variable connection between the to the Orebody Aquifer and the Oakover Formation, with connection restricted by the presence of the lower hydraulic conductivity unmineralised Nammuldi Member in regions proximal to the Oakover Formation. Where connection occurs, it facilitates linkage of hypersaline water in the Fortescue Valley basin and the fresher water aquifer system located along the flank of the Chichester Range.
- Strong hydraulic connection between the orebody aquifer (near current and proposed mining areas) and overlying Tertiary Detritals. Leakage from latter can limit the extent of drawdown associated with drawing water from the Orebody aquifer and thereby reduce saline water intrusion.
- The shallow Fortescue Marsh aquifer is generally separated from the deeper aquifer systems by the low permeability Tertiary clay layers; although recent chemical and stable isotope analyses suggests at least some degree of hydraulic conductivity between deep and shallow groundwater on the marsh operates, despite localised impermeable horizons of clay and calcrete (Skrzypek *et al.* 2013).
- Groundwater discharge from topographically-driven flow (in both the Tertiary and Marra Mamba Formation systems) is low, due to the poor hydraulic connection between topographic discharge areas (the surface of the Fortescue Marsh) and underlying aquifers. The presence of hypersaline water in the discharge zone (beneath the Fortescue Valley) also impedes groundwater discharge, as the saline groundwater creates an opposing density-driven flow potential. Recent chemical and stable isotope analyses of surface water and groundwater in the marsh suggest that vertical flow processes dominate the marsh groundwater system (Skrzypek *et al.* 2013).

Fortescue hydrogeologists have conceptualised the general spatial arrangement of these hydrostratigraphic units, their connectivity and relationship with the marsh water balance. The conceptual model is depicted in Figure 6.

2.6 Land systems

The Pilbara region has been surveyed by the Western Australian Department of Agriculture and Food (DAFWA), for the purposes of land classification, mapping and resource evaluation. The region consists of over one hundred land systems; distinguished on the basis of topography, geology, soils and vegetation (Van Vreeswyk *et al.* 2004).

The Fortescue Marsh is broadly coincident with the Marsh land system. The key attributes of this and surrounding land systems are further described in Table 1 and spatially depicted in Figure 7. The Marsh land system is classified as a Priority Ecological Community (PEC; category Priority 1) by the Department of Parks and Wildlife[4] (DPaW).

The Christmas, Cowra and Marillana land systems are restricted to the Fortescue Valley and considered to have conservation significance (EPA 2013). These land systems include broad depositional flats, and contain Mulga/mixed *Acacia* woodland and shrubland vegetation communities (including groved formations) of high conservation interest. The Christmas land system abuts the north-west portion of the Marsh land system. The Cowra land system forms an extensive band along the northern edge of the Marsh land system, and also occurs near the south western margin. The Marillana land system occurs south of the Fortescue Marsh.

The Calcrete land system is extensive along the southern margins of the Fortescue Marsh. It is typified by outcropping calcrete and surface mantles with abundant pebbles and cobbles of calcrete. The Warri land system also contains calcrete platforms, but with different vegetation associations. It has restricted distribution near eastern portions of the marsh, however field observations made near Christmas Creek suggest that shallow calcrete sheeting may be more extensive in this locality than the DAFWA mapping suggests. As such the Warri land system is likely to encroach more widely into the Cowra land system than is depicted in Figure 7; for example into the area between MGA Zone 50 Eastings 770000 and 780000. The low resolution of land system mapping near the marsh has also been identified by Kew (2011), who observed in areas south of the Cloudbreak mine "*The land system mapping is general and does not adequately depict minor changes in landform between the Cowra and Marsh land system*".

[4] Formerly the Department of Environment and Conservation

Table 1 The major land systems in and surrounding the Fortescue Marsh

Land system	Description	Geomorphology and soils
Calcrete	Low calcrete platforms and plains supporting shrubby hard spinifex grasslands.	Tertiary calcrete formed in valley fill deposits, with minor Quaternary alluvium. Drainage is generally indistinct. Soils are mainly shallow calcareous loams (<50 cm overlying calcrete), with minor calcareous loamy earths and red shallow loams.
Christmas	Stony alluvial plains supporting Snakewood and Mulga shrublands with sparse tussock grasses.	Depositional surfaces; level to gently inclined stony plains subject to sheet flow with numerous small, diffuse drainage foci and groves. Soil types mainly include deep red/brown non-cracking clays, with some deep red loamy duplex soils. Restricted to the Fortescue Valley and considered to have elevated conservation significance (EPA 2013).
Coolibah	Flood plains with weakly gilgaied clay soils supporting Coolibah woodlands with Tussock grass understorey.	Depositional surfaces; active flood plains and alluvial plains associated with the Fortescue river (i.e. non-Fortescue Marsh sections). Soil types mainly include deep red/brown non-cracking clays, with some deep red loamy duplex soils.
Cowra	Plains fringing the Marsh land system and supporting Snakewood and Mulga shrublands with some halophytic undershrubs.	Depositional surfaces; almost level plains of non-saline and weakly saline alluvium with gravelly surfaces. Drainage foci and tracts support denser vegetation, included banded formations in some places. Soils mainly include red loamy earths and duplex types; with abundant cobbles and stony mantles. Restricted to the Fortescue Valley and considered to have elevated conservation significance (EPA 2013).
Fortescue	Alluvial plains and flood plains supporting patchy grassy woodlands and shrublands and tussock grasslands.	Depositional surfaces associated with river channels and commonly subject to fairly regular flooding. Soils are mainly deep red/brown non-cracking clays and self-mulching cracking clays.

Land system	Description	Geomorphology and soils
Marillana	Gravelly plains with large drainage foci and unchannelled drainage tracts supporting Snakewood shrublands and grassy Mulga shrublands.	Depositional surfaces derived from Quaternary alluvium. Sheet flow areas occur and are associated with stony surface mantles. Broad, unchannelled drainage tracts can receive more concentrated through flow. Soils are generally deep red loamy earths, duplex soils or clays.
Marsh	Lakebeds and flood plains subject to regular inundation, supporting samphire and halophytic shrublands	Depositional surfaces derived from Quaternary alluvium and lacustrine deposits. Soils include red/brown clays, often with high alkalinity and gypsum content. Soils can be underlain by siliceous or calcareous hardpans. Defines the recognised Fortescue Marsh land unit.
Turee	Stony alluvial plains with gilgaied and non-gilgaied surfaces supporting tussock grasslands and grassy shrublands.	Mosaic depositional surfaces of low relief (hardpan, stony and gilgai plains) inter-dispersed with few drainage channels. Localised sheet flow can occur. Soils include various earths, loams and clays often with abundant surface cobbles.
Warri	Low calcrete platforms and plains supporting Mulga and Senna shrublands	Depositional surfaces of low relief. Calcreted valley fills and mosaics of calcrete tables, with narrow inter-table areas. Soil types mainly include calcareous shallow loams and loamy earths. Surface mantles commonly include calcrete pebbles and fragments.

2.7 Soils

Various investigations undertaken by Fortescue (refer to Section 4) have provided information on soil profiles near the northern fringe of the Fortescue Marsh. This has enabled broad soil attributes to be characterised.

Kew (2011) described soils in samphire vegetation communities fringing the marsh south of the Cloudbreak mine, which has been further informed by more recent backhoe pit excavations undertaken in association with Fortescue and University of Western Australia (UWA) research projects (Figure 8). The generalised soil profile in this location consists of a shallow fine clay loam A horizon (0-10 cm) overlying a light to light-medium clay B horizon with sub-angular blocky structure. Sub-soils are highly saline (dominated by NaCl) and strongly sodic (ESP[5] >15). The high salinity is likely to prevent deflocculation of the sodium saturated clays that would otherwise be expected with such high ESP values, thereby maintaining soil permeability and penetrability by plant roots. A massive siliceous red/brown hardpan at depths of 40 to 120 cm was omnipresent in the Cloudbeak marsh survey area, constituting an impeding layer for plant roots. Gypsic horizons (>20% visible gypsum) were commonly encountered in the B horizon by Kew (2011).

Additional backhoe pit excavations were undertaken south of the Christmas Creek mining area in April/May 2012. The generalised soil profile in this location is similar (Figure 8), but with the following notable differences:

- The surficial fine loamy horizon was typically 30 to 40 cm deep.
- The underlying B horizon was typically more loamy (i.e. lower clay content) than the Cloudbreak profiles, based on field texture classing (Clay loam to light clay).
- instead of a silcrete hardpan, the B horizon was underlain by a zone of permeable, nodular calcrete at depths of 1 to 2.5 m. The watertable was intersected at depths within the calcrete layer, as dictated by surface elevation. Samphire root systems were most extensive in the surficial layer, but some fine roots extended to the depth of the watertable.

[5] Exchangeable sodium percentage

2.8 Vegetation and flora

In mid-2012 ENV Australia Pty Ltd (ENV) completed vegetation mapping of portions of the Fortescue Marsh south and adjacent to the Christmas Creek mine site (ENV 2013). The ENV survey report also presented the results of previous broad scale vegetation mapping in areas north of the marsh: including work undertaken by ENV at Cloudbreak and Christmas Creek (ENV 2011; 2010); Mattiske Consulting Pty Ltd (Mattiske 2004; 2007) and Biota Environmental Sciences Pty Ltd (Biota 2004).

The ENV survey was consistent with a Level 2 survey as per EPA requirements for the environmental surveying and reporting for flora and vegetation in Western Australia. Floristic, vegetation structure and other environmental information was collected from 43 quadrats and eight relevés along eight transects extending from the upper Marsh margin to the lower Marsh; and a further eight quadrats and 31 relevés were located in additional survey areas to the north of the Marsh (ENV 2013).

Thirteen vegetation units were described across seven major landforms across seven major landforms within Fortescue Marsh and on the alluvial plains fringing the north of the marsh, described as follows:

- **Unit 1** - *Tecticornia* sp. Christmas Creek, *T. auriculata*, *Muehlenbeckia florulenta* low closed heath over *Eragrostis pergracilis*, *E. tenellula* scattered tussock grasses and *Cullen cinereum*, *Nicotiana heterantha*, *Pterocaulon sphaeranthoides* open herbland on red-brown loamy clay soil in mid-marsh.
- **Unit 2** - *Muehlenbeckia florulenta* shrubland to open heath over *Tecticornia indica* subsp. *bidens* low scattered shrubs to low open shrubland over *Eleocharis papillosa*, *Schoenoplectus dissachanthus* (very) open sedgeland with *Nicotiana heterantha*, *Marsilea hirsuta* (open) herbland on brown silty clay soil in lower marsh.
- **Unit 3** - **Vachellia farnesiana*, *Acacia ampliceps* open scrub over *Tecticornia* sp. Christmas Creek (K.A. Shepherd & T. Colmer et al. KS 1063), **Aerva javanica* and *Cullen cinereum* low open shrubland over **Cenchrus setiger*, *Dactyloctenium radulans* and **C. ciliaris* tussock grassland on red-brown sandy soil on low rises, ridges.
- **Unit 4** - *Melaleuca glomerata* open scrub over **Aerva javanica*, *Tecticornia* spp. low open shrubland over *Cleome viscosa*, *Nicotiana heterantha*, *Swainsona kingii* herbland on brown sandy loam on low rises.

- **Unit 5** - *Acacia synchronicia*, *Melaleuca glomerata*, *Eremophila youngii* subsp. *lepidota* scattered tall shrubs over *Tecticornia indica* subsp. *bidens*, *Eremophila spongiocarpa* low open shrubland over *Sporobolus virginicus*, *Cenchrus ciliaris, *Dactyloctenium radulans* tussock grassland on red-brown sandy loam, mostly in drainage lines.
- **Unit 6** - *Tecticornia* sp. Dennys Crossing (K.A. Shepherd & J. English KS 552), T. *indica* subsp. *bidens*, *Muehlenbeckia florulenta* low open heath over *Eragrostis pergracilis* (very) open tussock grassland and *Cyperus bulbosus* scattered sedges with *Nicotiana heterantha*, *Swainsona kingii* scattered to very open herbland on red-brown sandy clay in mid-marsh (and lower marsh).
- **Unit 7** - *Tecticornia indica* subsp. *bidens*, *T.* sp. Dennys Crossing (K.A. Shepherd & J. English KS 552), *Eremophila spongiocarpa* low open heath to low closed heath over *Eragrostis* spp., *Enneapogon* spp., *Cenchrus spp. scattered tussock with *Nicotiana heterantha*, *Pterocaulon sphaeranthoides*, *Gomphrena kanisii* scattered herbs on red-brown sandy clay in lower marsh and depressions as well as upper marsh.
- **Unit 8** - *Tecticornia auriculata* (and T. sp. Dennys Crossing (K.A. Shepherd & J. English KS 552) open heath over *Eragrostis pergracilis*, *Chloris pectinata* tussock grassland and *Cyperus bulbosus* scattered sedges with *Swainsona kingii*, *Nicotiana heterantha* scattered herbs on redbrown loamy clay soil in mid-marsh.
- **Unit 9** - *Acacia synchronicia* scattered tall shrubs over *Tecticornia indica* subsp. *bidens*, *Eremophila spongiocarpa* low open shrubland over *Eragrostis pergracilis*, **Cenchrus ciliaris* tussock grassland with *Lawrencia densiflora*, *Euphorbia australis*, *Goodenia forrestii* scattered herbs on brown sandy loam on low rises.
- **Unit 10** - *Acacia synchronicia*, *A. xiphophylla* high shrubland over *Eremophila* spp., *Enchylaena tomentosa* var. *tomentosa*, *Maireana pyramidata* scattered low shrubs over **Cenchrus ciliaris*, *Eragrostis pergracilis*, *Triraphis mollis* very open tussock grassland and *Goodenia forrestii*, *Sclerolaena cornishiana*, *Stemodia grossa* scattered herbs on red-brown sandy loam on low rises.
- **Unit 11** - Lake bed likely to support annual herbs and grasses episodically.
- **Unit 12** - *Acacia synchronicia* scattered shrubs over *Eremophila spongiocarpa*, *Atriplex bunburyana* and *Sclerolaena cuneata* low shrubland to low open shrubland, over *Dactyloctenium radulans*, *Eragrostis pergracilis* and *Panicum decompositum* scattered tussock grasses on red brown silty-clay on alluvial plains north of the marsh.

- **Unit 13** - *Acacia synchronicia* scattered tall shrubs over *Senna artemisioides* subsp. *oligophylla* (thinly sericeous), *Atriplex bunburyana* and *Sclerolaena cuneata* low open shrubland over *Dactyloctenium radulans* scattered tussock grasses on red-brown clay on alluvial plains north of the marsh.

The survey findings indicated that samphire species are abundant in most vegetation units: in particular units 1, 2, 3, 6, 7 and 8. Within the mapping boundary Unit 7 is the most prevalent vegetation along the fringe of the marsh, whilst Unit 2 is most prevalent further into the marsh (Figure 9). Vegetation dominated by *Tecticornia indica* subsp. *bidens* is also widespread in marsh fringe areas further west (i.e. south and west of the Cloudbreak mining area). Unit 4 including stands of mature *Melaleuca glomerata* has a restricted distribution within the marsh, but may provide important nesting and roosting habitat for waterbirds. All vegetation units including *Tecticornia* spp. and conservation significant *Eremophila* spp. on the Marsh Land System (i.e. units 1 to 9 inclusive) correspond to the Fortescue Marsh PEC.

A total of 196 taxa representing 110 genera and 35 families were recorded in the survey (ENV 2013). The most taxon-rich families were; Poaceae (39 taxa), Chenopodiaceae (34 taxa), Fabaceae (22 taxa), and Asteraceae (15 taxa). The marsh environs include a number of priority listed taxa, eight of which were recorded in the survey including: *Eremophila spongiocarpa* (Priority 1), *Nicotiana heterantha* (Priority 1), *Tecticornia globulifera* (Priority 1), *Tecticornia* sp. Christmas Creek (Priority 1), *Atriplex flabelliformis* (Priority 3), *Eleocharis papillosa* (Priority 3), *Tecticornia medusa* (Priority 3) and *Eremophila youngii* subsp. *lepidota* (Priority 4). Fifteen introduced flora were also recorded.

Much of the remainder of the marsh proper has not been floristically assessed, however the DPaW has recently commenced a floristic survey of the marsh supported by Fortescue.

2.9 Conservation Values

The Fortescue Marsh is recognised as being a unique and extensive inland floodplain system within the Pilbara region (McKenzie *et al.* 2009). A summary of the identified conservation values of the marsh is provided in Table 2.

The Fortescue Marsh is classified as a wetland of national importance within the Directory of Important Wetlands in Australia (DIWA) based on criteria 1, 2, 3 and 6 further described as follows (DEC 2009):

1. It is a good example of a wetland type occurring within a biogeographic region in Australia. It is the largest ephemeral wetland in the Pilbara and the only feature of this type in the Pilbara bioregion.
2. It is a wetland that plays an important ecological or hydrological role in the natural functioning of a major wetland system/complex.
3. It is a wetland that 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. It is a significant drought refuge area for native vertebrate fauna in the bioregion. It is also known to support migratory waterbird species, including Clamorous Reed-warbler (*Acrocephalus stentoreus*), Great Egret (*Ardea alba*), Swamp harrier (*Circus approximans*) and Whiskered Tern (*Chlidonias hybridus*), as well as Sacred Kingfisher (*Todiramphus sanctus*). It is a major breeding area for the Australian Pelican (*Pelecanus conspicillatus*) and Black Swan (*Cygnus atratus*).
6. It is a wetland of outstanding historical or cultural significance. The marsh Yintas, such as Moorimoordinina Pool, are of cultural significance to the local Aboriginal people.

It is also notable that the Fortescue Marsh has been proposed as a Ramsar wetland, however no formal nomination has been made to date. If listed, the Fortescue Marsh will become legally recognised as an area of National Environmental Significance, and be subject to the provisions of the Commonwealth *Environment Protection and Biodiversity Conservation Act* (EPBC Act).

The DPaW's current classification of the Fortescue Marsh land system as a PEC includes the following descriptor (DEC 2013):

"Fortescue Marsh is an extensive, episodically inundated samphire marsh at the upper terminus of the Fortescue River and the western end of Goodiadarrie Hills. It is regarded as the largest ephemeral wetland in the Pilbara. It is a highly diverse ecosystem with fringing mulga woodlands (on the northern side), samphire shrublands and groundwater dependant riparian ecosystems. It is an arid wetland utilised by waterbirds and supports a rich diversity of restricted aquatic and terrestrial invertebrates. Recorded locality for Night Parrot and Bilby and several other threatened vertebrate fauna. Endemic *Eremophila* species, populations of priority flora and several near endemic and new to science samphires. Recognised threats include: mining, altered hydrology (watering with fresh water), grazing and weed invasion"

Table 2 The documented conservation values of the Fortescue Marsh

Value	Place of record
Wetland/landscape biogeographic value	1. *Directory of Important Wetlands in Australia*- wetland of national importance under criteria 1, 2, 3 and 6. 2. Register of the National Estate 3. *Caring for our Country* High Conservation Value Aquatic Ecosystem classification (DEHWA) – inferred 4. DEC submission to Fortescue Marsh strategic plan working group
Contribution to a greater wetland ecosystem complex	1. *Directory of Important Wetlands in Australia* 2. *Caring for our Country* High Conservation Value Aquatic Ecosystem classification (DEHWA) - inferred
Waterbirds	1. Ramsar Convention nomination materials 2. JAMBA and CAMBA 3. Register of the National Estate 4. Recognised as a nationally important Bird Area (Dutson *et al.* 2009) 5. The Marsh supports the second largest recorded populations of waterbirds in Western Australia after Lake Gregory (McKenzie *et al.* 2009).

Value	Place of record
Unique samphire vegetation	1. Classification as a PEC (DEC 2009) 2. DEC submission to Fortescue Marsh strategic plan working group 3. The samphire vegetation types are locally restricted to the Marsh and unique in the central Pilbara region (Fisher *et al.* 2004)
Other vegetation values of conservation interest (*e.g.* Mulga communities)	1. Classification as a PEC (DEC 2009) 2. DEC submission to Fortescue Marsh strategic plan working group
Rare flora (endemic *Eremophila* and other Priority species)	1. Classification as a PEC (DEC 2009) 2. DEC submission to Fortescue Marsh strategic plan working group 3. At least nine Priority listed taxa are known to occur in the Marsh (Greg Barrett & Associates 2009).
Rare vertebrate fauna (*e.g.* Night Parrot & Bilby)	1. Classification as a PEC (DEC 2009) 2. DEC submission to Fortescue Marsh strategic plan working group
Rare invertebrate fauna (locally restricted aquatic invertebrates)	1. Classification as a PEC (DEC 2009) 2. DEC submission to Fortescue Marsh strategic plan working group
Aboriginal cultural values	1. *Directory of Important Wetlands in Australia* (criterion 6) 2. Register of the National Estate (provisionally – identifies that additional assessment of these values is required) 3. *Report on an Ethnographic Aboriginal Heritage Survey of the Christmas Creek Hydrological System, Western Australia* (Goode 2009)

3 Fortescue Marsh environmental management framework

3.1 EPA Report 1484

In July 2013, the EPA defined a Fortescue Marsh management area consisting of seven sub-zones partitioned into three conservation significance categories (EPA 2013; Figure 10). This was done to provide clarity and consistency in relation to environmental assessment and approvals processes relevant for mining and mining-related activities in the vicinity of the marsh. The process of developing and describing the management areas involved wide ranging stakeholder consultation.

The Fortescue Marsh management areas reflect the distribution of environmental values and their relative priority in and around the Fortescue Marsh. Values and management objectives for each zone are described in Table 3.

The Christmas Creek life-of-mine (LOM) expansion project area lies within Zones 1a and 3a, with potential encroachment into fringes of the Fortescue Marsh (Zone 1b) resulting from modified hydrology. Environmental aspects of relevance to the eco-hydrology of the Fortescue Marsh include:

- protection of groundwater systems, including fresh/brackish springs and seepages.
- protection of samphire vegetation communities, including their habitat values for flora and fauna of conservation significance.
- protection of floristically unique Mulga woodlands and shrublands, including their habitat values for flora and fauna of conservation significance.
- protection of the Cowra land system.

The EPA has identified a range of management strategies for protecting environmental values in the management area, consistent with the management objectives. The strategies applicable to Zones 1a, 1b and 3a with key relevance for the Christmas Creek LOM expansion project can be summarised as follows:

- Surface water
    - Minimise disruption to natural surface flow regimes including:
        - through the appropriate design and placement of infrastructure.

        - avoiding locating infrastructure on, or in close proximity to, major Marsh tributaries
    - Manage water discharges in order to:
        - prevent discharge of excess water directly to the Fortescue Marsh wetland or indirectly via industry induced surface expression of saline or fresh water. If discharge is proposed it should be in accordance with an approved management and monitoring plan and ideally be of an episodic nature (campaign discharge) to coincide with natural flooding/inundation events.
        - manage surface discharge of excess water in the vicinity of springs and riparian habitats; restrict to episodic (campaign) discharges.
        - ensure that changes to the rate and timing of seasonal discharges to the tributaries do not significantly alter their hydrological and ecological integrity
- Groundwater
    - Apply an independent peer review of hydrological models to support water and environmental assessments. The review should be consistent with National Water Commission's Australian Groundwater Modelling Guidelines (2012).
    - Excess water should be re-injected in accordance with the Department of Water's Pilbara Water in Mining Guideline (2009).
    - Zone 1b - Installation of bores that penetrate multiple aquifers will require a minimum standard of an Australian Drilling Industry Association (ADIA) Class 2 driller or have equivalent Water Drilling certification approved by the Department of Water.
    - Manage groundwater mounding and drawdown in order to:
        - minimise impacts to natural spring flows and water quality.
        - minimise disruption to groundwater levels or water quality gradients in aquifers that support mulga or samphire vegetation communities.

        - minimise disruption to groundwater levels or water quality gradients in aquifers that support important habitats (for example significant aquatic invertebrate populations; waterbird habitat).
        - ensure that riparian vegetation along major tributaries is not significantly impacted (for example prevent loss of keystone species within riparian communities, such as *E. victrix*, along major tributaries.

- Vegetation
    - Avoid (where possible) and minimise clearing of mulga vegetation, samphire and/or other halophytic vegetation, and any other native vegetation that represents important habitat for conservation significant flora and fauna species.
    - Seek acquisition and reservation of mulga-dominated woodland and shrubland vegetation types in the 2015 pastoral relinquishment conservation reserve system.
    - Undertake an assessment of cumulative impacts to mulga vegetation communities.
    - Undertake surveys to identify and map distributions of conservation significant species.
    - Zone 1b - undertake surveys to delimit and define samphire vegetation communities.
- Terrestrial fauna and habitat
    - Undertake surveys to identify and map distributions of conservation significant species and their habitat.
    - Undertake feral predator control measures (for the protection of the Night Parrot; Northern Quoll; Fortescue Marsh ecosystem).
    - Seek acquisition and reservation of suitable Night Parrot and Northern Quoll habitat in the 2015 pastoral relinquishment conservation reserve system.

- Subterranean fauna and habitat
    - Define habitat requirements of conservation significant subterranean fauna and ensure that hydrological regimes are maintained.
    - Enhance survey effort to document the presence and richness of subterranean fauna.
- Land systems and landforms
    - Reinstate natural landforms following mining where possible in accordance with the EPA's *Guidelines for Mine Closure Plans*.
    - Add areas supporting the Cowra system to the conservation reserve system.
    - Zone 1b - minimise disturbance activities with a preference to use previously disturbed areas for new disturbance footprints, e.g. existing dilapidated fence lines and corridors for vehicle movements.
    - Zone 1b - any ground-disturbing activity within the proposed 2015 pastoral lease relinquishment boundaries (Appendix A) should be undertaken in a manner consistent with DEC conservation estate management guidelines (where available). Prior to the availability of these guidelines, consultation with the DEC is considered essential.
- Improving knowledge
    - Undertake research and monitoring to determine the extent of cumulative hydrological impacts on the Marsh.

3.2 Recent EPA assessments

3.2.1 Cloudbreak Life-of-Mine expansion project

The Cloudbreak LOM expansion project was referred to the EPA in September 2010. A level assessment was set at Public Environmental Review (PER) under the *Environmental Protection Act 1986* (EP Act).

The proposal involved the expansion of the existing Cloudbreak Iron Ore mine, located approximately 40 km west of the Christmas Creek project area and approximately 2.5 km from the Fortescue Marsh at the closest point.

Relevant aspects of the proposal included:

- Expansion of the existing open pit strip mining footprint by 8,133 hectares (ha) and the continuation of ore production at an increased rate of up to 50 Mtpa of iron ore for approximately 14 years.
- Orebody dewatering of up to 100 GL/a, with surplus volumes (over and above operational usage) to be injected into the local groundwater system. This will result in substantial areas of groundwater drawdown and mounding over the life of the project, beyond the direct disturbance footprint. These impacts will extend to the periphery of the Fortescue Marsh in some areas. Drawdown and mounding is predicted to be mostly be transitory (less than 2 years) in exposed areas.

The EPA provided advice to the Minister for Environment in EPA Report 1429 in February 2012 (EPA 2012). The identified key environmental factors evaluated by the EPA included:

- flora and vegetation.
- conservation significant fauna.
- surface water flows.
- groundwater quantity and quality.
- rehabilitation and closure.
- residual impacts.

The project was approved by the Minister for Environment in June 2012 subject to the conditions described in Statement 899.

Aspects of the proposal involving potential indirect impacts on the values of the Fortescue Marsh, arising from modified hydrology (*i.e.* mounding, drawdown, ponding and shadowing), are further described in Appendix 2. This includes a summary of impact mitigation and management requirements recommended by the EPA and adopted in Statement 899.

3.2.2 Christmas Creek Water Management Scheme project

The Christmas Creek Water Management Scheme (CCWMS) project was referred to the EPA in May 2011. The level assessment was set at Assessment on Proponent Information (API) under the *Environmental Protection Act 1986* (EP Act).

The CCWMS proposal involved modifications to approved dewatering and discharge rates at the existing Christmas Creek mine approved under Statement 707 in 2005. Additional dewatering and handling of groundwater was required to enable mining of iron ore below the water table. The CCWMS included three main components:

- Dewatering of the orebody aquifer at a rate of up to 50 GL/a.
- Use of abstracted water for operational purposes such as, ore processing, dust suppression and construction.
- Injection of water, surplus to the operational demand, into nearby aquifers; involving partitioning surplus water into brackish and saline components, and injecting each component into aquifers with similar hydrochemical characteristics. The injection strategy was designed to partially offset drawdown associated with orebody dewatering, within the dictates of practical constraints.

The EPA provided advice to the Minister for Environment in EPA Report 1402 in June 2011 (EPA 2011). Key environmental factors relevant to the proposal that were identified and evaluated in the report included:

- flora and vegetation.
- fauna and habitat.

The project was approved by the Minister for Environment in August 2011 subject to the conditions described in Statement 871.

The EPA considered that significant vegetation types could be indirectly impacted by modified groundwater levels and quality as follows;

- mulga communities – not vulnerable to drawdown, but potentially susceptible to mounding within 2 m of the land surface. The EPA took the view that mounding should not result in the groundwater rising to within 2 m of the ground surface in mulga dominated communities.
- samphire communities – not expected to be impacted, on the basis that watertables underlying samphire communities would remain within their natural variation range. Hydrogeological modelling predicted a drawdown or mounding response of up to 1 to 1.5 m at the boundary of the Fortescue Marsh.

- creekline and drainage line vegetation – 3.6% (82 ha) of mapped vegetation types dominated by *Eucalyptus victrix* (Coolibah) and *E. camaldulensis* (River Red Gum) was considered to be vulnerable to impacts (potential health decline) in areas where a 5 m decline in groundwater levels to 20 m below ground level was predicted. This amount of vegetation was not considered to be significant.
- conservation significant fauna – potential impacts were considered unlikely to be significant, due to minimal potential loss of habitat resulting from modified hydrology.

The EPA considered that designs for water conveyance infrastructure, management and monitoring proposed by Fortescue could acceptably minimise impacts to mulga communities potentially exposed to modified overland flow regimes. Key design elements to maintain the surface flow regime included:

- burial of pipelines at regular intervals to prevent obstruction of surface water flows.
- construction of major stream crossings using cement stabilising at stream bed level.
- rock spalls downstream of major stream floodways to dissipate energy and reduce flow velocities.
- raised crossings designed to permit flood debris to be carried over in peak flows without obstruction.
- using floodways in preference to culverts.
- where required, culverts to be used across the full width of any raised crossing or preferably incorporated into level crossings over incised gullies with steeper banks (requiring infill).

Aspects of the proposal involving potential indirect impacts on the values of the Fortescue Marsh, arising from modified hydrology (*i.e.* mounding, drawdown, ponding and shadowing), are further described in Appendix 3. This includes a summary of impact mitigation and management requirements recommended by the EPA and adopted in Statement 871.

3.3 Implications for the Christmas Creek LoM project

With respect to the current environmental management framework for the Fortescue Marsh (i.e. as per EPA 2013), key findings of relevance for the Christmas Creek LoM project are likely to include:

- significant flora species and riparian Eucalypt, Mulga and Samphire vegetation types between the Chichester Range and Fortescue Marsh fringe are considered by the EPA to have local conservation significance (EPA Reports 1429 and 1402).

  The extent of these significant vegetation types in the overall Christmas Creek LoM project area and disturbance footprint requires quantification using suitably accurate vegetation mapping.

- Indirect impacts to significant vegetation types arising from mounding, drawdown, ponding and shadowing in the Cloudbreak area were predicted by the proponent and evaluated under the EIA process. Conditions for the Cloudbreak project were set (Statement 899 - Condition 6) such that indirect impacts were not permitted to exceed the predicted extent. Vegetation monitoring to EPA specifications was a condition of project approval to ensure this outcome.

  The extent of potential indirect impacts to significant vegetation types in the Christmas Creek LoM project area requires accurate quantification.

- The magnitude of predicted groundwater level changes in the Fortescue Marsh for the Cloudbreak LoM and CCWMS projects was less than the extent of natural fluctuations in groundwater levels that occur in the Marsh. These are estimated to be up to ≈2 m near the marsh fringe based on Fortescue bore records (Fortescue 2012a). The Cloudbreak LoM and CCWMS projects both received conditions restricting groundwater mounding/drawdown at the fringe of the marsh to 1 m to 1.5 m (depending on bore location).

  For the Christmas Creek LoM project, if the extent of drawdown beneath samphire vegetation communities is predicted to extend beyond the range of natural watertable fluctuations, additional analysis and research will be necessary to predict potential impacts on the samphire vegetation and the eco-hydrological function of the marsh more generally.

- Vegetation monitoring programs designed to validate the predicted extent of indirect impacts to vegetation from modified watertables were approval conditions for both the Cloudbreak LoM and CCWMS projects.

For the Christmas Creek LoM project, it will be necessary to implement a suitable vegetation monitoring program capable of detecting impacts to vegetation from modified hydrology and validating impact predictions. This program will need to provide early warning of potential impacts and inform management responses to prevent unacceptable impacts.

- Consistent with the previous project approvals, it is expected the proponent will modify its groundwater strategy in the event that significant detrimental impacts on vegetation are detected within the approved monitoring program. In Report 1402 the EPA considered that the ability of the proponent to redistribute water to prevent near surface mounding was an important control for preventing potential impacts to significant vegetation.

  The Christmas Creek LoM project requires groundwater strategy contingency options such that any unforeseen indirect impacts to significant vegetation types (as detected within the ambit of the vegetation monitoring program) can be prevented.

- In Report 1402 the EPA accepted that there is a low risk that water quality would be significantly impacted, due to inherent hydrogeological controls that would prevent saline water from migrating to the surface/vegetation root systems. The EPA noted that the DoW is able to manage this issue through the proponen’s approved Groundwater Operating Strategy. Therefore, the EPA was of the view that the impact on groundwater quality can be readily managed.

  The Christmas Creek LoM project is subject to the same inherent hydrogeological controls.

- In Report 1402 the EPA anticipated the possibility of the Christmas Creek LoM expansion project, and emphasised its expectation that the proponent must provide timely, robust and comprehensive information that demonstrates that the local and regional impacts to flora, vegetation, fauna, and groundwater, in particular those associated with the Fortescue Marsh, can be managed. The EPA stated that in order for the expansion assessment to be undertaken, the proponent should ensure the following prior to submitting the first draft of the environmental review document:

- completion of all relevant surveys and investigations to acceptable standards, as identified in consultation with appropriate decision-making authorities.
- identification of suitable impact mitigation measures.
- assessment of potential cumulative impacts, including cumulative impacts of the proposal on the environmental values of the Proposed Conservation Reserve (PCR) in connection with the expiry/renewal of pastoral leases in 2015.

The Christmas Creek LoM project environmental review document will need to explicitly address these items.

In Report 1429 the EPA considered that residual impacts to vegetation communities of conservation significance (i.e. Riparian Eucalypt, Mulga and Samphire) should be offset, on the basis that:

- part of the proposal falls within a proposed conservation reserve.
- the condition of the vegetation of conservation significance ranges from excellent to good.
- the Mulga vegetation is at its most northern extent within Western Australia.
- the Samphire vegetation is located within the Fortescue Marsh PEC.

Associated impacts to the habitat of fauna of conservation significance (i.e. Night Parrot, Mulgara and Bilby habitat) were also considered to require offsets. The EPA's recommendations were adopted by the Minister and embodied in Conditions 15 and 16 of Statement 899. The offset requirement included a financial contribution to a strategic regional conservation initiative for the Pilbara as determined by the Minister on advice of the EPA, based on the following cost schedule[6]:

[6] Valuations indexed to the Perth consumer price index (CPI)

- $3,000 per hectare for direct and indirect impacts to mulga vegetation in the proposed conservation reserve within the Project Area, excluding mulga vegetation in the Existing Mine area[7];
- $1,500 per hectare for direct and indirect impacts to mulga vegetation outside of the proposed conservation reserve and within the Project Area, excluding mulga vegetation in the Existing Mine area;
- $3,000 per hectare for direct impacts to Samphire vegetation within the Project Area, excluding Samphire vegetation in the Existing Mine area; and
- $1,500 per hectare for direct impacts to Coolibah/River Red Gum creekline vegetation within the Project Area, excluding Coolibah/River Red Gum creekline vegetation in the Existing Mine area.

On the basis of EPA precedent, the Christmas Creek LoM project can be expected to receive similar offset requirements. Accurate vegetation mapping and delineation of direct and indirect impact areas is required to underpin offset valuation calculations.

It is notable that under Statement 899 Condition 15 offset requirements for indirect impacts only applied to mulga vegetation and not samphire or riparian Eucalypt vegetation communities. The EPA Report 1429 provided no clear basis for this distinction.

[7] Project area approved under Statement 721

Table 3 Description of the Fortescue Marsh management zones (EPA 2013)

Management Zone	Relative priority for protection and conservation	Environmental values	Management objectives
1a – Northern Flank	High	Fresh/brackish springs and seepages (along the southern edge of this zone) Groundwater dependent ecosystems Floristically unique mulga woodlands and shrublands Flora and fauna of conservation significance[8]. Stygofauna and troglofauna present, with potential for restricted species but limited data. Cultural and spiritual heritage Christmas and Cowra land systems (restricted to the Fortescue Valley).	Protect natural pools and springs. Minimise disruption to groundwater in aquifers supporting groundwater dependant ecosystems. Protect the hydrological and ecological integrity of major tributaries entering the Marsh. Maintain the natural flow regime at the boundary between Northern Flank and Marsh zones. Protect Mulga and mixed *Acacia* woodland and shrublands. Minimise disruption to groundwater dependent ecosystems. Maintain groundwater levels to protect mulga vegetation communities. Protect species of conservation significance (in particular Night Parrot and Northern Quoll) and their habitat. Enhance knowledge of local subterranean fauna. Minimise impacts to the Christmas and Cowra land systems.

[8] Australian Bustard; Bilby; Bush Stone-curlew; Night Parrot; Northern Quoll; Peregrine Falcon; *Eremophila youngii* subsp. *lepidota; Goodenia nuda*

Management Zone	Relative priority for protection and conservation	Environmental values	Management objectives
1b - Marsh	High	Pools present for prolonged periods following flow events Fresh/brackish springs Unique, ephemeral wetland Hydrogeology Samphire vegetation communities Aquatic invertebrates Waterbirds Flora of conservation significance[9] Fauna of conservation significance[10] Cultural and spiritual heritage Recreation	Protect natural pools and springs. Minimise disruption to aquifers supporting the Marsh. Maintain the natural flow regime of the Marsh (including at the Marsh boundary). Minimise disturbance to native vegetation. Maintain water quality in the Marsh. Protect species of conservation significance and their habitat. Protect samphire and halophytic vegetation. Enhance understanding of samphire (*Tecticornia*) species. Enhance knowledge of local invertebrates. Protect waterbird habitat and foraging habitat.

[9] (*Atriplex flabelliformis; Eleocharis papillosa; Eremophila spongiocarpa; E. youngii* subsp. *lepidota*; *Nicotiana heterantha*; *Peplidium* sp. Fortescue Marsh (S. van Leeuwen 4865); *Tecticornia* sp. Christmas Creek (K.A. Shepherd *et al.* KS 1063); *T.* sp. Fortescue Marsh (K.A. Shepherd *et al.* KS 1055); *T.* sp. Roy Hill (H. Pringle 62))

[10] Bilby; Common Greenshank; Eastern Great Egret; Night Parrot; Wood sandpiper

Management Zone	Relative priority for protection and conservation	Environmental values	Management objectives
Calcrete Flats (2a)	Medium - important to protect and rehabilitate where possible	Natural water regimes Subterranean fauna Aquatic invertebrates Vegetation communities Flora of conservation significance[11] Cultural and spiritual heritage	Maintain the natural flow regimes, especially at the Marsh boundary. Maintain natural cycles of wetting for clay pan habitats. Minimise disruption to aquifers from activities in neighbouring zones. Enhance understanding of local subterranean fauna Enhance understanding of aquatic invertebrates Minimise impact to native vegetation communities Rehabilitate native vegetation where possible. Protect species of conservation significance and their habitat
2b - Poonda Plain	Medium	Natural water regimes Fortescue Valley sand dune communities (PEC Priority 3). Flora of conservation significance[12]	Maintain the natural flow regime at the boundary between Northern Flank and Marsh zones. Maintain the natural flow regime of tributaries entering the Marsh. Protect the hydrological and ecological integrity of major tributaries entering the Marsh.

[11] *Eremophila spongiocarpa; Goodenia nuda; Myriocephalus scalpellus*
[12] *Themeda* sp. Hamersley Station (M.E. Trudgen 11431

Management Zone	Relative priority for protection and conservation	Environmental values	Management objectives
		Fauna of conservation significance[13] Subterranean fauna Aquatic invertebrates Cultural and spiritual heritage	Protect the Fortescue Valley sand dune PECs. Protect species of conservation significance and their habitat. Enhance understanding of local subterranean species. Enhance understanding of aquatic invertebrates.
2c – Fortescue River Coolibah	Medium	Natural water regimes Riparian vegetation (stands of *Eucalyptus victrix*) Fauna of conservation significance[14] Subterranean fauna Cultural and spiritual heritage	Maintain natural water balances and function of the aquifer. Maintain the natural flow regime at the Marsh boundary. Minimise impacts to riparian native vegetation. Maintain the natural surface water flows and flooding regime of the alluvial and gilgai plains. Minimise disruption to aquifers supporting groundwater dependent ecosystems and riparian vegetation. Protect species of conservation significance and their habitat. Enhance understanding of local subterranean fauna.

[13] Australian Bustard; Bilby; Bush Stone-curlew; Ghost Bat; Northern Quoll; Western Pebble-mound Mouse; Mulgara
[14] Bilby

Management Zone	Relative priority for protection and conservation	Environmental values	Management objectives
3a - Kulbee Alluvial Flank	Low	Natural water regimes Natural springs and pools Mulga woodlands Flora of conservation significance[15] Fauna of conservation[16] significance Subterranean fauna Cultural and spiritual heritage	Maintain the natural flow regime at the Marsh boundary. Protect the hydrological and ecological integrity of major tributaries entering the Marsh. Protect the natural pools and springs. Manage impacts to Mulga vegetation. Manage overland surface water flows. Protect species of conservation significance and their habitat. Enhance understanding of local subterranean fauna.
3b - Marillana Plains	Low	Natural water regimes Land systems Mulga woodlands Flora of conservation significance[17] Fauna of conservation significance[18]	Maintain the natural flow regime at the Marsh boundary. Manage impacts to the Marillana land system (which is restricted to the Fortescue Valley). Manage impacts to mulga vegetation. Maintain the natural overland surface water flow regime.

[15] *Eremophila youngii* subsp. *lepidota; Goodenia nuda; Rhagodia sp. Hamersley (M. Trudgen 17794)*
[16] Australian Bustard; Bush Stone-curlew; Ghost Bat
[17] *Atriplex flabelliformis; Calocephalus beardii; Goodenia nuda*

Management Zone	Relative priority for protection and conservation	Environmental values	Management objectives
		Subterranean fauna Aquatic invertebrates Cultural and spiritual heritage	Minimise native vegetation clearing. Undertake surveys to identify and map distributions of conservation significant species. Enhance understanding of local subterranean fauna. Enhance understanding of local aquatic invertebrates.

[18] Australian Bustard

4 Fortescue Marsh targeted studies & investigations

4.1 Overview

This section summarises the objectives, methods and results of the following research projects and targeted investigations relating to the Fortescue Marsh:

1. UWA/ARC Linkage Project LP0882350 '*Ecophysiology of stem succulent halophytes subject to changes in salinity and water availability: distinguishing natural dynamics from potential mine related impacts*'.
2. CSIRO/UWA Fortescue Marsh pilot study of remote sensing tools for eco-hydrology investigations.
3. UWA assessment of vegetation water use of upland and lowland communities associated with the Fortescue Marsh based on measurements of naturally occurring isotopes.
4. Astron assessment of mulga root system architecture near Cloudbreak and Christmas Creek.
5. Astron assessment of salt loads and surface salinity near Cloudbreak and Christmas Creek.
6. Astron Soil & Water unsaturated zone modeling of Fortescue Marsh soil profiles and marsh vegetation communities.

All of these studies have been implemented or supported by Fortescue.

4.2 UWA/ARC Linkage Project - halophyte ecophysiology

4.2.1 Overview

In the period 2008 to 2011 Fortescue provided industry funding support to an Australian Research Council (ARC) research project entitled "*Ecophysiology of stem succulent halophytes subject to changes in salinity and water availability: distinguishing natural dynamics from potential mine related impacts*" (ARC Linkage Project LP0882350). The project was led by the UWA School of Plant Biology, in collaboration with the WA Herbarium. The UWA research was managed by Prof. Tim Colmer and Prof. Erik Veneklaas, with the experimental work largely implemented by PhD student Louis Moir-Barnetson.

The project had the following objectives:

- To identify which samphire species (the dominant taxa in the Fortescue Marsh vegetation communities) are present and which environmental factors explain their distribution pattern;
- To relate samphire population dynamics with the dynamics of water availability (flooding and water deficit) and salinity, as related to weather conditions (rainfall, air temperature, and evaporative demand);
- To relate key plant health indicators, including transpiration, water status, ionic relations, organic osmolytes, pigment composition (chlorophyll and photoprotective carotenoids) and chlorophyll fluorescence, with varying levels and combinations of stress factors (salinity, drought, flooding) as these occur in the field; and
- To rigorously test, in controlled environments with defined treatments, hypotheses developed during the field work regarding physiological processes contributing to resistance of salinity, drought, and flooding, and also to ascertain reliable early-warning stress indicators.

UWA prepared an interim project report for Fortescue in late 2010 (UWA 2010). Several journal papers related to the project have also been published including:

- a major review on halophyte physiology and salinity tolerance (Flowers & Colmer 2008)
- a review on halophyte flooding tolerance (Colmer & Flowers 2008).
- a review on flooding tolerance in plants (Colmer & Voesenek 2009).
- taxonomic work resulting in the formal description of two new samphire species (*Tecticornia globulifera* and *Tecticornia medusa*) (Shepherd & van Leeuwen 2011).

The original timeline for completion of the project publications (end of 2011) was not met. Three research papers from the project PhD thesis, addressing fieldwork and glasshouse experiments, are now at an advanced stage of preparation[19]. The proposed paper titles include:

- "Submergence tolerance in stem-succulent halophytes is associated with resistance to the osmotic swelling and rupturing of shoot tissues."

[19] Planned for submission to peer reviewed journals in late 2013

- "The distribution and population dynamics of stem-succulent halophytic shrubs (*Tecticornia* species) at an ephemeral inland salt lake in arid-zone northwest Australia."
- "Ecophysiological responses of *Tecticornia* species to seasonal changes at Fortescue Marshes"
- "Salinity tolerance in *Tecticornia* species"

Fortescue supported a Phase 2 ARC Linkage Project submission in 2011, however the application was unsuccessful. Despite this outcome, Fortescue has supported several additional research activities since late 2011 which complement the project including:

- an expanded glasshouse experiment examining drought and salinity tolerance (and their interactions) of *Tecticornia indica* subsp. *bidens, T. auriculata* and *T. medusa.*
- investigation of spectral signals and indices associated with samphire pigment accumulation, to inform the development of ground based and remote sensing vegetation health monitoring tools. This has included a combination of field and glasshouse pigment and spectrophotometer measurements.

A literature review and interim project reports addressing the latter item have been completed by UWA (Marchesini 2011, 2012a, 2012b). A journal paper addressing the expanded glasshouse experiment is now at an advanced stage of preparation (proposed title "Drought tolerance of three *Tecticornia* stem succulent halophytes of an inland arid-zone salt lake system").

A short summary of the methods and available results to date are provided as follows. Further details are provided in Appendix 4, which includes the UWA (2010) and Marchesini (2011, 2012a,b) project reports.

4.2.2 Methods

The ARC Linkage project and affiliated research activities have involved the following core components:

Field measurements

Field observations of climatic, soil and samphire vegetation parameters were conducted at two locations over a three year period commencing in October 2008. The first location

(Site A) is immediately south of the Cloudbreak mine, within the potential zone of influence of mine pit dewatering activities. The second location (Site B) is approximately 20 km west of the first location, more distant from any influence of the Cloudbreak mine.

Each location included two replicate 20 x 20 m plots in each of three samphire communities dominated by *T. indica* subsp. *bidens*, *T. auriculata* and *T. medusa* respectively. *T. indica* subsp. *bidens* is the pre-eminent species on the upgradient margins of the marsh ecophysiographic boundary. *T. auriculata* occurs slightly further into the marsh, whilst *T. medusa* only occurs deep within the marsh in lower elevation areas (about 1 to 1.5 km from the marsh boundary). Hence these three species span an ecological gradient with respect to soil water and salinity dynamics, depth to watertables and frequency of flooding within the marsh ecosystem.

A weather station was installed at Site A at the outset of the experiment, providing continuous records of rainfall, shortwave radiation, temperature, relative humidity, wind speed and wind direction. Following heavy rains in February 2009 (>100 mm event on February 28th), a prolonged period of minimal rainfall occurred between April 2009 and December 2010 (213 mm rainfall received). In comparison the period January to April 2011 was relatively wet (466 mm rainfall received). Strong seasonality was observed in temperature and radiation, with typical daily rates of potential evapotranspiration of 8-10 mm in mid-summer and 3-5 mm in winter.

Soils were sampled by coring to 50 cm depth, collected on an approximately 3-monthly basis[20]. Measured parameters included gravimetric water content, pH and electrical conductivity (EC) in the 0-1 cm, 1-10 cm, 10-20 cm, 20-30 cm and 30-50 cm depth layers. Instruments to continuously measure soil moisture were also installed, however these did not perform satisfactorily in the saline marsh soils.

Hand installation of shallow piezometers was also undertaken, however at Site A these were impeded by the presence of silcrete hardpans in the *T. indica* subsp. *bidens* and *T. auriculata* plots. The shallow watertable was only intercepted in the down-gradient *T. medusa* plots.

[20] Field sampling dates were Oct-08; Feb-09; Jun-09; Oct-09; Feb-10; May-10; Sep-10; Jan-11; Jun-11

Samphire vegetative articles were sampled for tissue water content and solute analysis on an approximately 3-monthly basis (as per soil sampling). Freeze-dried tissue samples were analysed for the inorganic ions Na, K and Cl, as well as the organic solutes sucrose, glucose and fructose (sugars) and glycinebetaine. Samples were also analysed for pigment content (chlorophyll-a, carotenoids and betacyanins). The osmotic potential of live, succulent stem sections was measured using a psychrometer.

Plant growth was assessed by measuring plant height and crown dimensions at the start and end of the project, and 3-monthly shoot extension and lignification on tagged branches.

Information on plant water use of *T. indica* subsp. *bidens* and *T. auriculata* was collected using sapflow techniques (continuous recording by data-loggers in six instrumented plants of each species) and gas exchange measured 3-monthly. These data were used to derive plant scale transpiration fluxes, based on measurements of sapwood cross sectional area in the instrumented plants. Transpiration fluxes per unit land area were then estimated using measurements of samphire stem cross sectional area per unit land area in the UWA plots.

Glasshouse experiments

Controlled glasshouse experiments were undertaken to test species responses to the individual and combined effects of salinity, water deficit, flooding. Seed from *Tecticornia indica* subsp. *bidens*, *T. auriculata* and *T. medusa* was sourced from the Fortescue Marsh and used to propagate seedlings for use in the experiments. Destructive harvests of plants were taken at the commencement and end of treatment periods. Vegetative articles were sampled for tissue water content, solute analysis, pigment concentrations and osmotic potential using comparable methods to the fieldwork measurements. In the most recent (expanded) experiment, spectral signatures of the plants were also measured using a spectrophotometer.

While the first glasshouse experiment used artificial soil media, the latter experiment used soil sourced from a salt lake in the north eastern Wheatbelt region. This was selected based on its similarity to Fortescue Marsh soil types.

4.2.3 Results

Samphire distribution patterns

The data show that *Tecticornia medusa* grows where soil salinity is highest and soils are most subject to waterlogging and periodic inundation, followed by the *T. auriculata* zone, and then the *T. indica* subsp. *bidens* zone growing near the marsh fringe. Plant size class distributions for each species were suggestive of infrequent large recruitment events, without significant continuous rejuvenation. During the study the *T. medusa* plots were subjected to several episodes of flooding inundation after large rainfall events. Shallow watertables (<1 m depth) were maintained in these plots during the interflood periods. In contrast soil moisture in the soil profiles of the *T. indica* subsp. *bidens* and *T. auriculata* plots remained well below field capacity over the life of the study.

Field measurements

Gravimetric soil moisture content in the top 50 cm of the profile fluctuated in response to seasonal rainfall patterns. Data for the *Tecticornia indica* subsp. *bidens* and *T. medusa* is presented in Figure 11[21]. Gravimetric soil moisture content in the *T. indica* subsp. *bidens* and *T. auriculata* plots generally ranged between 0.1 to 0.2 g/g below the surface, whilst in the *T. medusa* plots it ranged more widely between 0.1 and soil saturation (i.e. >0.4).

Over the life of the project mean soil $EC_{1:5}$ below 10 cm depth was 7, 11 and 17 dS m^{-1} respectively in the *T. indica* subsp. *bidens* , *T. auriculata* and *T. medusa* plots. Soil salinity showed an increasing trend during prolonged periods without rain, presumably due to evaporative concentration effects. This was most pronounced in the *T. medusa* plots, with much smaller changes evident in the *T. indica* subsp. *bidens* and *T. auriculata* plots. This suggests that there was minimal upward transport of salt (i.e. less or general lack of capillarity to the soil surface) in the up-gradient species plots.

Plant water use data, as assessed by sap flow techniques, indicated that *T. indica* subsp. *bidens* and *T. auriculata* continued to take up water during prolonged dry conditions from the saline soil profiles. There was little evidence that *T. indica* subsp. *bidens* and *T. auriculata* reduced their transpiration due to limited soil water availability over the life of the project; although tissue osmotic potentials less than -7 MPa were measured in

[21] Note - data for the *T. auriculata* plots showed broadly similar trends to the *T. indica* subsp. *bidens* plots.

all species. This finding, combined with water mass balance changes in the top 50 cm of the soil profile, suggested that these species were able to extract water from relatively dry soils and access soil water from depths beyond 50 cm. Subsequent samphire root systems excavations have shown that although the woody root systems are confined to about the top 70 cm, the fine roots can extend up to 2.5 m where unimpeded by indurated layers (e.g. silcrete hardpans).

T. indica subsp. *bidens* exhibited higher rates of sapflow and transpiration flux than *T. auriculata*, estimated by scaling up plant sap flow measurements from Site A. The sapwood cross sectional area density of the *T. indica* subsp. *bidens* and *T. auriculata* plots were 8.32 and 1.48 cm^2/m^2 land area respectively, derived using regression relationships between sapwood cross sectional area and total stem cross sectional area obtained from destructively sampled plants. The estimated monthly mean daily transpiration flux per unit ground area for *T. indica* subsp. *bidens* ranged from 0.1 to 0.7 mm/day, with a seasonal peak in the wetter summer months. Maximum monthly mean daily transpiration flux values ranged from 0.1 to 1.5 mm/day

Gas exchange measurements confirmed that *T. indica* subsp. *bidens* is a species with C4 photosynthesis. C4 plants have greater water use efficiency than C3 plants, which can provide a competitive advantage in warm climates prone to drought.

Marchesini (2012) analysed time series changes in plant pigment concentrations from the field sites. *T. indica* subsp. *bidens* exhibited the most pronounced changes. Correlations between pigments (putative betacyanins and chlorophyll a) and four environmental variables were examined: a) Soil water storage in the top 50 cm, b) cumulative monthly precipitation of the month before the sampling date, c) mean daily radiation and d) mean daily air temperature were examined for this species. Putative betacyanin concentrations showed a seasonal peak in the winter months, and were negatively correlated with cumulative rainfall in the previous month, mean air temperature and solar radiation (r^2 values 0.6 to 0.84). Chlorophyll-a concentrations did not exhibit a clear seasonal pattern, but were positively correlated with cumulative rainfall in the previous month (r^2=0.6). In subsequent field and glasshouse measurements, good correlations were obtained between pigment concentrations and spectral signals measured using a handheld spectrophotometer. Spectral measurements show promise as a tool for monitoring the health of *T. indica* subsp. *bidens* exposed to drought stress, however more work is required to separate out the confounding effects of other factors affecting plant colouration.

Glasshouse experiments

In salinity experiments, the growth of all three species was optimal over a wide salinity range. Growth decreases were only observed at low salinity (10 mM and below) and very high salinity (above 800 mM). Extreme salinity (e.g. 2000 mM NaCl) in the absence of drought impeded the growth, and induced mortality in, *T. indica* subsp. *bidens*. This was attributable to the failure of this species to cope with the high osmotic stress causing tissue water content to decline, and possibly also in combination with tissue ions exceeding tolerable levels. The study demonstrated that the three *Tecticornia* species from Fortescue Marsh are amongst the most salt tolerant halophytes recorded world-wide.

In the first drought experiment, all three species survived a 7-week period of withholding water that resulted in gravimetric soil water contents decreasing from 0.36 to approximately 0.14-0.25 g/g, depending on species and treatment. Combinations of experimental treatments suggest that tolerance thresholds were affected by the rate of stress imposition. Growth reductions were primarily attributable to soil water deficits, rather than the effect of concentrating NaCl. Drought stress induced reduced tissue water content concentrations, which contributed to declines in tissue osmotic potentials of less than -7 MPa. Upon re-watering for an additional 7-week period, growth rates returned to the levels observed in well-watered plants in all three species. *T. indica* subsp. *bidens* (C4 photosynthesis) showed a higher transpiration efficiency than *T. auriculata* and *T. medusa* (both C3 photosynthesis) over a range of combined soil water deficit and salinity conditions, and hence was the most drought tolerant species.

In the 2012 expanded glasshouse experiment, all three *Tecticornia* species responded similarly to gradually drying soils. Key findings included (Prof. E. Veneklass UWA, pers. comm. August 2013):

- All three *Tecticornia* species exhibited similar physiological responses and tolerances under experimental drought.
- The plants sustained transpiration by both soil water uptake and use of water from succulent tissue.
- Tissue osmotic potential decreased to less than -10 MPa (Figure 12), largely explained by tissue water loss with no significant osmotic adjustment.
- Transpiration decreased.

- Shoot growth was depressed, and root growth increased.
- Tissue chlorophyll concentration decreased, with no clear trends in carotenoids and betacyanins.

All species displayed a high level of drought tolerance; however mortality under prolonged drought occurred first in *T. medusa* and *T. auriculata*. The buffer volume of water contained in the samphire succulent tissues appears to be important particularly in situations of severe stress, when there is no hydraulic gradient anymore for uptake of water from the soil. The samphire plants in the experiment were found not to recover from drought stress once they had lost all succulent tissue.

In inundation experiments, *T. medusa* showed a greater tolerance to submergence than *T. auriculata* and *T. indica* subsp. *bidens.* The succulent tissues of *T. auriculata* and *T. indica* subsp. *bidens* swelled and ruptured when submerged, whereas *T. medusa* resisted such damage and was able to photosynthesise underwater. Therefore, prolonged submergence is potentially a selective stress factor that prevents *T. indica* subsp. *bidens* and *T. auriculata* from invading low-lying habitats subjected to longer and deeper flooding events.

In the 2012 expanded glasshouse experiment, changes in reflection spectra were observed in all three *Tecticornia* taxa both at tissue and plant scale. However these changes were only statistically significant for *T. auriculata*. Comparison between glasshouse and field measurements suggest that environmental factors besides drought, such as radiation (ultraviolet) or low temperature, may be important for stimulating pigment biosynthesis. Due to these confounding factors, no immediately applicable drought stress monitoring indicators based on plant colouration have been identified from the work to date.

4.2.4 Interpretation and key outcomes

- Samphire species tolerances to environmental stresses corresponded to their natural abundance across ecosystem gradients. The more flooding and salinity tolerant *T. medusa* occurs in low elevation basins in the interior of the marsh, with persistent shallow watertables. The slightly more drought tolerant *T. indica* subsp. *bidens* occurs in the outer margin of the marsh samphire communities where soils are drier, and deeper watertables may not be accessible to plant root systems. *T. auriculata* occurs in areas intermediate between these two extremes.

- The similar responses of the three *Tecticornia* species to simulated drought stress may relate to the opposing gradients in drought and salinity in their natural habitats. To continue to extract soil water in the drying soils of the marsh, the plants must overcome:
    - a decrease in soil matric potential due to soil drying; and
    - an increase in soil osmotic potential due to increasing salinity.

  Although *T. medusa* generally grows in moister soils than *T. indica* subsp. *bidens* and *T. auriculata*, these areas are typically more saline.
- The experimental work (field and glasshouse) has provided evidence that the Fortescue Marsh samphires are highly tolerant of low rainfall (drought) and salinity and in terms of growth and survival. *T. indica* subsp. *bidens* was shown to use C4 photosynthesis, which would be expected to confer a higher tolerance of dry soil than *T. auriculata* and *T. medusa*. This was borne out in the glasshouse drought experiments. All of the samphire species showed an ability to maintain low stem tissue osmotic potentials (less than -7 MPa), extract water from relatively dry soils, and recover from imposed drought stress.
- The field pigment analysis showed that *T. indica* subsp. *bidens* increased chlorophyll-a concentrations following significant rainfall events. This implies an opportunistic water use and growth strategy, directly attributable to the rain but also possibly due to increased plant available water resulting from salt dilution in the surface soil layers.
- Estimations of samphire transpiration fluxes in the *T. indica* subsp. *bidens* and *T. auriculata* communities in the field plots were low, equivalent to less than 200 mm/year. This is an indicator of the difficult growing conditions experienced in the saline marsh environment, and suggests that these plants adopt a conservative water use strategy. This finding is consistent with the slow growth rates (i.e. low rates of photosynthetic biomass accumulation) observed in the marsh samphire communities over the life of the project.

  Sap flow measurements are useful for informing the estimation of stand level transpiration flux, because stem flux densities effectively integrate plant and soil water interactions under complex and dynamic growing conditions (e.g. related to soil heterogeneity and daily temporal dynamics of plant water use). However it is important to note that the accuracy of scaling up the plant sapflow measurements can be affected by radial and azimuthal variation in stem conductivity, and errors in the estimation of the total conductive surface area (commonly interpreted as the sapwood cross sectional area) within individual plant stems and across ground surfaces containing multiple plants. Determination of stem flux densities is also influenced by natural thermal gradients, which can effect interpretation of the heat pulse signal inherent to the measurement apparatus. For these reasons, the transpiration flux per unit ground area estimates obtained in the study should be used conservatively in site water balance estimations.

- Spectral indices show promise for underpinning samphire vegetation health monitoring tools using ground based or remote sensing methods, however further work is required to disentangle the various factors influencing pigment dynamics for spectral methods to be used in operational monitoring programs.

4.3 CSIRO/UWA Fortescue Marsh pilot study of remote sensing tools

4.3.1 Overview

In 2011 CSIRO was engaged by Fortescue to investigate the potential for developing remote sensing (RS) tools to monitor the eco-hydrology of the Fortescue Marsh. RS is a potentially attractive technology for vegetation health monitoring in the marsh, due to the availability of historical satellite datasets (enabling retrospective analysis for pre-disturbance baselining) and the ability to cover large areas that would otherwise be impractical and cost prohibitive.

The study was implemented as a pilot project with the following objectives:

- to illustrate the capability of RS techniques to identity land cover classes characterised by their differing responses to changes in hydrological conditions.
- to explore whether RS techniques are useful for water balance estimation in the Fortescue Marsh environs.
- to determine the suitability of existing monitoring activities for validating RS techniques, and identify additional options and approaches for validation purposes.
- to propose a framework for monitoring vegetation function and condition in the Fortescue Marsh using RS techniques.

A short summary of the methods and results provided as follows (refer to Appendix 5 for client study report).

4.3.2 Methods

The study methodology included two main components:

- Land cover classification of the marsh surface and surrounding areas, using spectral indices derived from Landsat imagery spanning the period of the UWA ARC Linkage Project (LP0882350) field experiment (i.e. 2008 – 2011). The classification methodology applied was originally developed by CSIRO for the National Water Commission (NWC) Groundwater Dependent Ecosystems (GDEs) Atlas (Barron *et al*. 2012 – in review). It involves a two-step classification procedure, including unsupervised classification of time series RS data and analysis of the class centre values to distinguish land cover classes. Different trajectories of land surface change can indicate different ecosystem behaviours, such as seasonal patterns and potential dependence on groundwater. Normalised Difference Vegetation Index (NDVI) and Normalised Difference Wetness Index (NDWI) were the primary indices used in the analysis; however Enhanced Normalised Vegetation Index (EVI) and Structure Insensitive Pigment Index (SIPI) were also tested for comparative purposes.

- Examination of spatial and temporal patterns in actual evapotranspiration (ET) using two RS based methods with different theoretical underpinnings:
    - surface energy balance analysis (SLST) - based on a daily heat balance approach.
    - vegetation index and wetness index analysis (CMRSET) – based on spectral index algoirthms applied to MODIS satellite data. The method has been calibrated using observed ET data from seven sites in Australia (including two forests, two open savannas, a grassland, a floodplain and a lake) but not the Pilbara region.

The results were qualitatively compared with on-ground observations of soil water dynamics made at the UWA ARC Linkage Project (LP0882350) study sites.

4.3.3 Results

Land cover classification

Land classes distinguished using the classification procedure for various paired Landsat image acquisition dates displayed the following patterns:

a) May 2009 to November 2009 - all land classes exhibited a reduction in NDVI and NDWI (i.e. reduced greenness and wetness).

b) May 2009 to April 2010 - all land classes exhibited a reduction in NDVI and NDWI, similar to (a) indicating that there were no major changes in overall drying patterns during the summer period.

c) May 2009 to December 2010 - all land classes exhibited a reduction in NDVI and NDWI. A wider range in the magnitude of these changes between land classes was observed in comparison with (a) and (b).

d) November 2009 to December 2010 - despite the overall reduction in both NDVI and NDWI over this period, multiple image analysis (5 satellite acquisition dates) indicated that some increases in the NDVI during July 2010 for the majority of land classes, and similarly in the NDWI in the period April to July 2010. These changes corresponded with autumn 2010 rainfall patterns.

Initially (during the period May 2009-November 2010) greater changes were associated with areas where ephemeral inundation or stream flow occurred in autumn 2009. Fewer changes occurred during the following summer but the landscape became much drier over the following winter and spring. No land cover type was associated with invariant NDVI and NDWI over long periods (greater than 7 months). Vegetation associated with drainage tracts, spillways and basins within the marsh was characterised by wetter and greener land cover. The trends observed were in general agreement with on-ground observations made by the UWA team.

The use of the EVI and SIPI spectral indices in the land classification procedure yielded similar spatials distribution of identified land classes in comparison with NDVI and NWDI indices, providing confidence in the robustness of the land classification techniques.

ET estimation

Spatio-temporal ET patterns interpreted using both methods were in general agreement with expected ET trends. The inundated areas in the Fortescue Marsh were characterised by high annual ET in 2009, summer ET exceeded winter ET in 2009 and 2010, commensurate with both available water and potential evaporation. Higher ET rates were associated disjunct portions of the marsh including some fringing areas, which could indicate areas where overland flows accumulate and/or groundwater discharges. They could also be related to particular vegetation types and canopy densities. Comparing the results with the land cover classification, greater ET values were associated with the land classes characterised by greater NDWI and NDVI values.

Although the two methods used to estimate total ET from the marsh and surrounding region give similar patterns, the absolute ET estimations were significantly different: with the SLST heat balance method being little over half the CMRSET index based method. Note that these methods have been developed and tested in other parts of the Australian continent, and have not been validated for the Pilbara region. Although the qualitative trends are expected to be reliable, on ground validation of ET is necessary to enable quantitative ET estimations using the RS methods in the Fortescue Marsh environs.

Ecohydrological monitoring framework

An ecohydrological monitoring framework was proposed, consisting of the following key elements:

- Land surface change detection using RS methods, including characterisation of historical land cover variability in response to natural wetting and drying cycles.
- Change interpretation involving validation of RS analysis with on-ground observations of groundwater surfaces, soil moisture and salinity, and vegetation characteristics and behaviour. These data would inform the development of criteria for vegetation health assessment and impact measurement using the RS tools.
- Linking changes to the regional water balance, to enable the influence of mining (and other disturbance) activities to be landscape scale ecohydrological processes.

The conceptual structure of the proposed framework is presented in Figure 13 and further described in Appendix 5.

4.3.4 Interpretation and key outcomes

- The pilot study demonstrated that land cover classes in the Fortescue Marsh and surrounds can be characterised by RS analysis, and RS data can also define the spatial and temporal variability in ET. The distribution of land cover types and temporal patterns of ET generally accorded with on-ground appraisal of land surfaces, however some notable discrepancies were apparent. For example, high ET areas along the northern flanks of the Hamersley Ranges to the south of the Marsh and along the southern slopes of the Chichester Ranges were unexpected and warrant further investigation.

- At a broad level, the study findings were not suggestive of the occurrence of large areas of groundwater discharge in the Fortescue Marsh, based on:
  - all land classes exhibiting declining greenness and wetness over the period mid 2009 – 2011, coinciding with a period of low rainfall.
  - correspondence between land cover classes, ET trends and surface drainage features such as drainage tracts, spillways and basins.

The findings of the study are useful for informing the ongoing development of Fortescue's vegetation health monitoring programs.

4.4 UWA isotope studies

4.4.1 Overview

The overall objective of this study was to determine the source of water accessed by samphire communities on the boundary of the Fortescue Marsh (lowlands) as well as the *Acacia aneura* and *Acacia xiphophylla* woodlands and shrublands further upslope (uplands) using natural abundance isotopic tracers. This work was performed in 2012 by Dr Pauline Grierson, Dr Gerald Page & Dr Grzegorz Skrzypek of the Ecosystems Research Group at UWA. The scope of work included the following tasks

- Design a sampling regime for soil and plant measurements that will complement on-going studies of samphire communities, mulga water requirements and other studies (including hydrogeology) within areas of the Fortescue Marsh near Fortescue's Chichester operations.
- Undertake initial sampling of soils, groundwater, surface water and plant xylem water from uplands and lowlands corresponding to topographic differentiation and shifts in vegetation communities.
- Assess the oxygen isotope composition of collected soil, shallow groundwater (where accessible) and plant tissue (twigs and roots) samples.

- Compile a written report summarising the methodology, results and key outcomes of the study in context of other vegetation research previously undertaken in the area.

A short summary of the methods and results is provided as follows. The UWA team is preparing a final report on the study, which is expected to be completed later in 2013. Some of the interim findings have been collated and are presented in Appendix 6.

4.4.2 Methods

The field work was undertaken in the period May 7-11, 2012. Eleven backhoe pits were excavated at locations near the Cloudbreak and Christmas Creek mine sites. Maps of the sites including images of the aboveground vegetation community and soil pit at each location are provided in Appendix 6). The GPS coordinates along with a physical description of each pit are provided in Table 4. Soil samples were collected at 20 cm depth increments from the surface to the base of each pit. Samples of twigs and roots were collected from dominant plant species immediately adjacent to the pits. Where encountered, groundwater was collected from the base of the pits. Observations of plant root systems (e.g. depth, distribution, presence of tap root) and the soil profile were also recorded at each pit.

Gravimetric soil moisture content was measured in all soil samples. Water isotopic composition ($\delta^{18}O$ values[1]; and $\delta^{2}H$ values) were measured in samples extracted from soil, groundwater and plant samples (primarily from twigs but also occasionally roots and spinifex grass).

4.4.3 Results

The UWA report is yet to be finalised. However, the following preliminary findings have been made:

- Plant root systems did not have pronounced taproots and were mostly confined to the surface 50 to 70 cm; however a low abundance of fine roots was occasionally observed to the base of the excavation.
- Of the four sites in samphire shrubland, three had a saturated zone present. Two of these saturated zones were above a hardpan at Christmas Creek and the other was

[1] the ratio of stable isotopes ^{18}O:^{16}O

hypersaline and at a depth of 2.6 m below the samphire/spinifex boundary at Cloudbreak.

- There was no saturated zone present in all five trenches excavated at 'upland' sites (trench depth > 2.20 m at all sites).
- Two mulga sites were located much closer to the Marsh boundary (designated as mid-slope) than the 'upland' sites and had very different soil profiles. One site (CC3) was associated with a calcrete outcrop on a tributary that was likely a source of freshwater. The other was a very shallow dry profile over an impermeable silcrete hardpan at 100 cm depth.
- Depth profiles of $\delta^{18}O$ in soil water are shown in Appendix 6. Some pits show a clear evaporation front at between 50-75 cm depth, most obviously at Cloudbreak sites 5 and 7. This boundary generally coincided with a cementing of the soil matrix, although not an obvious change in soil texture. The shape from the surface to the front results from vapour diffusion while the shape from below this depth is caused by downward diffusion of isotopes. However, a number of sites are far more linear in their profile. Rainfall can push the enriched water downward but the isotopic composition of soil water is still likely to be depleted in heavy isotopes (more negative) since a downward diffusion process is taking place. The profiles lacking an obvious evaporation front still grade from more evaporated at surface to more depleted at depth.
- Upland and lowland plants are clearly using water that has been mainly replenished by a large rainfall event, consistent with Cyclone Heidi.
- Samphires and other marsh species sampled are clearly using water that has been mainly replenished by a large rainfall event, consistent with Cyclone Heidi.
- Xylem water from *A. aneura* growing above a calcrete outcrop on a tributary into the marsh closely resembles rainfall from Cyclone Heidi in January 2012. Soil water below 100 cm (i.e. below the evaporated surface layers) at this site was also closer to the isotopic composition that would be expected of large rainfall events (see Dogramaci *et al.* 2012; Skrzypek *et al.* 2013).
- Because a transition layer was observed at around 50-75 cm depth (average at ~ 60 cm) across many sites (either in soil texture, evaporation front or Cl^- profiles, and few roots were observed below this depth, plant water was examined in relation to above and below 60 cm. For most species at most sites (including all sampled

samphire species), xylem water was far less enriched (i.e. less evaporated) than the soil water at 60 cm depth or soil water sampled at the maximum excavated depth (generally >160cm). These observations suggest that the sampled plants are retaining turgor/plant water derived from a different source; we would suggest that at least some of the xylem water is stored water derived from rainfall inputs from Cyclone Heidi, which delivered heavy rains to the marsh in January 2012. Stem water storage can significantly influence seasonal water use patterns in many species, by enabling the plant to draw upon internal reserves during dry periods (Aranda *et al.* 2012).

4.4.4 Interpretation and key outcomes

- The isotope data provides evidence that the sampled plant taxa were (i) using water originally derived from a large rainfall event, both on the marsh and at upland sites. At most sites, including on the Marsh, plants are most likely accessing shallow soil water of meteoric origin. There was no clear evidence to suggest use of (saline) groundwater by the vegetation at the time of sampling. This finding is consistent with the observed samphire root morphology and distributions in the soil profile.

- These data are for a single sampling period during the early dry season and four months after a significant precipitation event associated with Cyclone Heidi. Without additional sampling (multiple time points), the capacity of the vegetation at these sites to alter their water-use and uptake strategy across seasons and/or years remains unquantified. This is particularly important to consider in the highly dynamic and variable climatic regime of the Fortescue Marsh area. Additional sampling that encompasses the range of hydrologic conditions at Christmas Creek and Cloudbreak (e.g. prolonged drought versus recent recharge from flood) is necessary to clearly identify all potential sources of water used by vegetation.

Table 4 Summary of UWA stable isotope sampling locations

Pit Ref.	Locality & landscape	MGA Zone 50		Soil sampling depth	Key vegetation sampled	Groundwater sampled (depth)
		East	North			
1 (CC1)	Christmas Creek; samphire marsh fringe	774602	7516180	260 cm	*Tecticornia indica* subsp. *bidens; Acacia synchronicia*	✓ (260 cm)
2 (CC2)	Christmas Creek; up-land mulga	775421	7517261	240 cm	*Acacia aneura* (subterete)	dry
3 (CC3)	Christmas Creek; near-marsh mulga	777253	7514797	200 cm	*Acacia aneura* (subterete); *Acacia synchronicia*	✓ (270 cm)
4 (CC4)	Christmas Creek; samphire marsh fringe	775493	7515474	100 cm[22]	*Tecticornia indica* subsp. *bidens* *Muehlenbeckia florulenta*	✓ (110 cm)
5 (CB5)	Cloudbreak; up-land mulga	737330	7530508	260 cm	*Acacia aneura* (subterete)	dry
6 (CB6)	Cloudbreak; up-land mulga	728417	7534172	240 cm	*Acacia aneura* (subterete)	dry

[22] to groundwater

Pit Ref.	Locality & landscape	MGA Zone 50		Soil sampling depth	Key vegetation sampled	Groundwater sampled (depth)
		East	North			
7 (CB7)	Cloudbreak; up-land mulga	738690	7527752	260 cm	*Acacia aneura* (subterete); *Acacia xiphophylla*; *Acacia tetragonaphylla*	dry
8 (CB8)	Cloudbreak west; Samphire /spinifex marsh fringe	727669	7528811	280 cm	*Tecticornia indica* subsp. *bidens*; *Triodia longiceps*	✓ (280 cm)
9 (CB9)	Cloudbreak; samphire marsh fringe	740600	7524930	140 cm[23]	*Tecticornia indica* subsp. *bidens*; *Tecticornia auriculata*	dry
10 (CB10)	Cloudbreak; Near-marsh mulga	738063	7525930	100 cm[23]	*Acacia aneura* (subterete); *Acacia tetragonaphylla*	dry
11 (CB11)	Cloudbreak west; up-land mulga	727840	7531407	220 cm	*Acacia aneura* (subterete); *Acacia xiphophylla*; *Acacia tetragonaphylla*	dry

[23] to silcrete hardpan

4.5 Mulga root systems assessment

4.5.1 Overview

In 2012, Astron Environmental Services (Astron) undertook an assessment of Mulga root system architecture in upland and lowland communities north of the Fortescue Marsh. The overarching objective of the assessment was to describe and quantify the depth and architecture of Mulga root systems in areas potentially exposed to water table fluctuations, and to contribute an understanding of the following:

- Where are Mulga roots located in the soil profile? What proportions of the roots are in different depth increments from the surface down to accessible depths?
- How variable are Mulga root systems between different sampling locations? Can differences (or similarities) be explained by edaphic (soil-related) factors?
- Based on root morphology (qualitatively assessed based on root direction and taper) and root depth, what functional water use strategies are Mulga likely to employ?
- Based on assessment of root systems, how is Mulga likely to respond to modified water tables (drawdown or mounding)?

A short summary of the methods and results provided as follows (refer to Appendix 7 for client study report):

4.5.2 Methods

The field work was undertaken in the period April 10-17 (Christmas Creek locality) and May 11-14 (Cloudbreak locality) in 2012. The root systems of Mulga trees were exposed by backhoe trenching at 16 locations near the Cloudbreak and Christmas Creek mines, as summarised in Table 5 and spatial depicted in Figure 15. At one additional site in the Christmas Creek locality the root system of the samphire *Tecticornia indica* subsp. *bidens* was exposed by backhoe trenching.

The distribution and abundance of different root diameter classes (fine <2 mm ; small 2-5 mm; medium 15–40 mm; large >40 mm) on vertical trench faces were quantitatively described using grid sampling methods. One tree per site was uprooted and extracted using the backhoe, taking care to keep the proximal root system as intact and in its original orientation as possible. The lateral distribution and density of woody roots (> 2 mm diameter) of the uprooted trees was quantified, and root taper measured on a subset of roots.

Soil profiles were described in accordance with the *Australian Soil and Land Survey Field Handbook* (The National Committee on Soil and Terrain 2009). Soil physicochemical parameters (pH, salinity, cations) were analysed using laboratory methods.

4.5.3 Results

The soil profiles supporting Mulga vegetation were relatively consistent, consisting of a silty loam A horizon (typically 30 – 40 cm deep) overlying poorly structured light to medium sub-soil clays (to 160 cm). The subsoil clay layers were generally circumneutral, low salinity and highly sodic (ESP>13). Varying amounts of gravel and cobbles were present in the profiles, sometimes occurring in distinct bands but generally grading to larger and more abundant gravel and cobbles at depth.

The root architecture of Mulga followed a broadly consistent pattern at all sampling locations, with the following principal root structural classes:

- Taproot – not always present; strongly tapered and typically not exceeding beyond depths of 100 to 150 cm.
- Lateral roots – pronounced and extending radially well beyond the projected canopy area of the foliage in surficial layers.
- Oblique roots – strongly tapering and branching roots emanating from taproots and lateral roots. Typically concentrated inside a zone defined by the vertical projection of the canopy circumference.
- Fine roots – extending to >160 cm depth, but mostly prevalent in the top 0.5 m of the soil profile.

The depth of the taproot and the distributions of small woody roots and fine roots were commonly influenced by the way in which gravels, cobbles and clays were layered. Putatively more favourable sites were able to support larger trees with larger, more expansive root systems compared to less favourable sites. Near the fringe of the Fortescue Marsh, roots systems were generally smaller and shallower and they contained numerous dead roots linked to parts of the tree that had died (natural root pruning), possibly as a result of drought, salinity, or waterlogging.

Note that low abundances of fine roots of Mulga were commonly observed in the 2 to 3 m depth range in backhoe pits excavated during the UWA stable isotope sampling study (refer to Section 4.4).

Table 4 Summary of Astron Mulga root system assessment sampling locations

Site Ref.	Locality & landscape	MGA Zone 50 Easting	MGA Zone 50 Northing	Soil sampling depth (cm)
Area 1	Cloudbreak west; upland mulga on relictual alluvial fan	726690	7534723	170
Area 2	Cloudbreak west; upland mulga on relictual alluvial fan	728391	7534281	170
Area 3	Cloudbreak west; mid landscape mulga in inter-drainage area	727848	7531402	240
Area 7	Cloudbreak; upland mulga on relictual alluvial fan	737299	7530512	170
Area 9	Cloudbreak; mid landscape mulga in drainage splay	738649	7527810	170
Area 11	Cloudbreak; near-marsh mulga in broad, poorly defined drainage tract	738063	7525930	140 silcrete hardpan at depth
Area 12	Cloudbreak east; upland mulga in banded formation	763380	7524253	150
Area 16	Christmas Creek; mid landscape mulga in drainage splay	775401	7517285	150
Area 18	Christmas Creek; upland mulga in drainage tract	776666	7519372	100
Area 19	Christmas Creek; upland mulga and *Acacia xiphophylla* in inter-drainage area	778084	7518963	150
Area 20	Christmas Creek; upland mulga in drainage tract	778171	7518135	160
Area 21	Christmas Creek; upland mulga in drainage tract	780245	7517037	160
Area 24	Christmas Creek; near-marsh mulga in drainage tract	778236	7514489	135
Area 26	Christmas Creek; near-marsh mulga in drainage tract	779238	7513949	125
Area 32	Christmas Creek; upland mulga in inter-drainage area	781494	7516743	160
Area 33	Christmas Creek; mid landscape mulga in inter-drainage area	780680	7514654	150
Area 31	Christmas Creek; near edge of samphire community fringing the Fortescue Marsh	774607	7516190	160

The *Tecticornia indica* subsp. *bidens* root system evaluated at Area 31 did not have a pronounced taproot, and the woody root system was predominantly confined to the top 70 cm of the soil profile (Figure 16). Vertical mapping of the fine roots on the trench face indicated a predominance of fine roots in the top 50 cm of the soil profile. This root system pattern was also observed at other locations containing samphire vegetation in backhoe pits excavated during the UWA stable isotope sampling study (refer to Section 4.4).

4.5.4 Interpretation and key outcomes

- Mulga root system followed a consistent architectural pattern, with the bulk of the root systems confined to the surface 100 cm of the soil profile. This pattern suggests a functional water use strategy dominated by the exploitation of surficial inputs (rainfall and intercepted overland flow) and stem flows. The Mulga at the sampled locations is likely to meet its ecological water requirements from the top 2-3 m of the soil profile.
- The results were consistent with other observations of Mulga root systems in Australia's arid zones. Physiological measurements of Mulga in various settings, including transpiration rates and stem water potentials, have demonstrated generic traits of strong drought tolerance and rapid pulse response to water availability in the species complex. These observations are consistent with a surface oriented functional water use strategy, without any dependence on deep soil stores (i.e. >5m depth) and groundwater.
- The Mulga vegetation in the vicinity of Fortescue's Chichester projects would not be expected to be affected by groundwater drawdown associated with any mine pit dewatering.
- Examination of the *Tecticornia indica* subsp. *bidens* root system evaluated at Area 31 south of the Christmas Creek mining area provided evidence that this taxon also has a functional water use strategy targeting surficial soil layers.

4.6 Salt loads and surface salinity assessment

4.6.1 Overview

In 2012 Astron Environmental Services (Astron) undertook an assessment of baseline soil salinity in vegetation communities fringing and upland from the Fortescue Marsh near Fortescue's Cloudbreak and Christmas Creek mining operations. The study objectives included:

- Assess whether the EM38 (Geonics Ltd, Canada) electromagnetic induction meter is a suitable tool for use in the Pilbara to measure soil salinity levels, and to calibrate the EM38 to the soil types surrounding Fortescue operations. The EM38 is a simple-to-use, hand held probe with a maximum sensitivity of 0.4 m if orientated in the vertical mode (effective depth range 1.5 m) and a maximum sensitivity close to the soil surface if oriented in the horizontal mode (effective depth range 0.75 m).
- Provide a baseline for monitoring salt levels in the environment surrounding Fortescue's operations focusing on mulga and inter-mulga patches, in and around drainage systems and transitional increasing salt levels in proximity to the Fortescue Marsh.

A short summary of the methods and results provided as follows (refer to Appendix 8 for client study report):

4.6.2 Methods

The field work was undertaken in the period April 24-30 2012 (Cloudbreak and Christmas Creek localities). Grid transect sites (50 m north – south spacing) were selected to provide sufficient representation of the areas of the landscape that surround, or are downstream of, current and proposed operational mining areas. This included areas of banded mulga and inter-mulga, drainage tracts lined by mulga, the Fortescue Marsh perimeter and samphire dominated areas inside the marsh categorsied as follows.

- Two transect and soils sample areas which border the Fortescue Marsh, 'Christmas Creek Marsh', 'Cloudbreak Marsh' which encapsulate an area that extends north from well within within the moist, saline, samphire dominated ecosystem to beyond the samphire border. The edge of the marsh is occasionally broken by fingers of mulga, as well as slightly elevated cobble/gravel covered open areas covered by sparse shrubs.

- 'Cloudbreak Mulga' which is a region of banded mulga interspersed with areas of surface cobble/gravel and occasionally mulga which lines shallow drainage depressions.
- 'Cloudbreak Drainage' which is an area of wide, open cobble/grave with very sparse vegetation occasionally broken by large drainage and washout areas which feed into the Fortescue Marsh.

EM38 readings in the vertical and horizontal modes were collected at all sampling locations, along with a GPS point and location photograph looking south.

Twenty four soil calibration pits were dug by hand to 50 cm depth and sampled from the following depth increments: 0-10 cm, 10-20 cm, 20-35 cm and 35-50 cm. The soils were briefly described (colour (Munsell 2009), texture class and coarse fragments) in accordance with the Australian Soil and Land Survey Handbook (McDonald *et al.* 2009) and the Unified Soil Classification System (USCS). All samples were sent to a commercial laboratory and analysed for gravimetric moisture content, salinity (1:5 water extract), and pH (1:5 $CaCl_2$ extract). Surface samples (0-0.1 m) were also assessed for salinity (EC paste extract), cation exchange capacity (CEC), exchangeable cations (Na, K, Mg, Ca) and particle size distribution (PSD).

4.6.3 Results

Soil samples EC(1:5) from a single depth range explained between 85% and 91% of variation in EM38 readings. EC(1:5) at depth 0.35-0.5 m was most strongly associated with measurements in the vertical mode (R^2 0.88) and EC(1:5) at shallower depth (0.2-0.35 m) was most strongly associated with measurements in the horizontal mode (R^2 0.85).

Taking multiple EM38 readings near a soil pit or including EC(1:5) from multiple depth ranges did not greatly improve the strengths of the relationships. Inclusion of other soil parameters in regression models (soil moisture, cations; % clay) did not significantly improve the models.

The EM38 transects completed in the marsh area at Christmas Creek and Cloudbreak confirmed that the Marsh is far more saline than upland areas distant from the marsh. Fingers of mulga extending to the edge of the marsh south of Cloudbreak were growing on more saline soil (EC range 27-527 mS m^{-1}) than those in upland areas (EC range 1-67 mS m^{-1}).

Soil salinity generally decreased with distance from the edge of the samphire boundary, however salinity in and immediately adjacent to the marsh was quite variable. Lower salinity was associated with drainage tracts and outwash areas, as depicted in Figure 17 which shows EM38 readings (vertical mode) collected in the Christmas Creek marsh fringing area. At this location highly saline patches (>600 mS m^{-1}) coincided with stands of *Muehlenbeckia florulenta* (lignum) and surface salt crusting. These findings indicate that the drainage systems contribute to salt flushing in the marsh channels and floodways, and that inflows and salinity are associated with vegetation patterns.

The study concluded that:

"The EM38 can provide a quick, cost-effective and accurate assessment of salt levels in soil in areas surrounding Fortescue operations where saline water is frequently used for dust suppression. The EM38 may not be accurate where a visible, thin layer of salt crust has formed on the surface of the soil, as was found in patches within the Fortescue Marsh. In these situations the salt level will be underestimated. Given the low levels of salt found in soils found where banded mulga occur, any accumulation of salt in the soil resulting from saline water dust suppression activities should be detectable if using the EM38 as a salt monitoring tool."

4.6.4 Interpretation and key outcomes

- The EM38 was shown to be a useful tool for measuring soil salinity in and adjacent to the Fortescue Marsh and Fortescue's current and proposed mining areas.
- Baseline soil salinity was low in upland areas distant from the Fortescue Marsh. Near the marsh soil salinity was much greater, but also spatially variable and influenced by drainage lines and flushing processes which are related to the observed vegetation patterns.

4.7 1D-unsaturated zone modelling

4.7.1 Overview

In 2011 Astron Soil & Water Pty Ltd (Astron S&W) was commissioned by Fortescue to develop a numerical model of the unsaturated zone water balance in samphire communities, targeting samphire communities containing *Tecticornia indica* subsp. *bidens* at the Fortescue Marsh fringe south of the Cloudbreak mine.

The following high level modelling objectives were identified:

- provide an improved understanding of soil moisture dynamics in the unsaturated zone profile on the Fortescue Marsh fringe, under different soil profile and climate scenarios (albeit under a simplified and conservative set of conditions).
- examine the potential contribution of groundwater to meeting vegetation water use requirements.
- evaluate the potential impacts of modified watertable depth on plant available soil moisture.
- test the hypothesis that "*the water requirements of the fringing samphire vegetation can be met by surface water inputs under most climatic regimes, including areas potentially exposed to modified groundwater depth*".

The project was implemented over several phases corresponding with iterative model development. A short summary of the methods and results provided as follows (refer to Appendix 9 for client study report).

4.7.2 Methods

HYDRUS1D (version 4.14) was selected as the preferred modelling platform for the study. HYDRUS is a general software package for simulating water, heat, and solute movement in two- and three- dimensional variably saturated media. The numerical computational programs in the HYDRUS package solve the Richards equation for variably-saturated water flow and the convection-dispersion equation for heat and solute transport. The water flow equation incorporates a sink term to account for water uptake by plant roots. The HYDRUS model has been successfully applied in numerous studies to analyse site-specific problems relating to plant water use and growth, soil moisture dynamics and soil salinisation (Simunek *et al.* 2008; Forkutsa *et al.* 2009a,b; Xie *et al.* 2011).

Two principal scenarios were evaluated in the study based on accumulated knowledge regarding marsh soil profiles and hydrologic conditions at the Fortescue Marsh fringe:

1. A shallow (100 cm) clay loam[24] soil profile available to plant roots, confined by a hard silcrete (impeding) layer which functions as an aquitard.

[24] Note - In early modelling iterations clay loams were found to perform better than clay soils, consistent with field texture classing and HYDRUS soil hydraulic parameters.

2. A deep (300 cm) clay loam soil profile available to plant roots, with potential capillary connection to the underlying groundwater at 300 cm depth.

These scenarios were incorporated into a 1D vertical profile modelling domain, with the lower boundary a constant head boundary simulating a hardpan layer or groundwater (for Scenarios 1 and 2 respectively) and the upper boundary the ground surface exposed to the atmosphere. The selected transient model period was 950 days (1st October 2008 to 8th May 2011), corresponding with the field work phase of ARC Linkage Project LP0882350 implemented by UWA (refer to Section 4.2).

Model parameters were selected based on soil profile and plant physiological information collected by UWA, Equinox and Kew (2011). Soil hydraulic properties for clay loam and clay soils were selected from the HYDRUS built-in soil database. Climate data was obtained from the UWA weather station located south of the Cloudbreak mine (740645E; 7525000N), and used to derive reference daily evapotranspiration. Where UWA data were missing, data from the Cloudbreak mine weather station and Newman Aero (BoM ID 007176) were used.

Root water uptake parameters were selected to populate the Feddes *et al.* (1978) water stress reduction model. The wilting point pressure head was set at – 7 Mpa, consistent with stem osmotic potentials of actively transpiring *T. indica* subsp. *bidens* measured by UWA in the field and glasshouse experiments (refer to Section 4.2). Rainfall interception was not accounted for but is recognised as an important component of the water balance of vegetated surfaces.

The model was calibrated against the time series UWA gravimetric soil moisture data from *T. indica* subsp. *bidens* (presented in Figure 11) and *T. auriculata* plots, spanning the period October 2008 to May 2011. Various model sensitivities were tested, including reducing the watertable from 3 mbgl and 5 mbgl in Scenario 2, which assumes connectivity between the surface and the watertable, to simulate a groundwater drawdown effect. Suggestions for improving the model concepualisation were provided, including describing the soil profiles as having an A and B horizon.

4.7.3 Results

The key findings included:

- All soil moisture profiles from the HYDRUS1D modelling indicate soil moisture levels that are comparable to field recorded values. Importantly this was the case for Scenario 1, the most likely hydrogeological profile underlying the UWA field plots, which was modelled with plausible 'worst case' scenario inputs
- Modelled root water uptake in Scenario 1 (mean= 0.22mm/day, median=0.09mm/day with 36% of values <0.05mm/day, maximum=2.30mm/day) were comparable in magnitude to the transpiration flux calculations derived from UWA sapflow data (refer to Section 4.2). Preliminary transpiration response curves generated from UWA glasshouse data, which show that the marsh samphire species have the ability to continue transpiration at very low soil water content levels (~10% of Field Capacity) with high salinity (500mM), were consistent with the Scenario 1 modelling results.
- For the groundwater drawdown scenario, a 2 m reduction in groundwater level had a minimal effect on the water content in the upper 100 cm of the soil profile.

4.7.4 Interpretation and key outcomes

- UWA field measurements were found to provide suitable information for calibrating the HYDRUS model.
- The modelling exercise was subject to various assumptions, simplifications and limitations, and was primarily intended to inform the development of more detailed models. It did not provide the basis for drawing conclusion about the potential response of the marsh samphires to drawdown for environmental impact assessment purposes. However the study successfully demonstrated that the HYDRUS model provides a useful platform for exploring water balance dynamics in the unsaturated profile of the Fortescue Marsh fringe. Fortescue has subsequently undertaken a more in-depth HYDRUS modelling study (refer to Section 5).

5 Fortescue Marsh conceptual eco-hydrological model

5.1 Conceptual model overview

Fortescue has developed a Fortescue Marsh hydrogeological conceptual model (Christmas Creek) which depicts the dynamic hydrological regime near the edge of the marsh in the Christmas Creek locality (Figure 18; Fortescue 2012a). The key components of this conceptualisation are summarised as follows:

- **Flood Events:** the marsh water balance is dominated by surface water inputs, which are received during infrequent flood events predominantly in the summer months. Water accumulates in the marsh from direct rainfall and catchment run-off. Some water percolates into the shallow, saline aquifer underlying the marsh and propagates into bank storage provided by the marsh surrounds. Fortescue has detected groundwater responses to marsh flooding in monitoring bores up to two kilometres from the marsh ecophysiographic boundary. This process is driven by the mounding of groundwater beneath the inundated basin areas, creating a reverse hydraulic gradient. In the period immediately following flood events, ponded water in the lowest elevation portions of the marsh evaporates. Evapotranspiration rates are relatively high in adjacent areas due to the combination of abundant moisture and high solar radiation flux.
- **Inter Floods**: During the ensuring post flood period, surface ponding recedes. The marsh sediments continue to evaporate, accumulating salts that were dissolved by the flood waters. The shallow groundwater system slowly re-equilibrates driven by direct evaporation from the soil and transpiration by the surrounding vegetation communities. These processes are sustained for some time, as soil water stores that were replenished by the flooding and associated landscape water redistribution processes are gradually depleted. Periodic minor rainfall events generally do not cause pond formation and probably contribute little to groundwater recharge.
- **Prolonged dry:** If the intervals between flood events are large, water discharged from the marsh system by the aforementioned processes progressively diminishes. The soils become drier and more saline, disconnecting capillary links between the shallow aquifer and the surface. The marsh enters a period of hydrologic stasis, with depth to groundwater in the marsh and surrounds stabilised by the soil evaporation extinction depth.

An conceptual ecohydrological model of the Fortescue marsh fringe south of the Christmas Creek LoM Project area has been developed to build on Fortescue's hydrogeological interpretations. This model integrates the accumulated knowledge described in previous report sections. The model is diagrammatically represented in Figure 19 and describes the ecotone between the extensive Fortescue marsh samphire communities (Figure 20) and the non-halyphytic vegetation further up-gradient. Four broad functional landscape/vegetation units are recognised in the conceptual model:

Landscape/Vegetation Unit 1

This unit includes the sparse, xerophytic shrubland associated with the Cowra, Warri and Turee land systems south of the Christmas Creek mining area near the marsh boundary (e.g. consistent with ENV Vegetation Units 12 and 13 as per Section 2.8 and Figure 9). These areas are typified by low relief, stony mantles, poorly structured sodic sub-soils and very open to sparse vegetation. Relatively high soil salinity was observed more than 500 m distant from the marsh ecophysiographic boundary at an elevation of AHD 409 m outside of the drainage tracts (refer to Figure 17), and the boundary with very low salinity soils observed further upslope was not located in the EM38 transects at Cloudbreak or Christmas Creek.

Surface expression of calcrete is quite common in this unit, which is likely to have formed under evaporitic conditions combined with fluctuating groundwater levels. The calcrete and soil salinity indicators suggest that the marsh boundary may have extended to higher elevations in the past, and has subsequently transitioned to the present xerophytic plant community. It is postulated that the transitional boundary to very low salinity soils could occur at about 410 m AHD, coinciding with the elevation of the marsh terminal drainage outlet at the Goodiadarrie Hills.

The expected ecohydrological features of Unit 1 are low rates of rainfall infiltration and recharge, minimal transpiration flux and a propensity for run-off generation in larger rainfall events. As such, areas within Unit 1 are likely to be water source areas for the drainage tracts and samphire communities immediately down slope.

Landscape/Vegetation Unit 2

This unit includes open samphire heath formations at the marsh ecophysiographic boundary, generally in the inter-drainage areas. These areas are sometimes associated with gravelly spurs and derelict floodways, or calcrete protrusions. Plant growth edge effects were observed in these communities (i.e. larger plants along the edge of the vegetation boundary) indicating that the ability of these sites to support samphire vegetation is constrained by water availability. Canopy cover and plant size and vigour is variable, suggesting quite heterogeneous growing conditions mediated by constrained water availability.

The expected ecohydrological features of Unit 2 are canopy densities and patterns of plant water use matched to available water, consistent with theories of ecological optimality (O'Grady *et al.* 2011; Ellis & Hatton 2008). The distributory drainage network dictates that these areas are unlikely to receive much run-on and the natural range of watertable depths is about 3 to 5 m. The principle water source for these communities is likely to be direct rainfall or very locally derived run-on, with soil infiltration behavior and soil water storage capacity controlling the cover and composition of species assemblages. The vegetation is highly drought tolerant, but also tolerant of infrequent flood events. *Tecticornia indica* subsp. *bidens* and the Priority 1 taxon *Eremophila spongiocarpa* are generally common in these areas.

Landscape/Vegetation Unit 3

This unit includes closed samphire health formations further down-gradient from Unit 2 or protruding into drainage tract outlets and spillways which receive run-on. The high canopy cover, combined with the general vigour of the plants, indicates that these areas are likely to have more abundant plant available water than Unit 2. The outer margins include *T. indica* subsp. *bidens* communities, however Unit 3 extends well into the marsh and includes other samphire species in zonal configurations related to soil water and salinity dynamics, depth to watertables and frequency of flooding within the marsh ecosystem.

Surface inputs are likely to constitute an important water source for the Unit 3 communities especially near the marsh fringe. Many of the small drainage channels penetrate some distance into the marsh proper. In addition to proving a fresh water source, salt flushing associated with drainage may be important for maintaining osmotic water potentials amenable for plant water uptake. Being at lower elevations than Unit 2, the groundwater is shallower and soil water replenishment via subsurface backflow from the marsh, or episodic surface interception of the shallow aquifer, may also be important for replenishing soil water stores used by the vegetation.

Indurated subsoil layers are largely absent from marsh soil profiles south of the Christmas Creek mining area, and hence samphire root systems potentially have unimpeded access to the shallow groundwater. Preliminary stable isotope analysis results suggest that the fringing samphires preferentially access shallow soil water where it is available. This is an intuitively appealing finding, as low salinity rainwater would be energetically more easily extracted by the samphires than the saline groundwater. The ability of *Tecticornia indica* subsp. *bidens* to maintain water uptake under highly variable conditions of drought and salinity, recover from extreme drought stress, and quickly respond to water availability by increasing chlorophyll-a concentration corresponds with its observed distribution at the drier marsh fringe. The species has a spreading roots system concentrated in the upper soil profile, without pronounced taproots (Figure 16). These traits are all suggestive of a functional water use strategy targeting surface water inputs and not groundwater. Other samphire species, such as *T. medusa* which grows much further into the marsh, may have a greater dependence on access to saturated soil layers.

Landscape/Vegetation Unit 4

This unit includes the small drainage channels and floodway tracts dissecting Unit 1 (not depicted in Figure 19), as shown in Figure 5 (e.g. Plate 6). These are interpreted as in-filled channel incision features, which support denser vegetation communities (including mulga) by virtue of their concentrated surface water inputs and relatively deep soil profiles with relatively high water storage capacity and accessibility by plant roots. The drainage flow lines provide a vector for seed dispersal, which may explain the occurrence of Mulga near the edge of the marsh ecophysiographic boundary. Mulga is able to establish in these areas, possibly due in part to the lower soil salinity compared with adjacent areas outside the drainage tracts as conferred by flushing processes. However, in comparison with upland areas many dead sub-mature Mulga individuals were observed near the marsh. This may be related to occasional waterlogging and salt accumulation in these areas associated with large, infrequent flooding events.

5.2 Numerical unsaturated zone model of the marsh fringe

5.2.1 Overview

In 2012, the Fortescue Water Management Team with assistance from Equinox undertook a detailed modelling study of samphire water use dynamics at the Fortescue Marsh fringe south of the Christmas Creek mining area (Fortescue 2012b). The objective of the study was to inform environmental impact assessment relating to the proposed Christmas Creek LoM Expansion Project. Fortescue has identified that that drawdown associated with orebody dewatering for the project may extend to the northern fringes of the Fortescue Marsh (Fortescue 2012a); and intersect samphire vegetation communities (Figure 20).

The design of the modelling study was informed by the conceptual ecohydrological model described in Section 5.1, in addition to the findings of the Astron S&W HYDRUS modelling study. The modelling study also was formulated to be consistent with advice provided by the EPA in Report 1402 regarding the Christmas Creek LoM Expansion Project.

A short summary of the methods, results and key outcomes from the modelling study is provided as follows. Further detail is available in the study report (Appendix 10; Fortescue 2012b).

5.2.2 Methods

The HYDRUS software package was used to construct a vertical 2-dimensional variably-saturated model to simulate soil water dynamics and plant water uptake by samphire vegetation on the fringe of the Fortescue Marsh. The model was used to investigate the effect of groundwater drawdown on samphire vegetation root water uptake and transpiration. The 2D HYDRUS model can simulate multiple vegetation surfaces in 2D space.

The model domain was based on an approximately 1,200 m long transect aligned perpendicular to the topographic contour at a representative location south of the Christmas Creek mine, including open and closed *T. indica* subsp. *bidens* communities consistent with Units 2 and 3 of the conceptual ecohydrological model described in Section 5.1. Photographic examples of the landscape and vegetation from two transect lines selected to be represented in the model are provided in Figures 21 and 22. Transect 1 targeted an inter-drainage zone, whilst Transect 2 targeted the entry point of a nearby small drainage line. Both transects were located in close proximity to backhoe pits and EM38 survey areas.

As a conservative approach, the model was configured to ignore the potential contribution of run-on or flood waters to samphire water use. The lower boundary of the model domain was set to a constant head boundary simulating groundwater levels, whilst the upper boundary was the ground surface exposed to the atmosphere. The upper boundary consisted of two segments containing dense samphire (100% canopy cover; segment length 448 m) at the down-gradient end and sparse samphire (30% canopy cover; segment length 738 m) at the up-gradient end.

The HYDRUS model was parameterised using similar inputs to those in the Astron S&W (2012) study (Appendix 9), but with the following modifications and additional components:

- Three year (01/01/2009 to 31/12/2011) reference daily evapotranspiration data from the UWA weather station, located at the marsh fringe south of the Cloudbreak mine.
- A dynamic canopy interception model derived from other published studies (Dunkerley 2008; Wang *et al.* 2012). The static canopy storage value was conservatively estimated to be 1 mm.
- A two layer soil profile (Loam 0-40 cm overlying Clay Loam 40 cm to depth).
- Saturated hydraulic conductivity (K_s) of the top layer derived from K_s measured in mulga grove and inter-grove areas on the north side of Fortescue Marsh, in soils of similar texture (Heyting 2011). The mean of K_s values from the intergrove areas was selected (0.33 mm/day), as this was slightly lower than the mean of K_s values from grove areas and therefore may indirectly compensate for possible salinity effects on K_s in the surface soil layer of the marsh.
- A stepwise normalised root water uptake function derived from the measured distribution of *T. indica* subsp. *bidens* measured by Astron (2012a) at Area 31 in their study of mulga root system architecture (refer to Section 4.4 and Figure 16).
- Compensated and uncompensated root water uptake scenarios as per the methods described by Simunek & Hopmans (2009). Note also that the Feddes *et al.* (1978)

water stress reduction model was used to describe the relationship between soil water content and root water uptake, with parameters estimated based on based on physiological measurements of *T. indica* subsp. *bidens* plants in field and glasshouse experiments conducted by UWA (Section 4.1). The values were adjusted to reflect the influence of salinity-induced osmotic potentials that would be expected in the marsh soils.

- Calibration of samphire transpiration parameters using the UWA sap flow dataset for *T. indica* subsp. *bidens* (Section 4.1), based on derived relationships between estimated transpiration flux per unit land area (mm/day) and reference evapotranspiration (used to define K_{cb} values).
- Model validation against measured soil water contents in the profiles of UWA backhoe pits 1, 3 and 4 south of the Christmas Creek mining area (refer to Table 4 and Figure 14); yielding acceptable RSME values.

A total of seven scenarios were included in the modelling simulations:

I. 3-year wet weather spell at GWL of 404 mAHD (base case groundwater level);

II. 3-year wet weather spell at GWL of 403 mAHD (i.e. 1 m drawdown);

III. 3-year wet weather spell at GWL of 402 mAHD (i.e. 2 m drawdown);

IV. 3-year dry weather spell at GWL of 404 mAHD (base case groundwater level);

V. 3-year dry weather spell at GWL of 403 mAHD (i.e. 1 m drawdown);

VI. 3-year dry weather spell at GWL of 402 mAHD (i.e. 2 m drawdown); and

VII. 3-year dry weather spell at GWL of 401 mAHD (i.e. 3 m drawdown).

The 3-year daily rainfall sequences for both wet and dry climate regimes were selected based on proximity of the moving sum 3-year precipitations to the 5th and 95th percentile 3-year cumulative rainfalls in the cumulative rainfall probability curve, in accordance with the methods of Srikanthan *et al.* (2007).

Sensitivity analysis was conducted for key input parameters including:

- Increase plant coefficient K_{cb} by 50%, reflecting a greater level of samphire water use for a given level of evaporative demand;

- Increase static canopy storage for rainfall interception to 1.5 mm, reflecting a greater proportion of rainfall interception loss and hence less water available for plant root uptake;
- Reduce fractional canopy cover in the sparse samphire segment to zero (to simul.ate bare soil conditions);
- Increase effective wilting point to -700 mH_2O (base case value -1000 mH_2O), reflecting greater samphire susceptibility to drought stress;
- Use of an alternative root water uptake function; and
- Use uncompensated root water uptake, reflecting a lower ability of samphire to access soil water from the soil profile.

5.2.3 Results

The base case simulation results showed that the root water uptake under both wet and dry weather spells (3-year) was not substantially affected by groundwater drawdown of up to 3 m, and soil water content was maintained above the wilting point (-1000 mH_2O) at all times even under conditions of prolonged drought and groundwater drawdown (i.e. 3 years of dry weather with 3 m groundwater drawdown).

Under wet weather conditions and no groundwater drawdown, the water use requirements of the dense samphire were fully met by rainfall inputs (Figure 23 LHS). This scenario resulted in net groundwater recharge of about 100 mm/year over the 3-year simulation period. Under prolonged dry conditions and 2 m drawdown, shallow groundwater contributed to replenishing soil water in the dense samphire root zone (in the order of 30 to 40 mm/year over the 3-year simulation period) (Figure 23 RHS).

With respect to model sensitivities:

- For the most extreme drying scenario (VI) increasing K_{cb} by 50% reduced the average root zone water content to a level very close to water content at permanent wilting point.
- The model was relatively insensitive to effective wilting point, static canopy storage and root water uptake distribution.
- The use of the uncompensated root water uptake model did not induce significant stress in the dry climate scenarios, based on the time series trajectories of water

stress index (ratio of actual to potential transpiration), which was consistently greater than 0.5 and commonly greater than 0.7 under all tested scenarios.

- The use of the uncompensated root water uptake model in the wet climate scenarios was associated with periods of short spikes of low water stress index values that were related to the anaerobiosis effect of waterlogged surface soil layers immediately after rainfall events (as per the Feddes *et al.* (1978) root water uptake model). Given the high tolerance of the samphires and other marsh species to waterlogging under the natural flooding regime, this result was regarded as an artifact of the modelling approach and not considered to reflect a risk factor for the survival of samphire vegetation communities.

The study concluded that groundwater drawdown of up to 3 m would not introduce any significant adverse impact on the samphire communities near the northern fringes of the Fortescue Marsh. Based on the modelled cumulative fluxes of different mass balance components in dense and sparse samphire areas under the various scenarios tested, the modelling results indicate that samphire water use requirements are likely to be met by rainfall under all but extreme and prolonged dry climate regimes.

5.2.4 Model limitations

Environmental models inevitably simplify the highly complex processes that occur in real ecosystems. Of particular note, the HYDRUS model was not able to directly simulate the effects of salinity on soil hydraulic parameters and plant water uptake. The Fortescue marsh is highly saline environment, and osmotic pressure due to elevated soil water salinity acts to reduce the effective wilting point in plant-soil systems. Under low soil water conditions, osmotic gradients are often the dominant constraint on plant root water uptake. This issue was recognised in the modelling study, and the following steps were taken to indirectly account for salinity effects on plant water uptake:

- the samphire basal plant coefficient, K_{cb}, was estimated from measured sap flows/transpirations fluxes in Fortescue Marsh samphires growing under representative saline conditions south of the Cloudbreak mine site.
- The selection of model parameters, such as samphire wilting point and transpiration rates, were derived from UWA experimental data from plants growing under high saline conditions (refer to Section 4.1). A conservative approach to parameter section

was adopted to provide insurance against the potentially inhibiting effects of salinity on root water uptake.

5.2.5 Interpretation of model outputs

- The modelling study usefully complemented and built upon the growing body of knowledge underpinning the ecohydrological characterisation of the Fortescue Marsh and it keystone samphire communities.

- The modelling study used a widely used and globally recognised software package combined with model parameterisation and calibration approaches informed by site specific soil and plant water use data. The most extreme drying scenarios were in excess of the predicted effects of orebody dewatering made for the Christmas Creek LoM project, and parameter selection was deliberately conservative. A range of models sensitivities including key parameters were tested.

- As a conservative measure, the model did not take into account lateral water inputs to the vegetation water balance, including floodwaters and run-off from up-gradient areas. However the landscape has many features suggesting that these processes are likely to supply additional water to vegetation growing at the marsh fringe.

- For these reasons, the study results provide confidence that drawdown of up to 3 m below baseline groundwater levels associated with the Christmas Creek LoM Project is unlikely to result any significant impacts on samphire survival and health.

- A key factor underpinning the modelling results was the low samphire transpiration flux measured in the UWA field trials. To further test and validate the model findings, additional measurements of samphire transpiration flux under field conditions would be valuable (principally in the *T. indica* subsp. *bidens* communities which have the highest potential exposure to mining related disturbances).

6 Potential impacts on the Fortescue Marsh and their management – a preliminary assessment

6.1 Overview of the Christmas Creek LoM Expansion Project

Mining at Christmas Creek commenced in 2008 and is subject to Ministerial Statements 707 and 871. Based on information provided to Equinox by Fortescue, the key characteristics of the currently approved project are summarised in Table 6. Note that Statement 707 also provided for mining at the Mindy Mindy deposits located approximately 70 km north of Newman and south of the Fortescue Marsh, however this project component has not been implemented at present.

The Christmas Creek LoM Expansion Project involves redefining the life-of-mine plan at the Christmas Creek iron ore mine (Table 6). This includes a series of additional pit developments, waste dumps, haul roads, dewatering infrastructure and a proposed above ground ore conveyor. It is proposed that the life-of-mine plan will be implemented over about a 15 year period (2013-2028). The initial development is concentrated around the existing disturbed area and gradually extends eastwards into the hilly terrain of the Chichester Range. This is followed by a westward expansion onto flat terrain south of the Chichester Range.

About 70% of the iron ore reserves at Christmas Creek are below the watertable (Fortescue 2012a). The Christmas Creek LoM Expansion Project may require modification to the current water management scheme approved under Statement 871, based on expanded below watertable mining. The current water management scheme stipulates limited dewatering and injection volumes (dewatering and injection rates of up to 50 GL/a and 42.5 GL/a respectively) for a limited time period (5 years). Higher rates of dewatering (up to 70 GL/a) and injection are anticipated under the life-of-mine plan.

Table 5 Key characteristics of the current Christmas Creek mining operation

Element	Statement 707 (as amended) relating to mining at Christmas Creek.	Statement 871	Proposed Christmas Creek LoM Expansion Project (as at September 2013)
Summary and main activities	The proposal encompassed open pit iron ore mines at Christmas Creek and Mindy Mindy, a beneficiation plant at Christmas Creek, a borefield and an east-west railway to link the Stage A north-south railway to Port Hedland with the Christmas Creek mine site. Iron ore strip mining, pit backfilling, ore crushing, beneficiation (at Christmas Creek), mine rehabilitation and closure.	Increase the dewatering rate up to 50 GL/a, with the injection of surplus water into two brackish and one saline injection zones at the Christmas Creek Mine.	This proposal is to redefine the life of mine plan at the Christmas Creek iron ore mine. Proposed changes include increasing ore production, developing new mine infrastructure and increasing dewatering and water disposal activities over the extended life of the mine.
Resource	Christmas Creek: 1,000 million tonne Marra Mamba ore (average pit depth 60 m).		
Contingent activities	Pit dewatering, ore transport by 119 km east-west rail link to approved north-south railway to Port Hedland for export or via road to Cloudbreak for transport to Port Hedland for export.	Increase the dewatering rate up to 50 GL/a. Injection of up to 42.5 GL/a surplus water into two brackish and one saline injection zones at the Christmas Creek Mine.	Increase the dewatering rate up to 70 GL/a. Injection of up to 58 GL/a surplus water into two brackish and one saline injection zones at the Christmas Creek Mine.

Element	Statement 707 (as amended) relating to mining at Christmas Creek.	Statement 871	Proposed Christmas Creek LoM Expansion Project (as at September 2013)
Areas disturbed	• Christmas Creek – up to 10,135.5 ha (including not more than 132 ha within the access/transport route between the Christmas Creek mine site and Marble Bar Road). • Mindy Mindy – 852 ha • Railway including associated infrastructure and sections of duplicate rail – 1,702 ha	Up to 600 ha (of the 10,135.5 ha approved hectares in Statement 707)	Approximately up to an additional 7,000 ha in a 25,022 ha disturbance envelope.
Water requirements	11.4 GL/a or 31.2 ML/day from borefield to be developed.	12 GL/a	Not confirmed – currently under assessment.

6.2 Groundwater drawdown

Drawdown refers to the lowering of the natural watertable caused by groundwater abstraction. Drawdown is generally most pronounced at the point of abstraction and diminishes with distance from the abstraction point. The magnitude and extent of drawdown is dependent on the rate and duration of abstraction, the hydraulic properties of the aquifer being pumped, and relationships between the pumped aquifer and the surrounding groundwater system. Geological heterogeneity and variable aquifer interconnectivity can strongly influence flow behavior, and consequently the magnitude and extent of drawdown, in complex groundwater systems (Eaton 2006; Giambastiani *et al.* 2012).

Drawdown at the margins of the Fortescue Marsh associated with the Christmas Creek LoM Expansion Project is predicted to occur indirectly, via the propagation of hydraulic head changes through the complex local groundwater system. The mechanism of drawdown involves the processes depicted diagrammatically in Figure 24 and further described as follows:

- Abstraction of groundwater will occur from the orebody aquifer.
- Drawdown will occur in the overlying Tertiary Detritals, which have strong hydraulic connection with the underlying orebody aquifer.
- Dewatering of the Oakover Formation will occur subject to its variable connection with the orebody aquifer.
- Dewatering and drawdown of the shallow Fortescue Marsh aquifer (in the Tertiary alluvium/colluvium) at its northern fringe, via leakage to the underlying dewatered Oakover Formation. This process is expected to be impeded by the low hydraulic conductivity of the Tertiary clay layers overlying the Oakover Formation.
- Injection of surplus water into brackish and saline aquifer zones will reduce the overall extent of drawdown, by up to approximately 2 m near the marsh fringe (Fortescue 2012a).

Fortescue has assessed the effect of increased dewatering and injection activities using FEFLOW(v6), a 3D finite-element groundwater flow and transport modeling tool (Fortescue 2012a). The model includes the major stratigraphic layers of hydrogeological importance as depicted in Figure 6. The modelling results predict that groundwater drawdown along the Fortescue Marsh edge will be less than 1 m in the first ten years of the project, and increase to about 1 - 2 m in the last three years of mining (2026-2028). This finding was consistent across a wide range of model parameter sensitivities. Changes of this magnitude are less than the magnitude of natural fluctuations in groundwater levels that occur at the marsh fringe based on Fortescue's historical bore records (Fortescue 2012a).

Injection of water that is surplus to operating requirements will partially offset the effects of drawdown, and is essential to prevent more significant drawdown near the Fortescue Marsh fringe (Fortescue 2012a). Surplus water will be segregated into brackish and saline management streams, and injected into aquifers with similar hydrochemical characteristics.

The drawdown predicted to result from the Christmas Creek LoM Expansion Project is unlikely to significantly impact on the values of the Fortescue Marsh for the following reasons:

- The vast majority of the marsh will not be affected.
- Drawdown of up to 2 m is within the range of natural water level fluctuations experienced at the marsh boundary.
- Drawdown of up to 2 m is not predicted to significantly affect the ecological water requirements of samphire fringing communities dominated by *Tecticornia indica* subsp. *bidens* (Fortescue 2012b).
- Drawdown is not predicted to extend to *Melaleuca glomerata* and samphire vegetation communities with potential and/or unknown dependence on the shallow aquifer.
- The ability of the marsh to support breeding populations of waterbirds following episodic flooding would not be significantly affected.
- Habitat for other fauna, including that of species with conservation significance and aquatic fauna, will not be significantly affected.
- The zone of drawdown does not include any persistent or permanent waterbodies, such as yintas.

6.3 Groundwater mounding

Groundwater mounding refers to the outward and upward expansion of watertables resulting from groundwater injection or surface recharge mechanisms (e.g. beneath a river, lake or unsealed dam). In the case of injection, mounding can occur:

- directly around the injection point in shallow, unconfined aquifers.
- indirectly via hydraulic displacement of water through more complex groundwater systems, resulting in hydraulic head changes more distant from the injection point.

The extent of mounding is affected by the rate and duration of injection. However as with drawdown, the manifestation of mounding is also influenced by groundwater system complexity. Intrinsic factors with the potential to affect mounding include prevailing hydraulic gradients, preferential flow paths, the effects of density and osmotic gradients, and dispersive mixing.

The Christmas Creek LoM Expansion Project is predicted to result in net drawdown extending widely beyond the mine pits, after taking into account brackish and saline injection volumes. Groundwater mounding is expected to be limited to small areas and will remain well below the land surface (Fortescue 2012a) based on:

- the anticipated injection volumes and injection rates.
- the depth of injection with the hydrostratigraphic sequence (no shallow injection will occur into unconfined aquifers in the Tertiary detritals).
- the hydraulic properties of the Oakover Formation, which is highly permeable and has a storage capacity that is much larger than the proposed injected volumes.
- the low hydraulic conductivity of the Tertiary Clays, which overlie the areas where saline injection bores will be located.

Consequently no significant influences or impacts on the Fortescue Marsh vegetation communities, or other vegetation types of conservation interest such as the mulga communities fringing the marsh, are anticipated.

6.4 Groundwater quality

Water management associated with the Christmas Creek LoM Expansion Project has the potential to affect the distribution of salinity in the local groundwater system. In particular the injection of saline water into fresh or brackish aquifers could affect the suitability of the receiving aquifers for stock drinking water and other beneficial uses.

The approach of segregating injection water into brackish and saline streams, and injecting these into deep aquifers with similar hydrochemical characteristics, will largely mitigate potential water quality impacts. In EPA Report 1402 addressing the Christmas Creek Water Management Scheme the EPA identified that "*Impacts to groundwater due to the migration of the saline transition zone are considered unlikely as altered salinity will occur predominantly in the deeper aquifers near mining areas. The introduction of saline water into the fresh-brackish Tertiary Detritals is not expected as this zone is isolated from the saline water by a clayey aquitard overlying the Oakover Calcrete* [i.e. Tertiary Clay]. *In addition to the protective effects of the clayey aquitard, the Tertiary Detritals are resistant to saline water intrusion due to the* [Tertiary] *Detritals" low permeability and high water storage properties*" (EPA 2011). In EPA Report 1429 addressing the Cloudbreak LoM Expansion Project the EPA similarly identified that "*Injected saline water will enter the saline aquifer at depths well below the water table and, given the calcrete aquifer has much higher permeability than the overlying tertiary detritals, the flow will be lateral rather than upward. The chemical composition of water at the water table near the Fortescue Marsh is therefore not expected to be changed by the injection process*" (EPA 2012).

The Christmas Creek LoM Expansion Project does not involve a significantly different approach to water management in comparison with the currently approved mining operation, and therefore is not anticipated to require alternative EPA assessment. No significant impacts on groundwater quality in the Fortescue Marsh or surrounding areas are anticipated.

6.5 Modified surface flow regime

Mining and infrastructure development associated with the Christmas Creek LoM Expansion Project will disturb the surface flow regime north of the Fortescue Marsh. Surface water control structures will be required to direct and/or control flows around mine pits and other infrastructure. Fortescue has developed systems and procedures to minimise the downstream impacts of modified hydrology, as described in the Fortescue Chichester Operations Surface Water Management Plan (Fortescue 2009).

The effects of modified surface flows on the water balance of the Fortescue Marsh and Christmas Creek LoM project area were recently assessed by Worley Parsons (2012). This study used hydrological modelling techniques to evaluate:

- Hydraulic changes to the drainage network north of the Fortescue marsh resulting from mine pits, waste dumps and associated infrastructure development.
- Potential disturbance to sheetflows in areas containing banded mulga vegetation (i.e. caused by throughflow shadow effects).
- Changes to the Fortescue Marsh water balance resulting from modified inflows entering from the Chichester Range catchments. This component considered potential cumulative impacts arising from the Cloudbreak, Christmas Creek and Roy Hill mining developments.

The modelling study assumed that all management measures detailed in the Chichester Operations Surface Water Management Plan would be implemented: such as the restoration of downgradient sheet flows within a 45^0 flow dispersion angle from disturbance (direct impact) zones. The key findings of the study were (Worley Parsons 2012):

Potential impacts on Mulga vegetation

- Significant changes to flow depths and velocities will be confined to major waterways within the mining development zone. No significant hydraulic changes in sheetflow areas, or downstream areas of distributed flow immediately north of the Fortescue Marsh, were apparent in areas outside directly impacted areas[25].

[25] i.e. areas anticipated to be subject to ground disturbance activities.

- Up to 920 ha of banded mulga vegetation at any point in time is predicted to potentially be exposed to sheet flow shadowing over the life of the project. Note that some areas exposed to shadowing will subsequently be developed for mining (i.e. directly impacted).

  Up to 21% of banded mulga vegetation could fall within the project clearing footprint, out of a total pre-disturbance amount of 7,400 ha within the project area. In addition, up to 13% of banded mulga vegetation in the project area may be indirectly impacted through exposure to shadowing effects (i.e. in areas not to be cleared).
- The combined Cloudbreak, Christmas Creek and Roy Hill mine developments (combined pit area of 190 km^2) are unlikely to significantly affect the Fortescue Marsh water balance. The modelled reductions on marsh inflow resulting from these projects on average did not exceed 1% of total inflow.

It is important to recognise that the effect of surface flow shadowing on mulga is difficult to predict. In the Cloudbreak LoM Project assessment, the EPA adopted a highly conservative approach and assumed that all mulga communities exposed to shadowing will contribute to a residual environmental impact requiring an offset (EPA 2012). This approach presupposes that the values of the mulga communities exposed to shadowing will be irreversibly lost; however impacts of this magnitude have not been demonstrated in historical situations where surface hydrology in mulga communities has been disturbed.

Potential impacts on Fortescue Marsh inflows

Disruptions to the surface flow regime north of the Fortescue Marsh predicted to result from the Christmas Creek LoM Expansion Project are unlikely to significantly impact on the values of the marsh for the following reasons:

- The vast majority of the marsh will not be affected by modified surface hydrology, including marsh vegetation and fauna habitat.
- At a local scale, minimal effects on marsh inflows from the distributed drainage network are expected near the northern fringe of the marsh. Changes to the flow regimes of individual drainage outlets are likely to be modest (i.e. no substantive reduction in or complete cessation of flows). Such flow disruptions are unlikely to significantly impact on the ecological water requirements of samphire fringing

communities dominated by *Tecticornia indica* subsp. *bidens* based on the modelling findings discussed in Section 5.2 (Fortescue 2012b).

- Regional scale flooding events dominate the marsh inflows, and contribute to the ecohydrological functioning of the marsh by flooding fringing vegetation areas and replenishing soil water stores as described in Section 5.1 and Figure 19. Reductions to marsh inflow resulting from the project will be less than 1% of average total inflow (Worley Parsons 2012); and therefore have a minimal effect on marsh ecology and ecohydrological processes. For example, the ability of the marsh to support breeding populations of waterbirds following episodic flooding is unlikely to be affected.

7 Conclusions

Since the commencement of mining of the Chichester iron ore deposits in 2008, Fortescue has accumulated significant knowledge and information relating to the ecohydrological aspects of the Fortescue Marsh. This knowledge has been gained through a combination of targeted investigations, hydrological modelling and general operational experience/observations.

A conceptual ecohydrological model of the Fortescue marsh fringe south of the Christmas Creek LoM Project area has been developed; based on the collective findings of studies addressing landform and soil profiles, surface hydrology, groundwater systems, vegetation types and distribution, and samphire vegetation water use and eco-physiology. This work suggests that the water balance dynamics of the Fortescue Marsh are principally controlled by surface water inflows from the greater marsh catchment, as dictated by episodic flooding events. The flood events replenish a shallow aquifer system in the Tertiary sediments beneath the marsh, which is gradually depleted by direct surface evaporation and evapotranspiration by the fringing vegetation communities. In periods of prolonged drought, the shallow watertable reaches a pseudo-steady state set by the evaporation extinction depth in the lowest parts of the marsh basin. The fringing vegetation is dominated by samphire communities which exhibit zonal species distribution patterns influenced by soil water and salinity dynamics, depth to watertables and flooding frequency.

The Christmas Creek LoM Expansion Project is predicted to cause drawdown of up to 3 m in the shallow aquifer near the marsh fringe, in association with dewatering of the Marra Mamba orebody aquifer. Fortescue has evaluated the potential effects of this amount of drawdown on the fringing samphire communities dominated by *Tecticornia indica* subsp. *bidens*, which occur with the span of the drawdown footprint. This has included numerical modeling of samphire water use dynamics at the Fortescue Marsh fringe south of the Christmas Creek mining area (using HYDRUS). In combination with empirical observations, in particular *T. indica* subsp. *bidens* demonstrated ability to tolerate drought and other stressors, the findings of the modelling study suggest that the ecological water requirements of the fringing samphire communities are wholly or predominantly met by surface inputs. The findings provide confidence that the predicted drawdown will not significantly affect samphire survival and health.

Based on a preliminary assessment, it is also predicted that other potential groundwater system impacts associated with the project water management strategy, such as injection mounding and water quality changes, are unlikely to be significant.

Mining and infrastructure development associated with the Christmas Creek LoM Expansion Project will disturb the surface flow regime north of the Fortescue Marsh, within a zone of relatively stable channel systems occasionally separated by sheetflow areas. The divergent channel drainage network downstream from these areas will remain largely unaffected by mining disturbances. Assuming effective implementation of the Fortescue Chichester Operations Surface Water Management Plan, minimal disruption to the downstream flow regime at the marsh fringe is expected. Where changes to the flow regimes of individual drainage outlets occur, these are predicted to be modest and unlikely to significantly affect the ecological water requirements of the Fortescue Marsh samphire communities.

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Figures

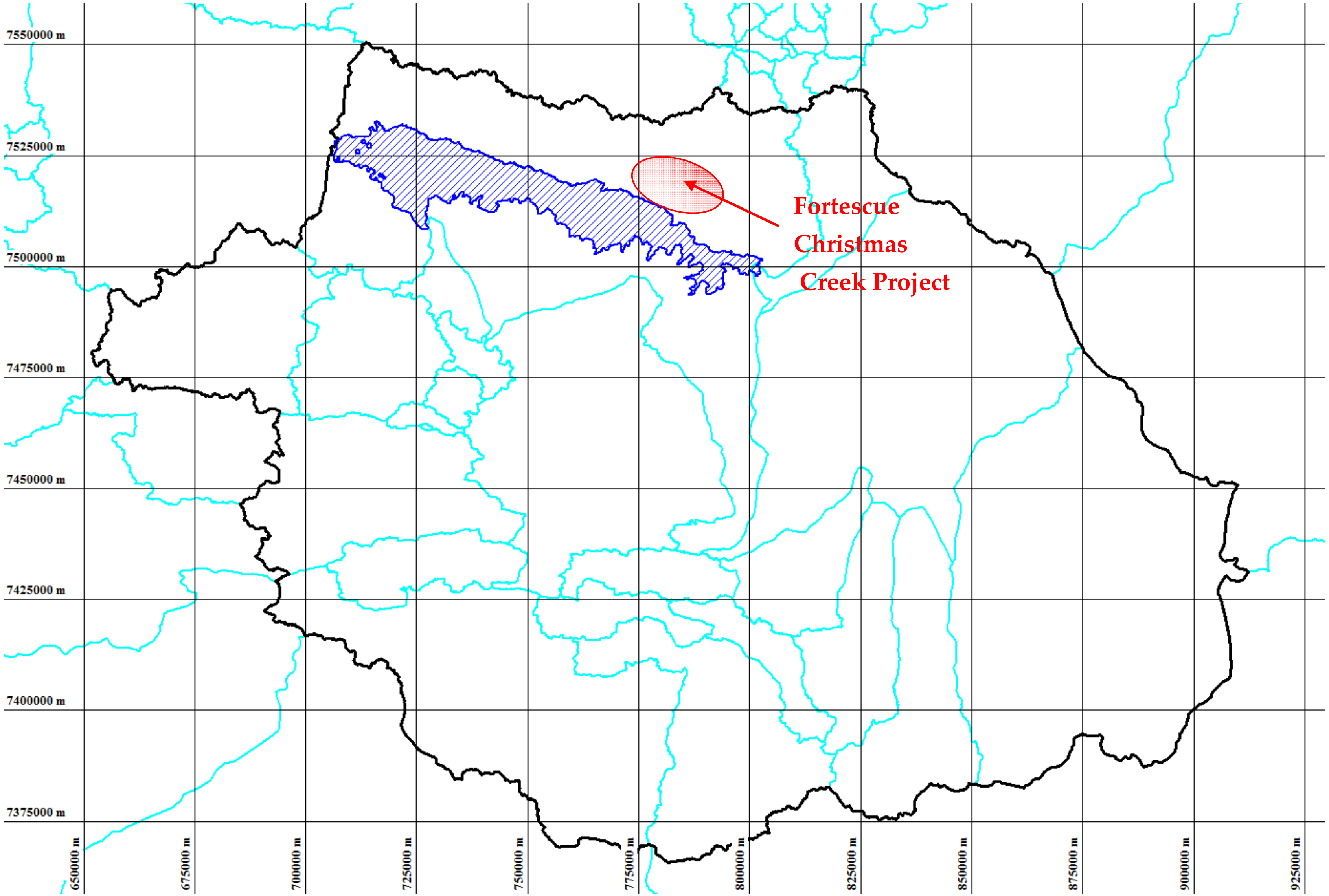


Figure 1 **Location of the Fortescue Marsh and its catchment/sub-catchments**

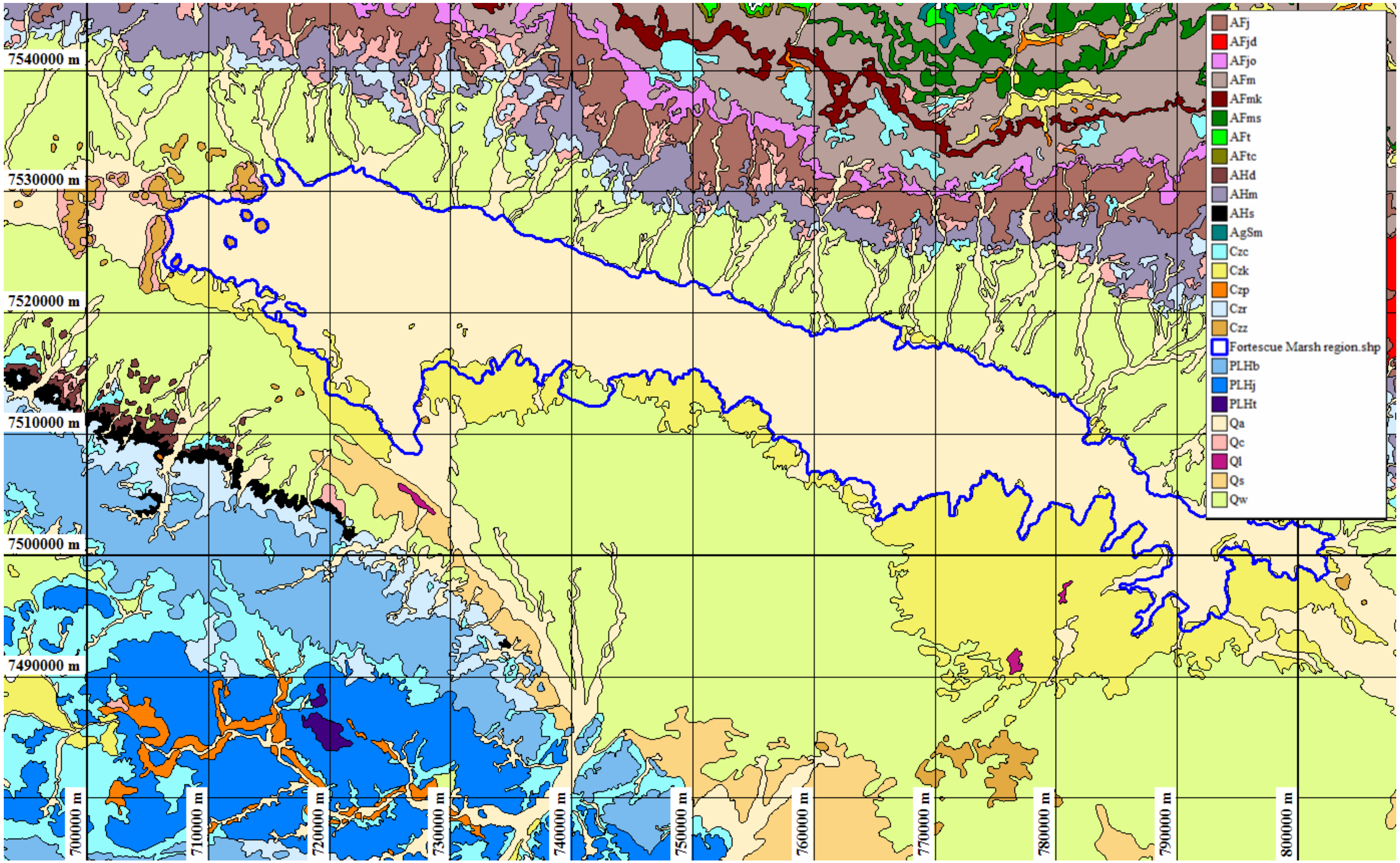


Figure 2 Surface geology of the Fortescue Marsh locality[26]

[26] refer to Appendix 2 for descriptions of geological codes

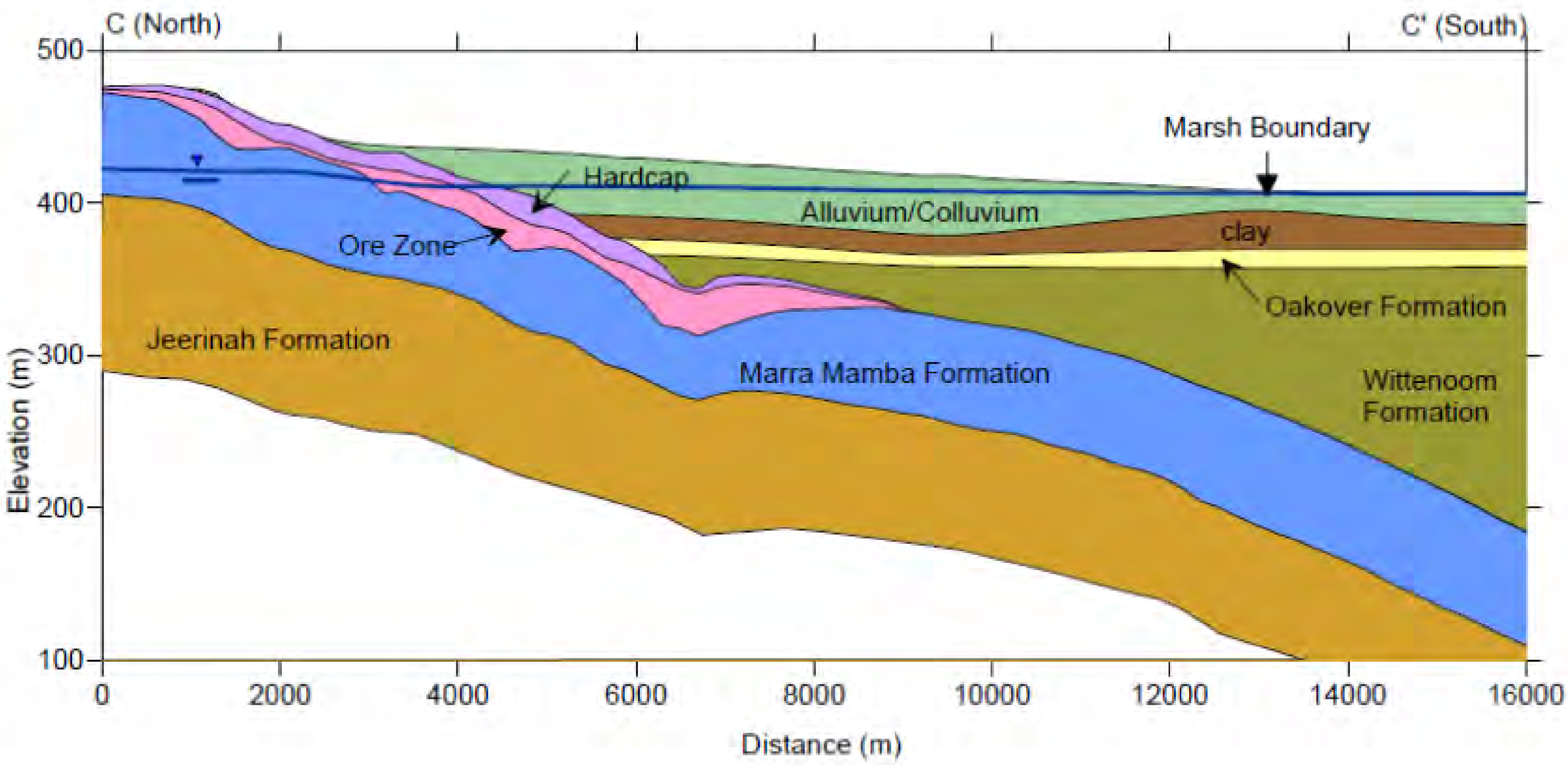


Figure 3 Generalised stratigraphic profile of the Christmas Creek locality (reproduced from Fortescue 2012a)

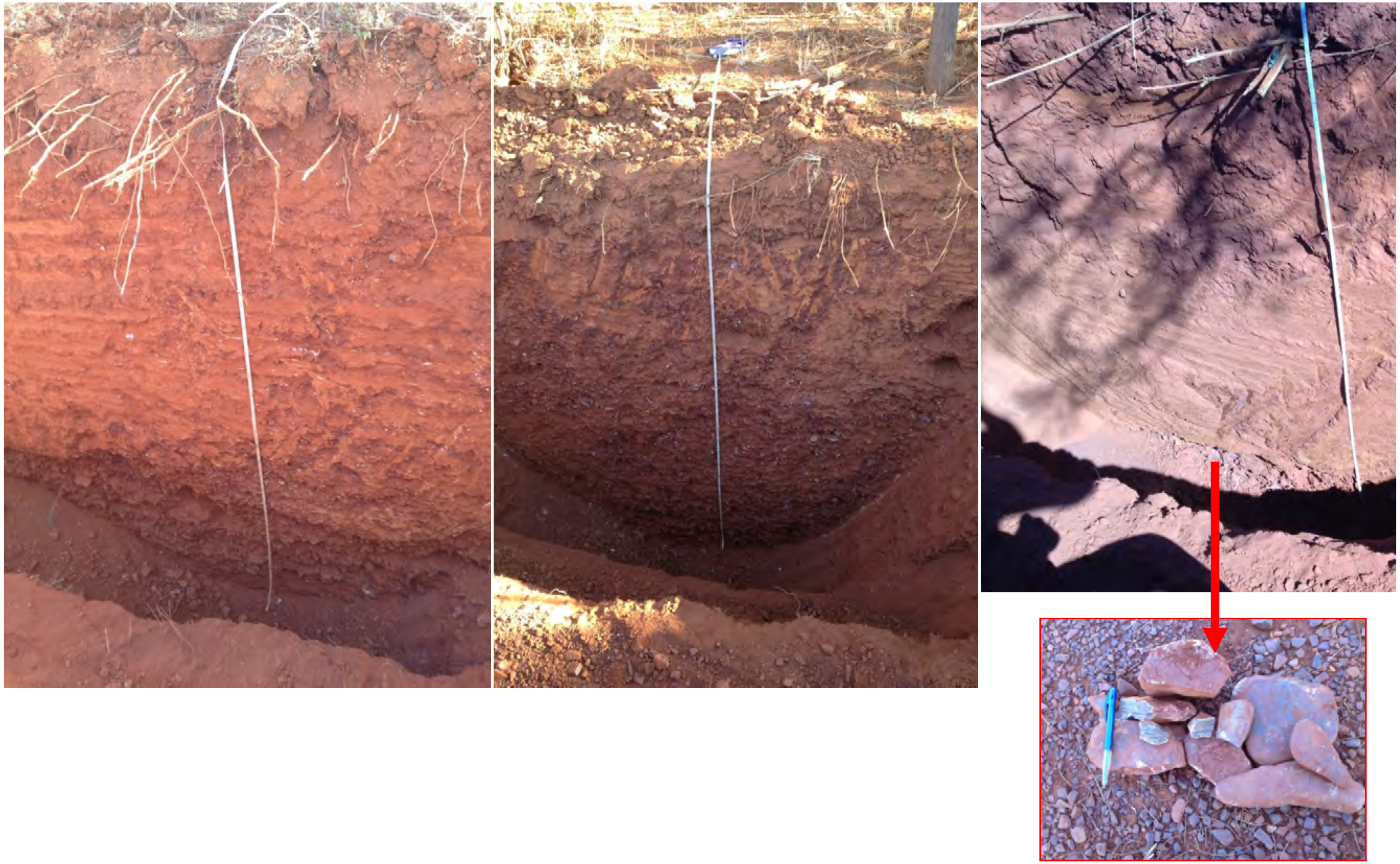


Figure 4 Soil profiles in mulga lined drainage tracts north of the Fortescue Marsh, showing cobble layers at depth

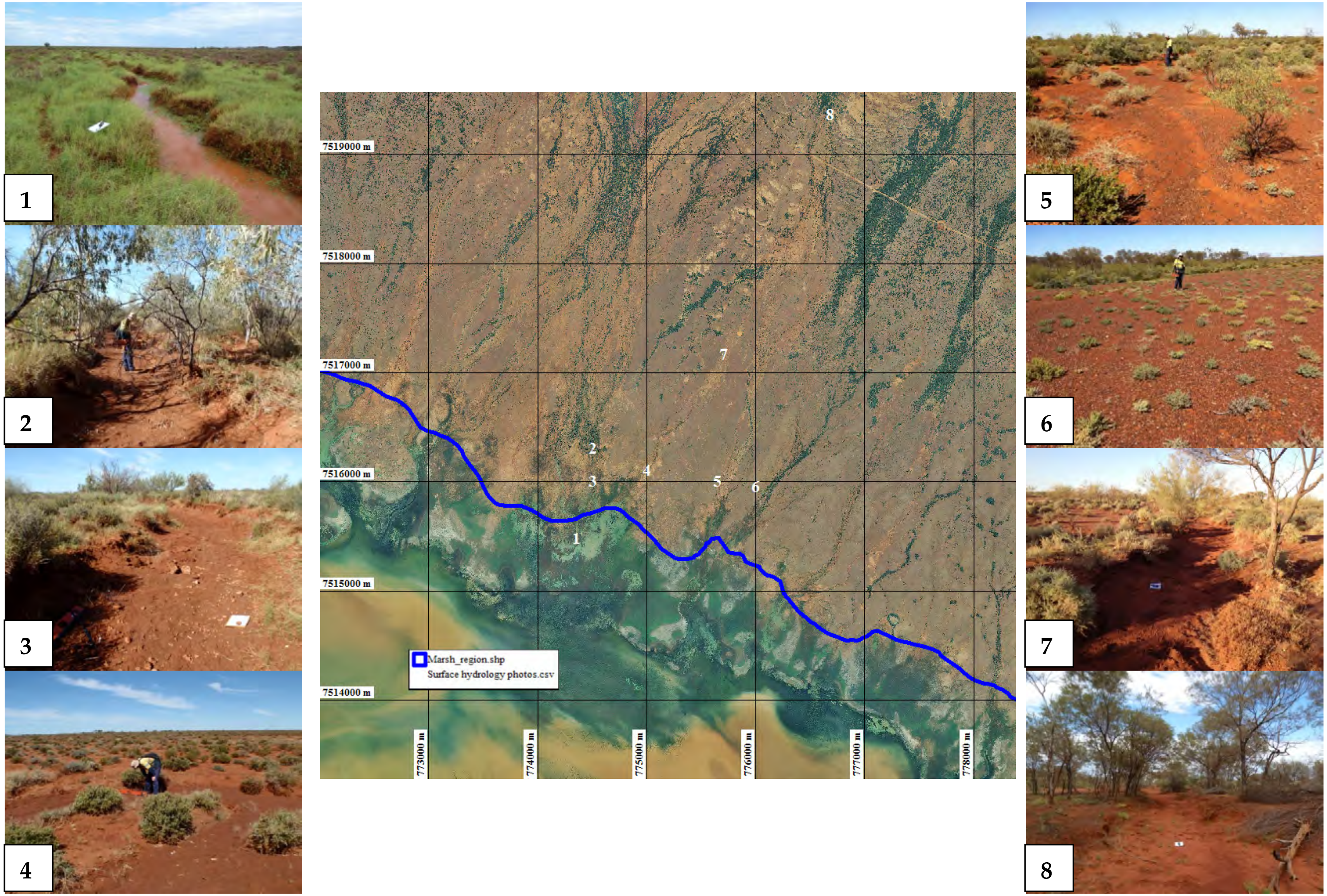


Figure 5 Drainage features in and near the Fortescue Marsh south of Fortescue's Christmas Creek operations

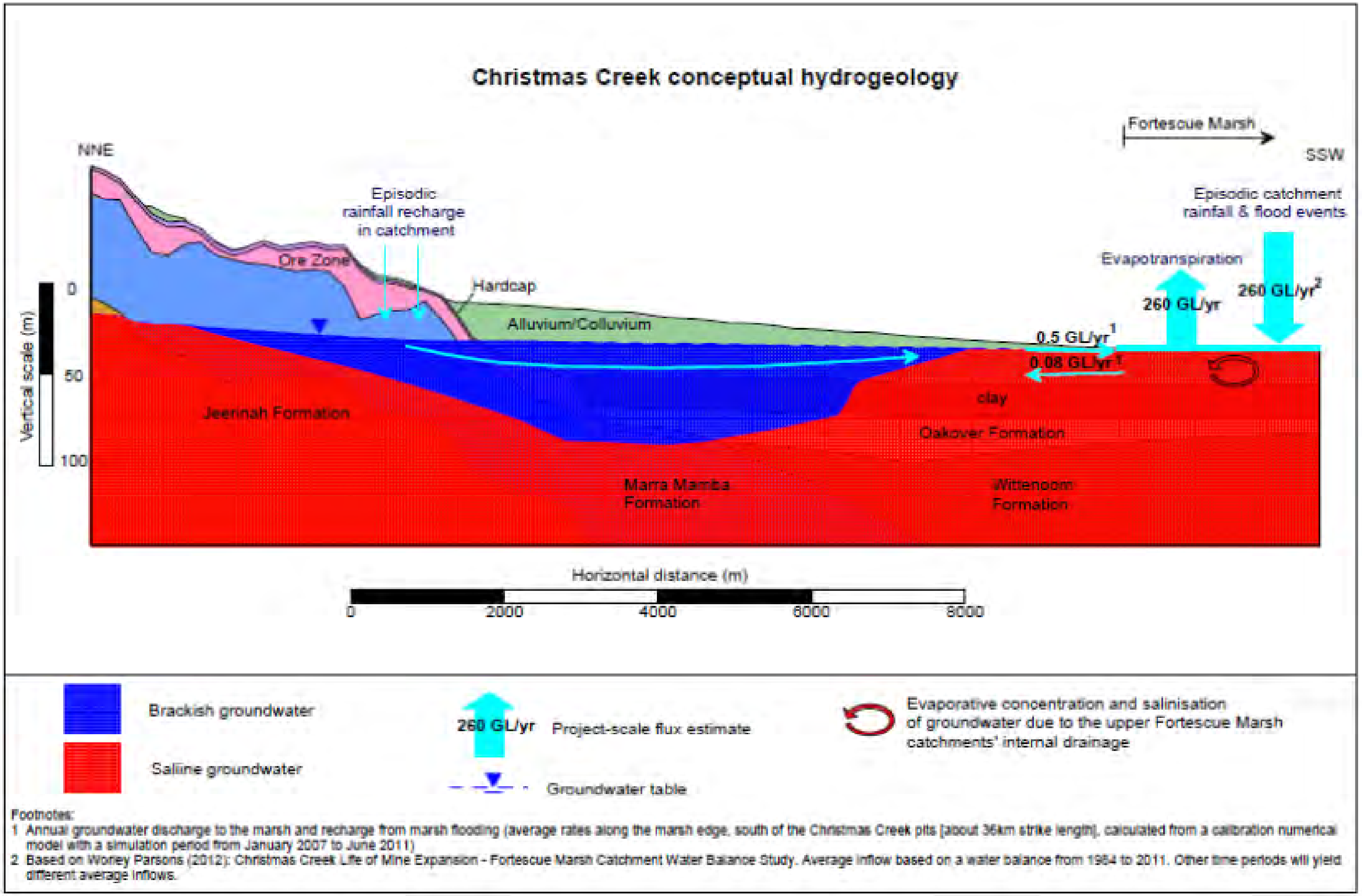


Figure 6 Conceptual hydrogeological model of the Christmas Creek locality (reproduced from Fortescue 2012a)

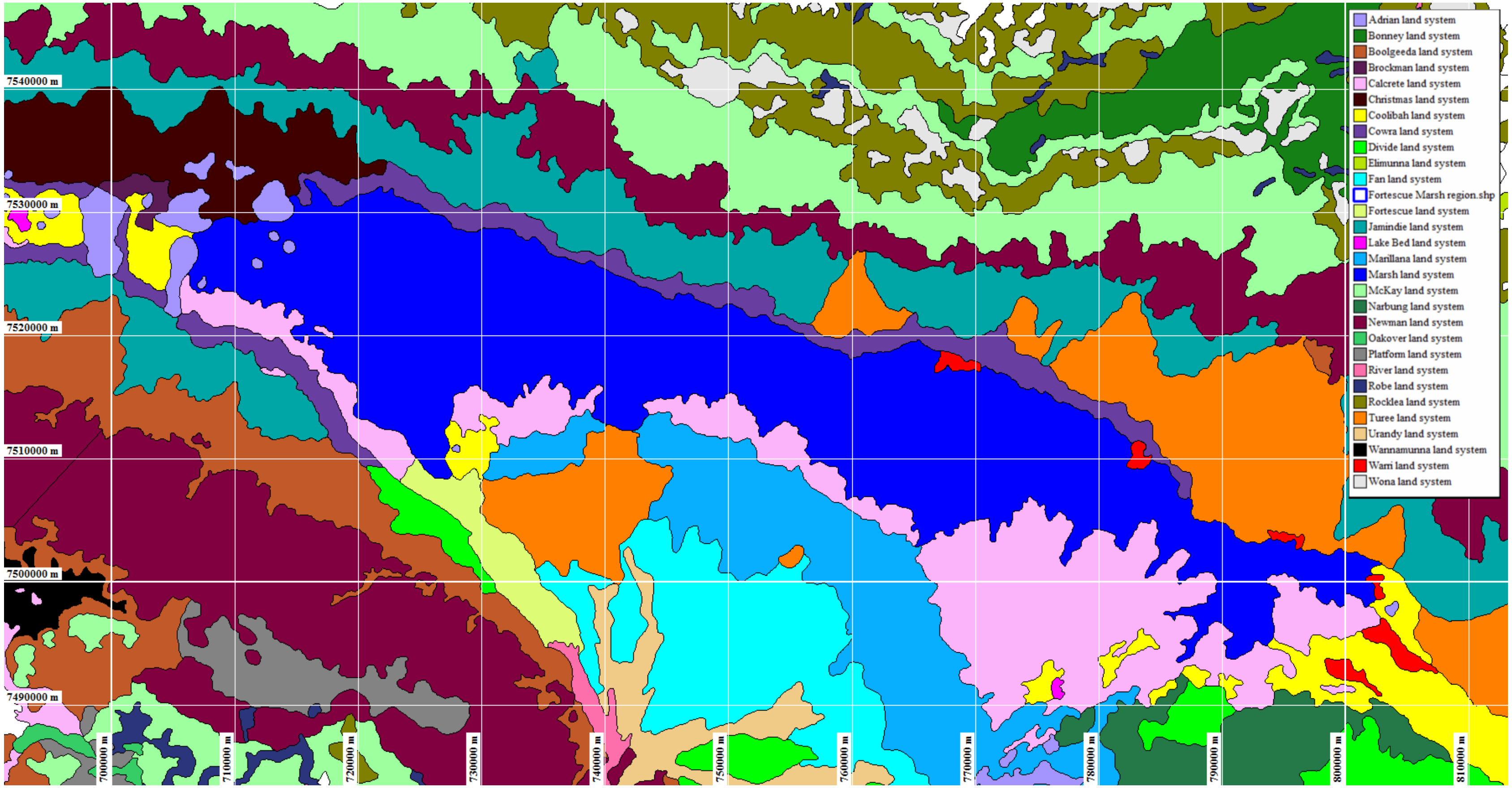


Figure 7 Land systems in the Fortescue Marsh locality

Sampling the soil profile – UWA Pit 9

UWA Pit 9 - Soil profile with massive, impenetrable silcrete at depth (inset)

UWA Pit 1

UWA Pit 4

UWA Pit 3

Figure 8 Representative soil profiles at the northern fringe of the Fortescue Marsh (top row south of Cloudbreak mining area; bottom row south of Christmas Creek mining area)

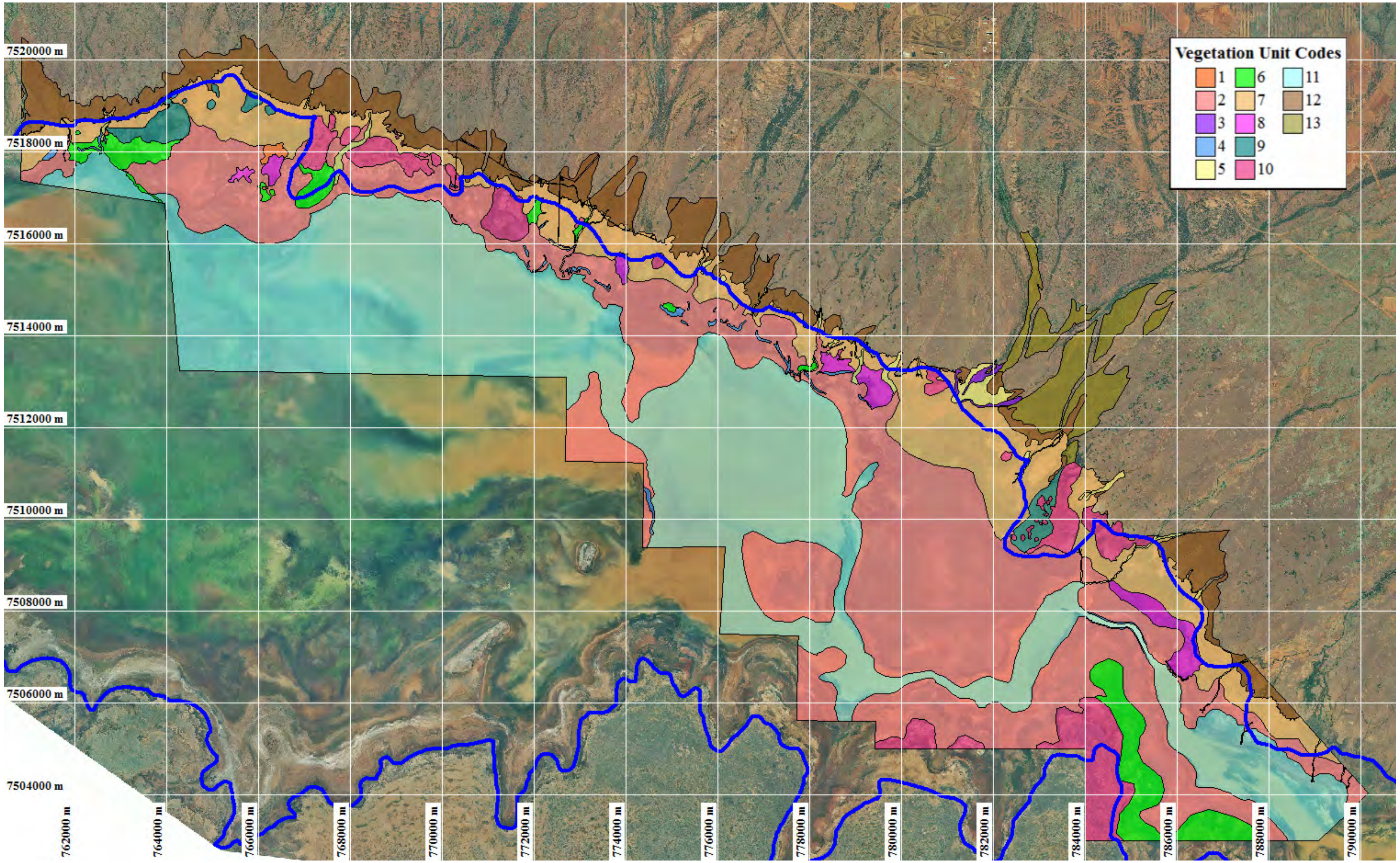


Figure 9 Fortescue Marsh vegetation mapping units south of the Christmas Creek LOM Expansion Project area. (refer to Section 2.8 for unit code descriptions)

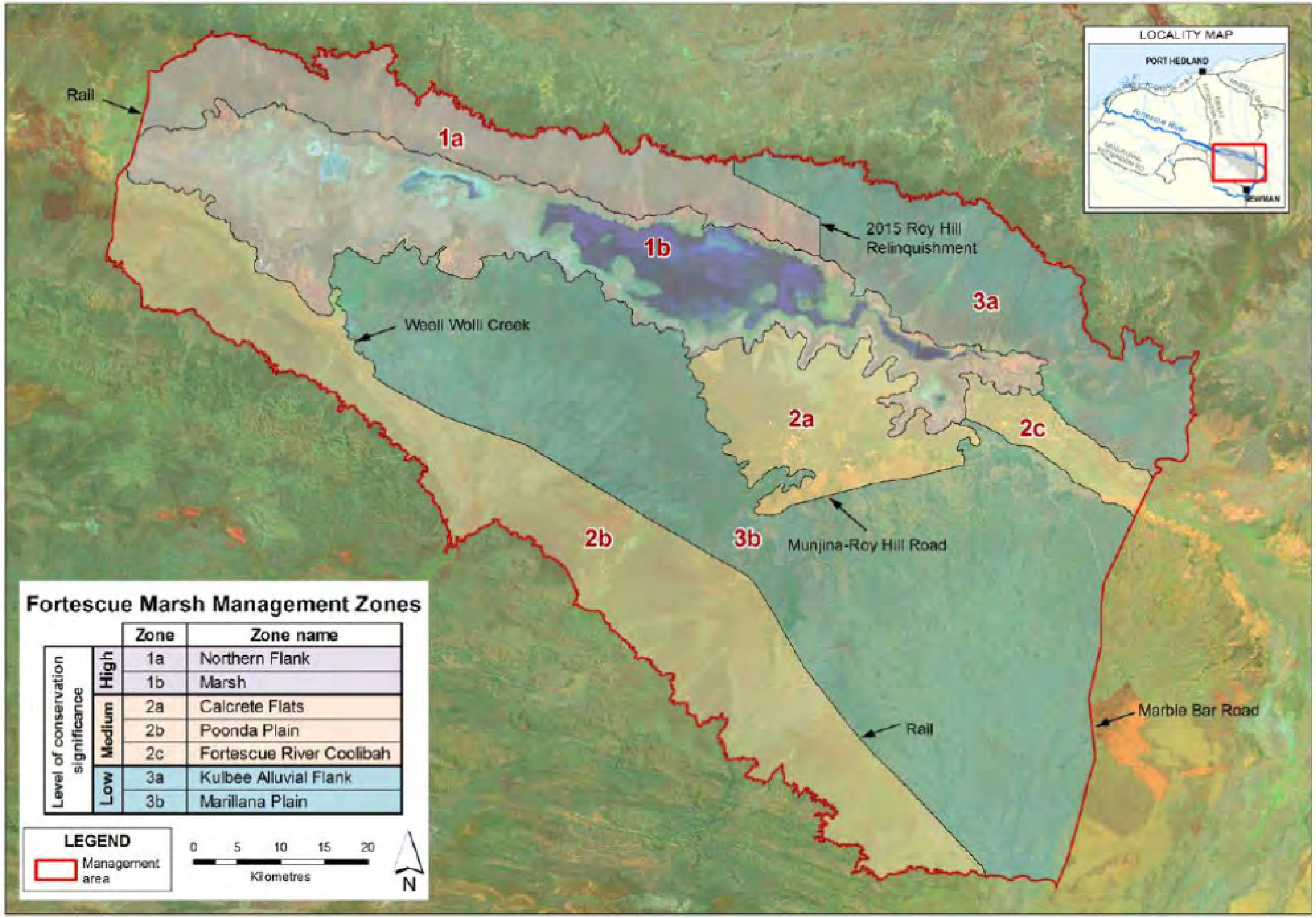


Figure 10 Fortescue Marsh management zones (reproduced from EPA 2013)

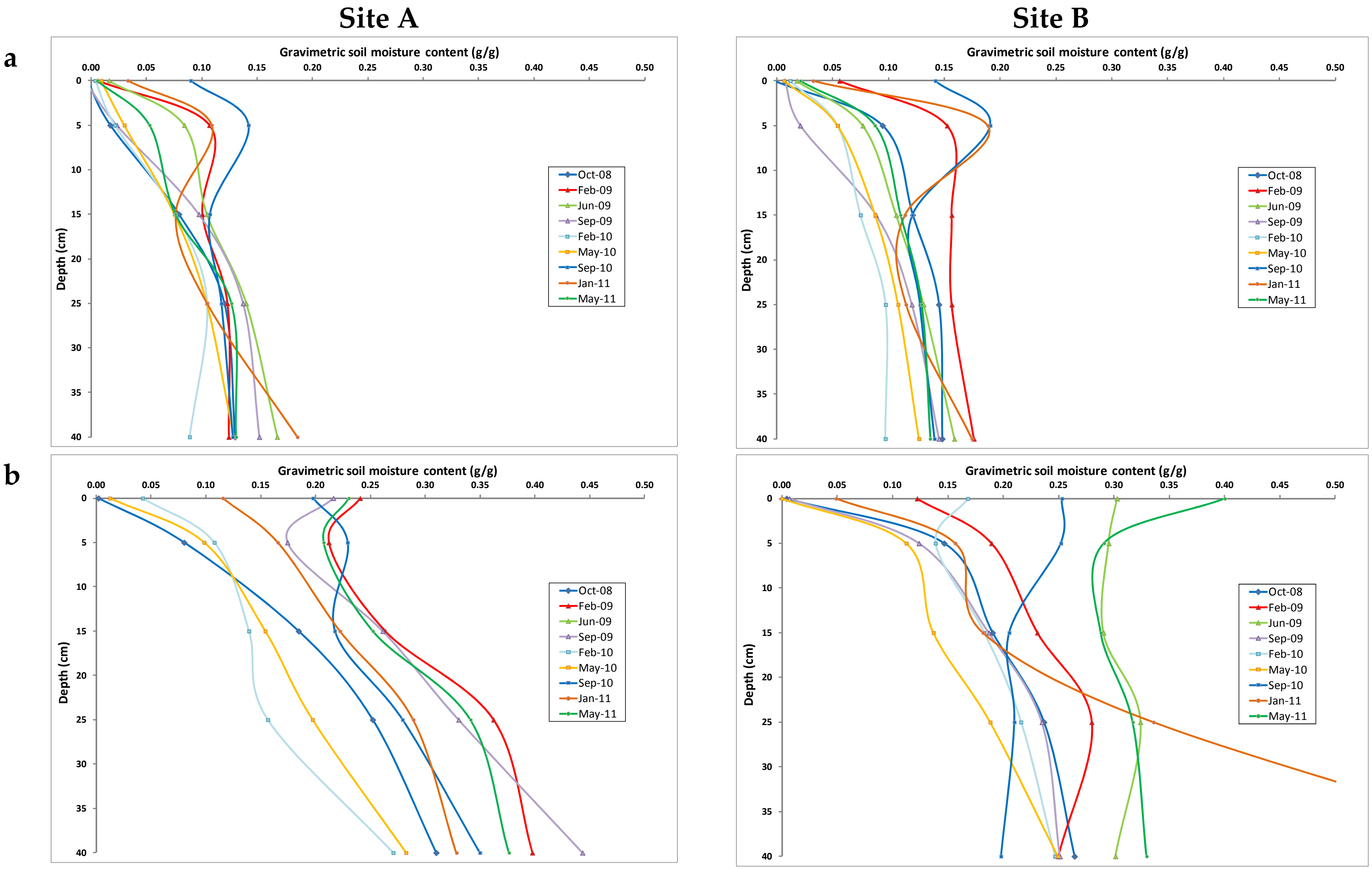


Figure 11 Changes in soil moisture in the period 2008-2011 at the UWA research plots a) *Tecticornia indica* subsp. *bidens* b) *T. mdeusa*

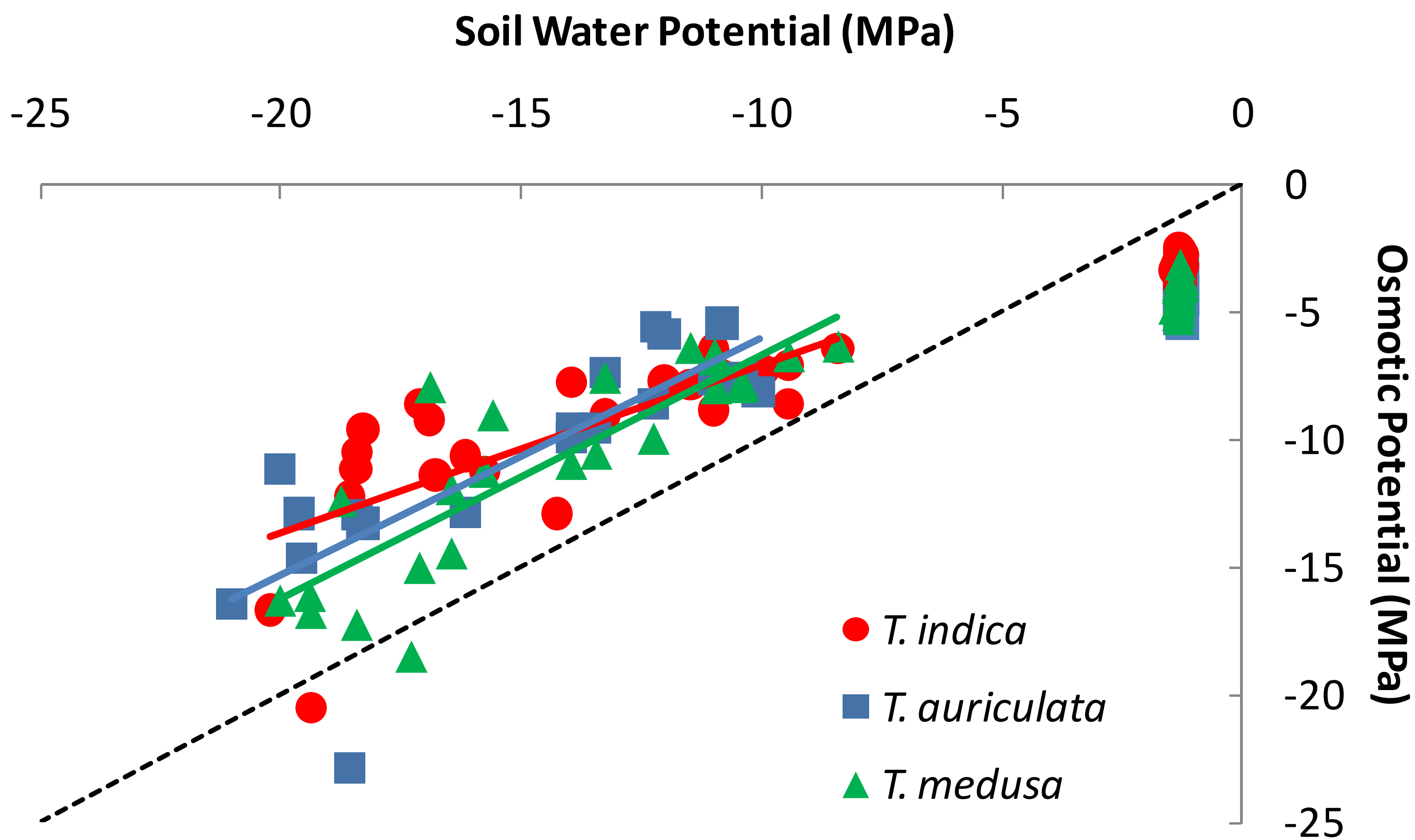


Figure 12 **Relationship between soil water potential and tissue osmotic potential for three *Tecticornia* species under drought stress (34 and 48 days of drought) in the 2012 expanded glasshouse experiment. All regressions were statistically significant at $P<0.05$ (reproduced with permission from UWA School of Plant Biology)**

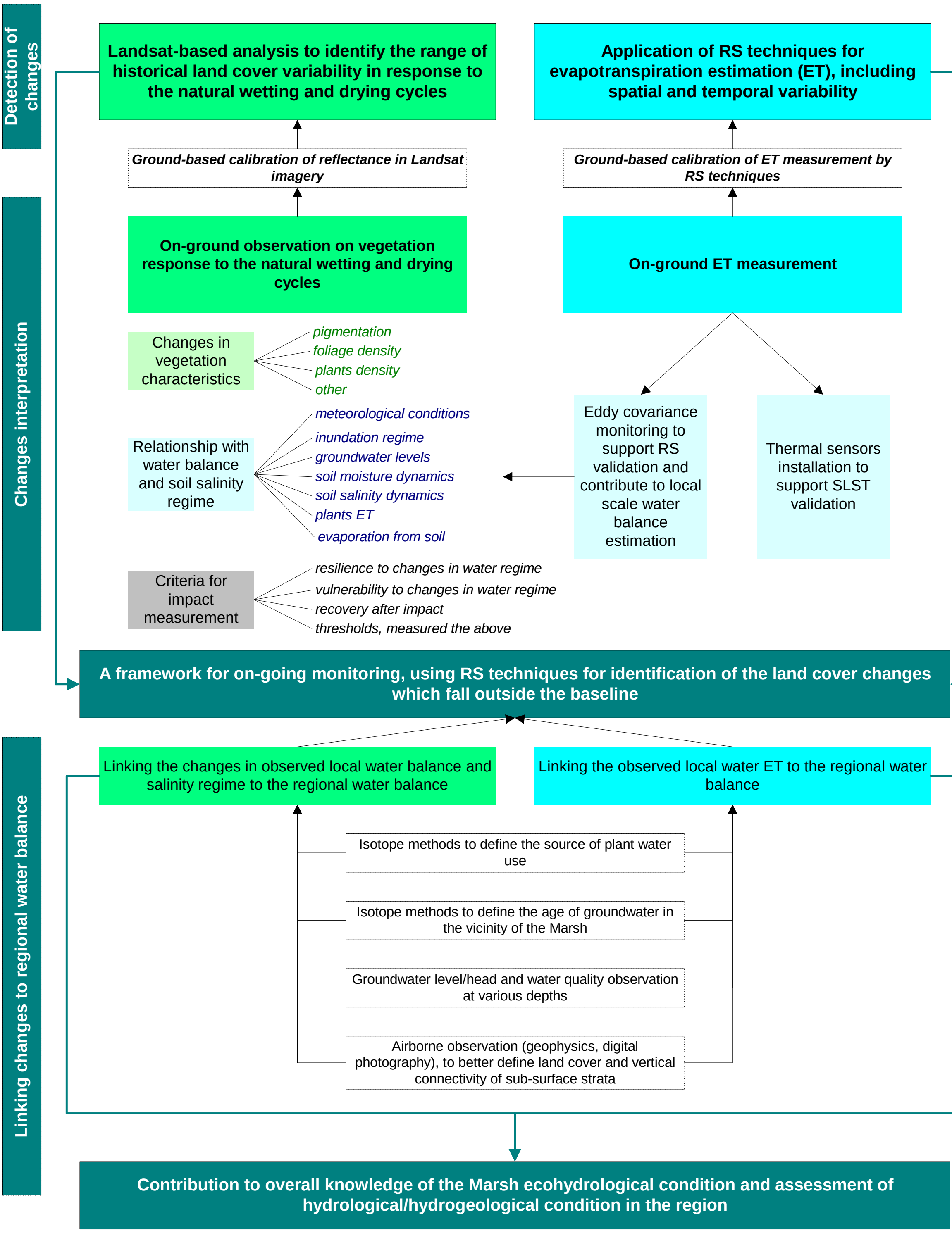


Figure 13 The conceptual structure of the proposed framework to monitor the ecohydrology of Fortescue Marsh using RS tools proposed by CSIRO (2012)

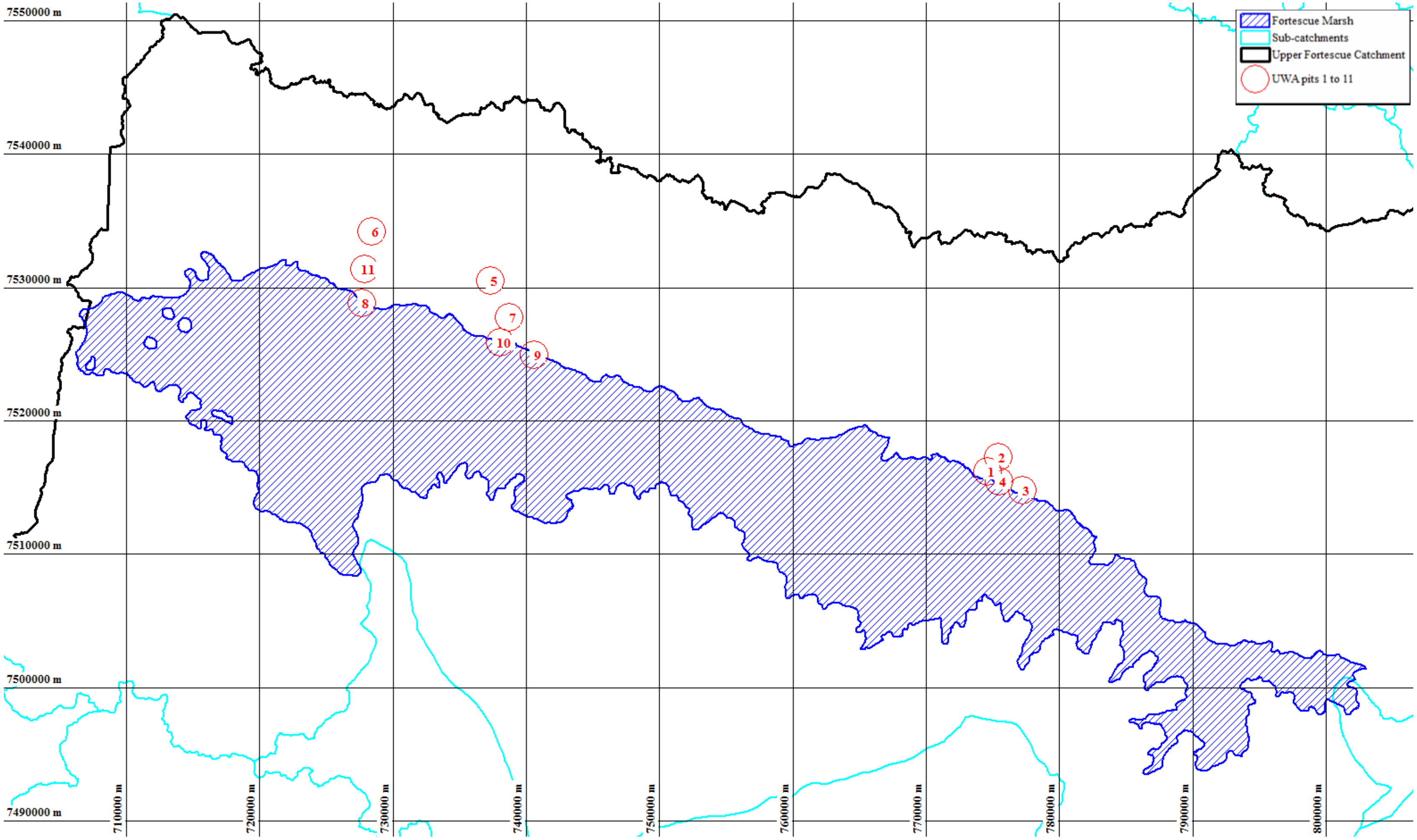


Figure 14 UWA stable isotope sampling locations (May 2012) near the Fortescue Marsh

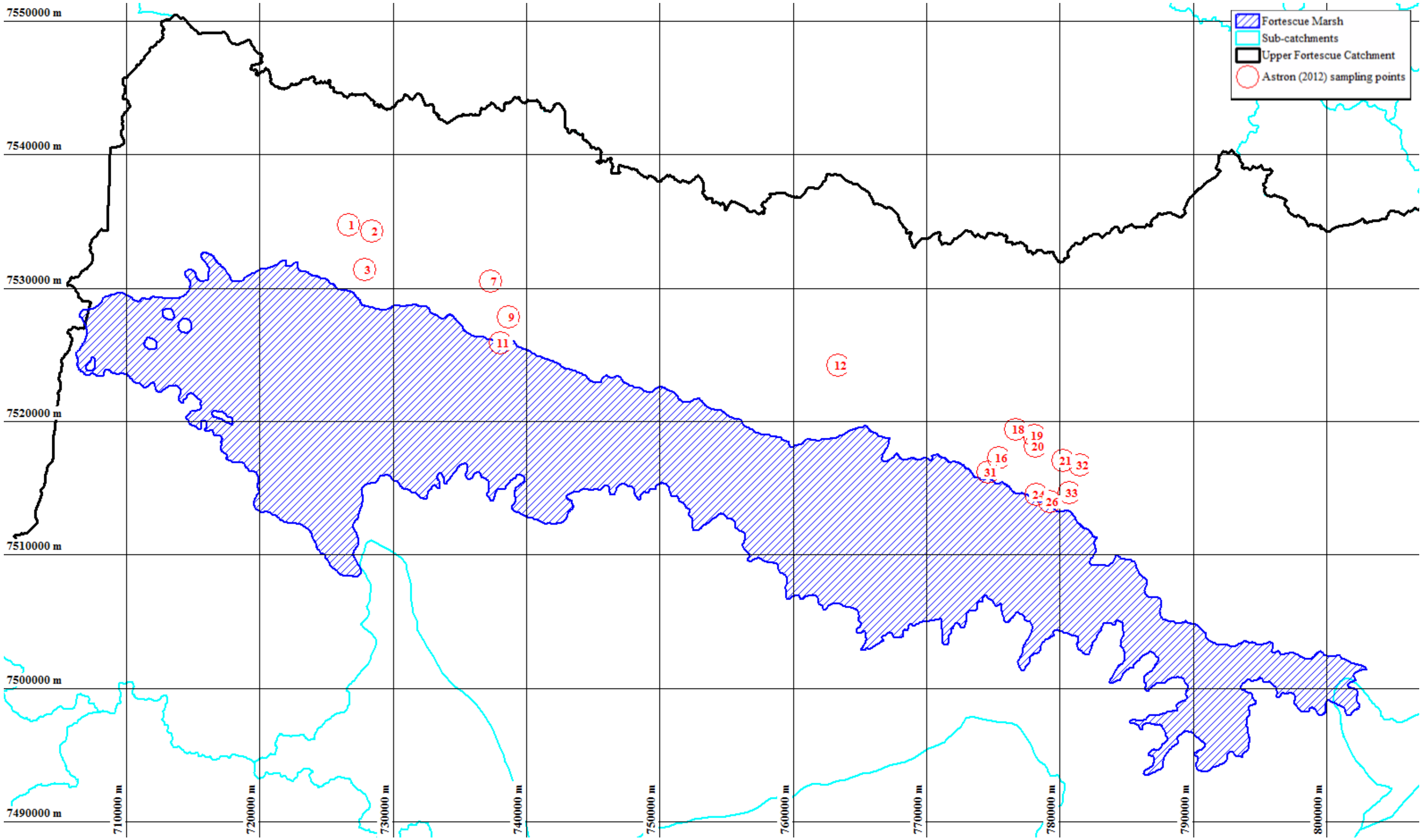


Figure 15 Astron (2012) vegetation root system sampling locations near the Fortescue Marsh

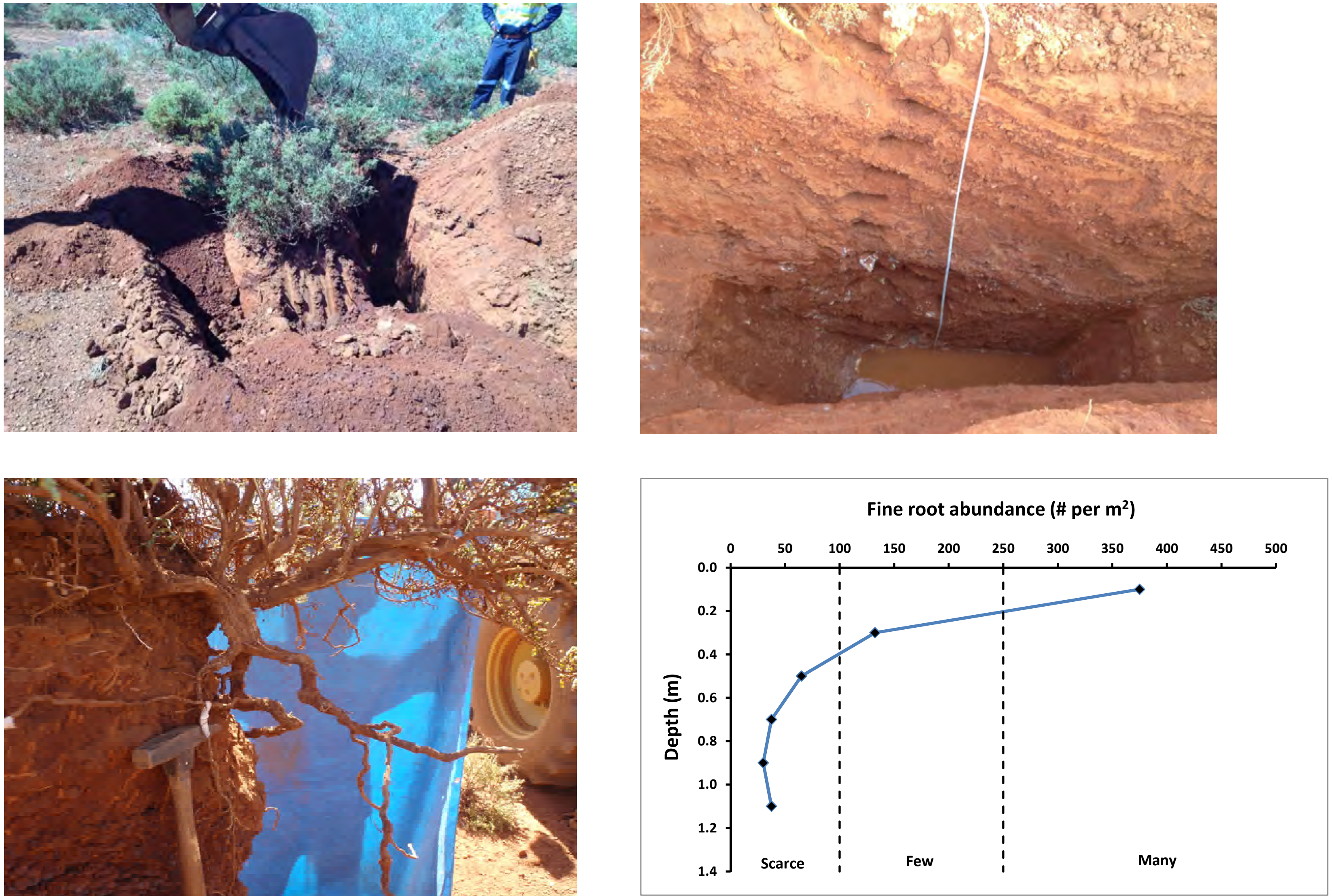


Figure 16 **Observations of *Tecticornia indica* subsp. *bidens* root system at the edge of the Fortescue Marsh.**

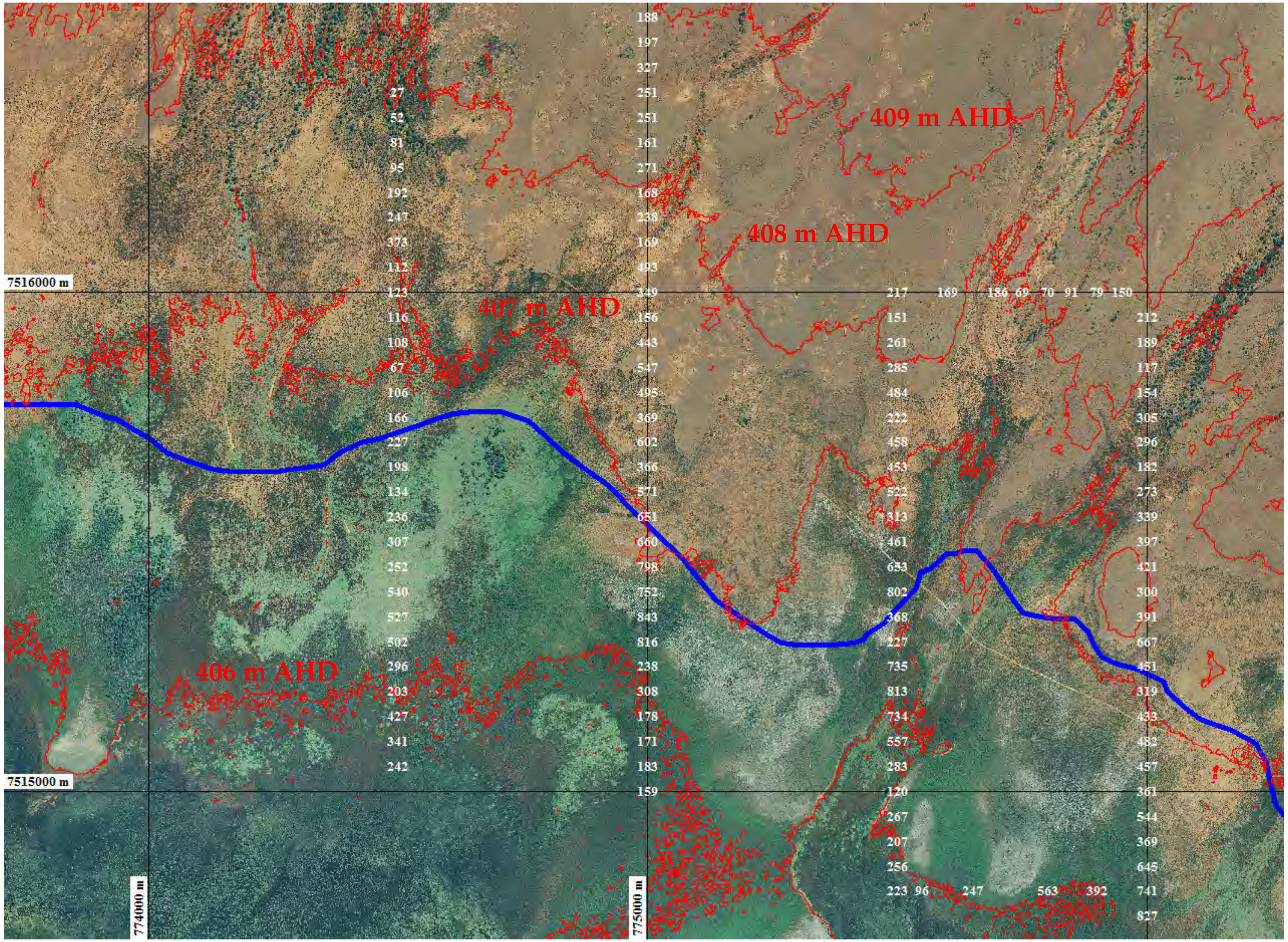


Figure 17 EM38 measurements (vertical mode; mS/m) near the Fortescue Marsh fringe south of the Christmas Creek mining area (white numbers); 1 m surface elevation contours (red) derived from LIDAR also shown.

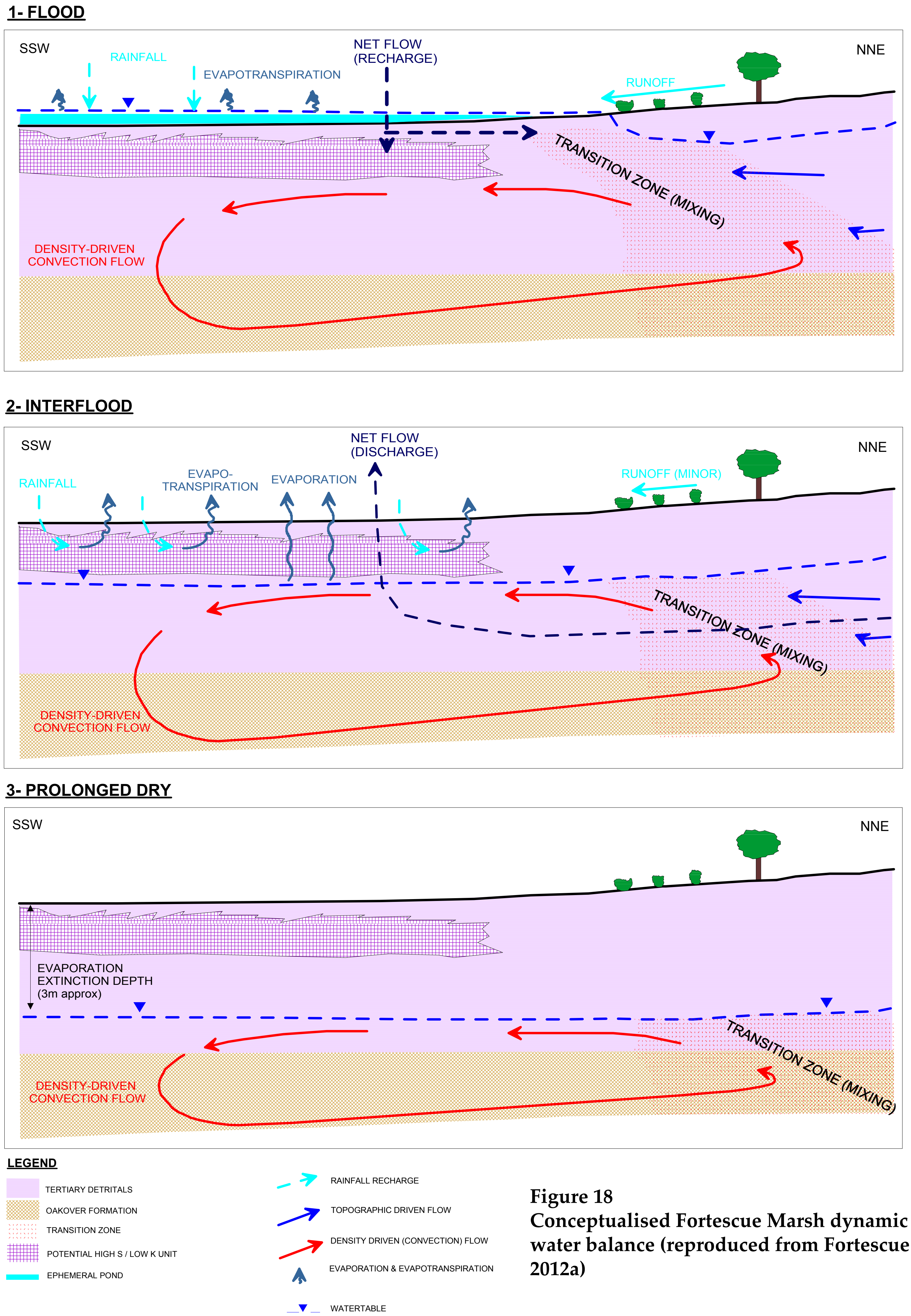


Figure 18
Conceptualised Fortescue Marsh dynamic water balance (reproduced from Fortescue 2012a)

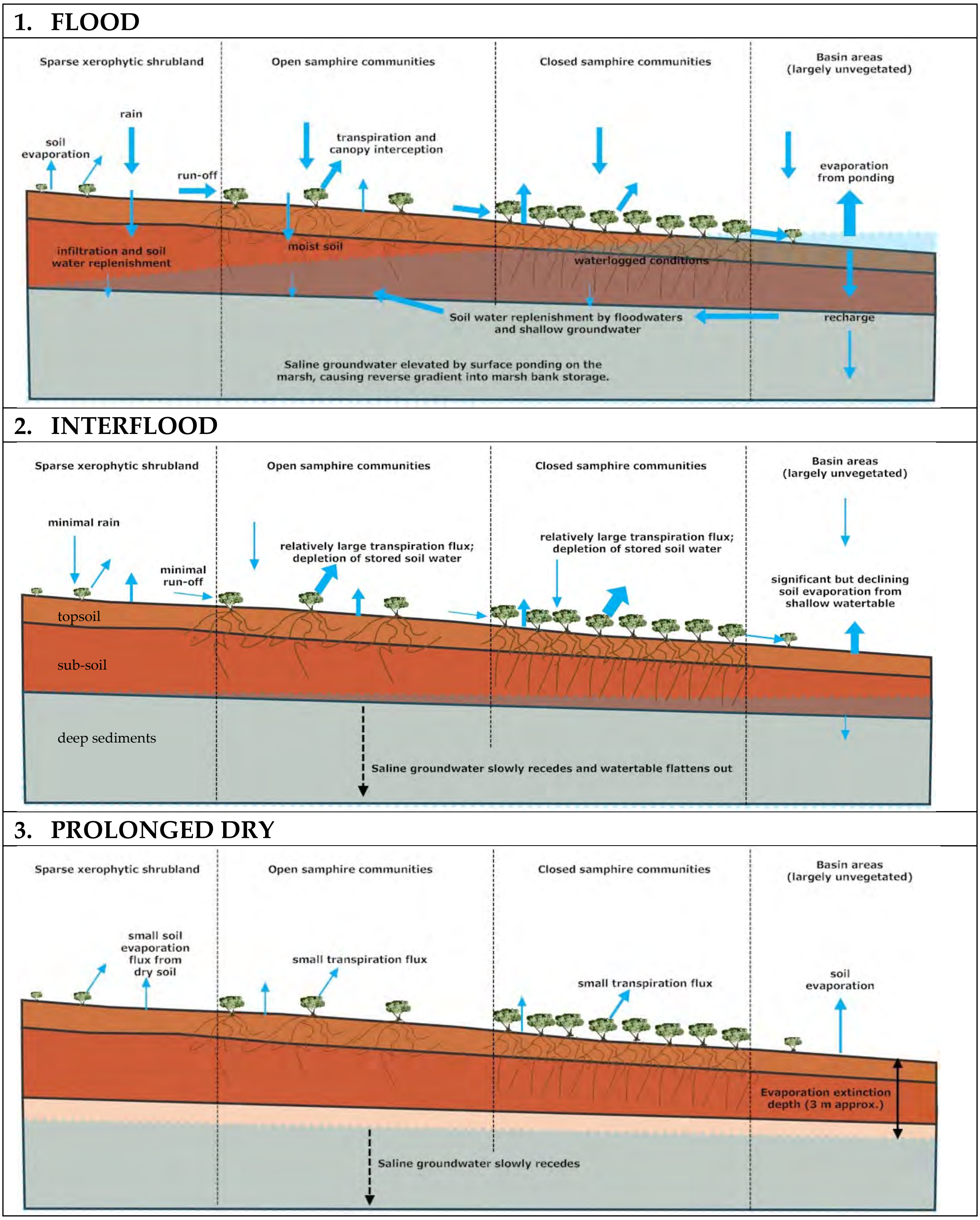


Figure 19 Conceptualised dynamic water balance of fringing marsh samphire communities south of the Christmas Creek LOM Expansion Project area

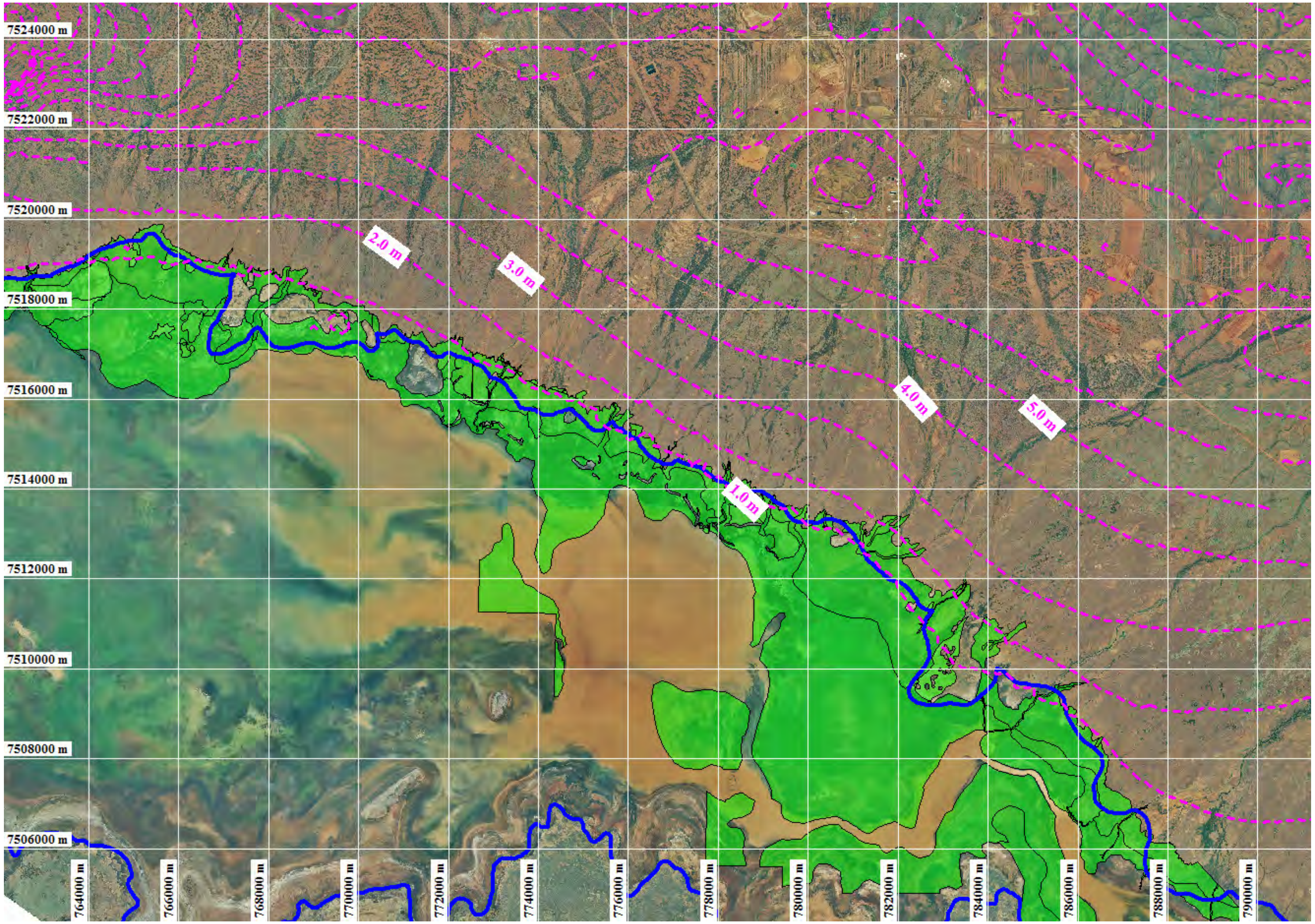
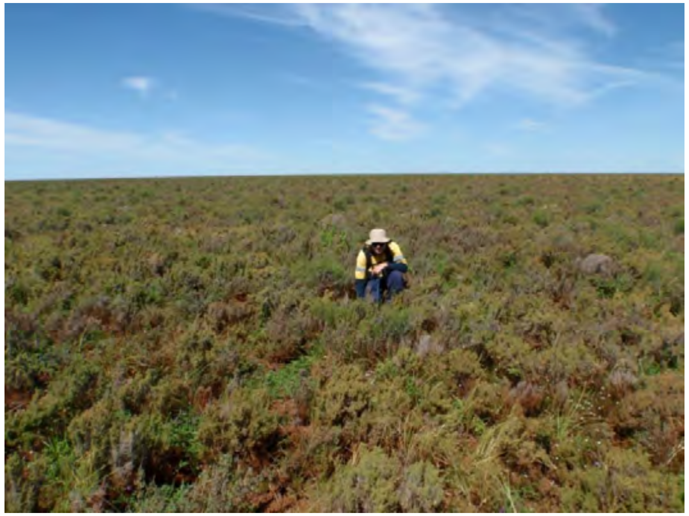


Figure 20 Fortescue Marsh samphire vegetation communities (green shaded), Marsh land system boundary (blue) and maximum predicted extent of drawdown below baseline water levels (pink dashed) under the Christmas Creek LoM Project

"Bare ground" land unit (775000E; 7516300N)

"Bare ground" land unit (775000E; 7515900N)

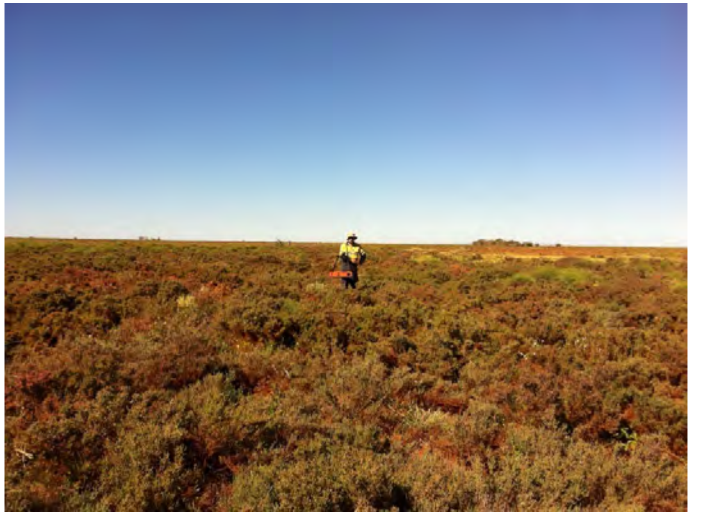
"Sparse samphire" land unit (775000E; 7515550N)



"Dense samphire" land unit (775000E; 7515200N)

Figure 21 Photographic examples of the land units depicted in the Fortescue Marsh conceptual ecohydrological model "inter-drainage" transect

"Dense samphire" land unit (775500E; 7514900N)



"Dense samphire" land unit (775500E; 7515150N)

"Dense samphire" land unit (776000E; 7515900N)

"Mulga tract" land unit in background (776000E; 7515750N)

Figure 22 Photographic examples of the land units depicted in the Fortescue Marsh conceptual ecohydrological model "drainage line" transect

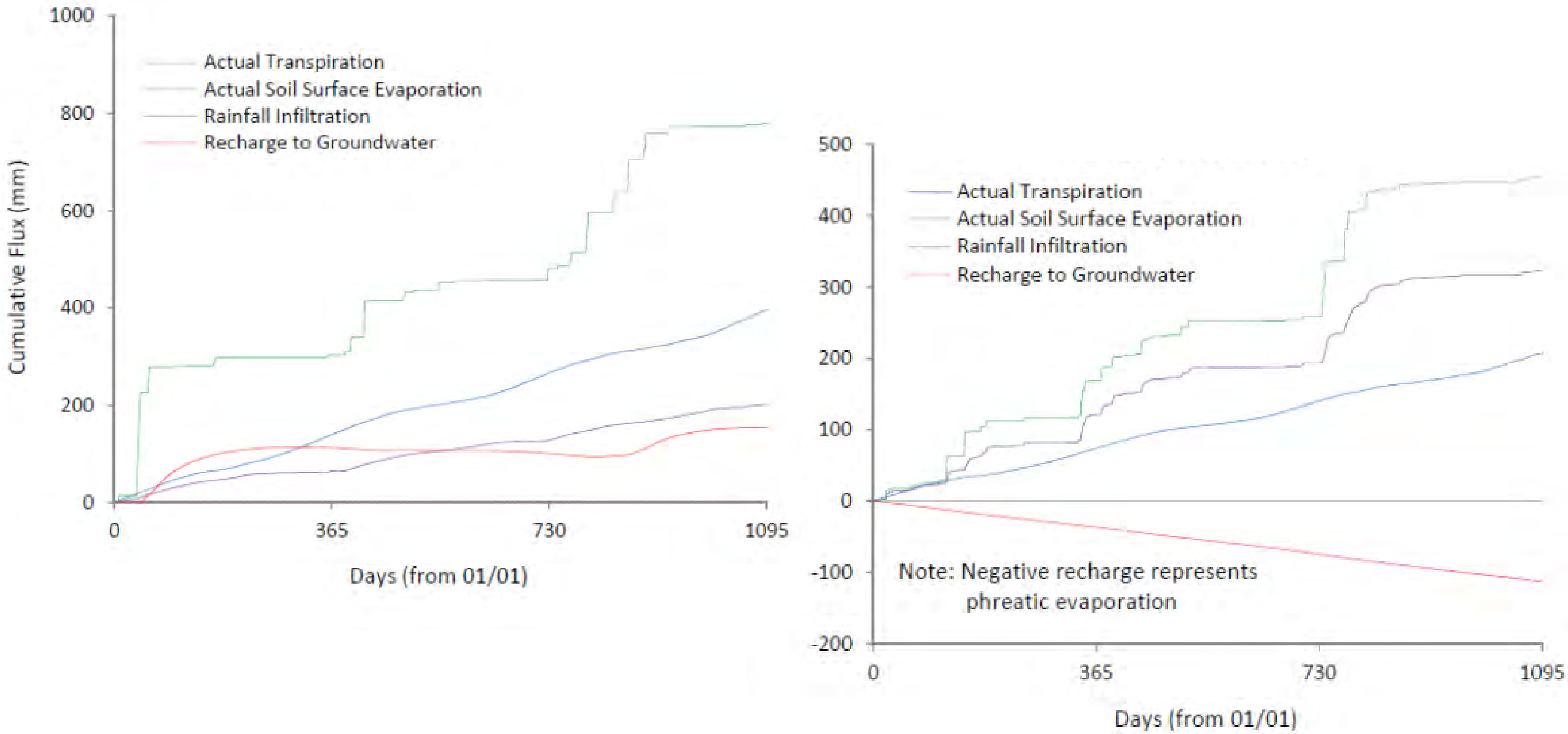


Figure 23 Cumulative water fluxes for key water balance terms simulated by HYDRUS-2D

LHS 3-year wet weather spell at GWL of 404 mAHD (i.e. base case groundwater level)

RHS 3-year dry weather spell at GWL of 402 mAHD (i.e. 2 m drawdown).

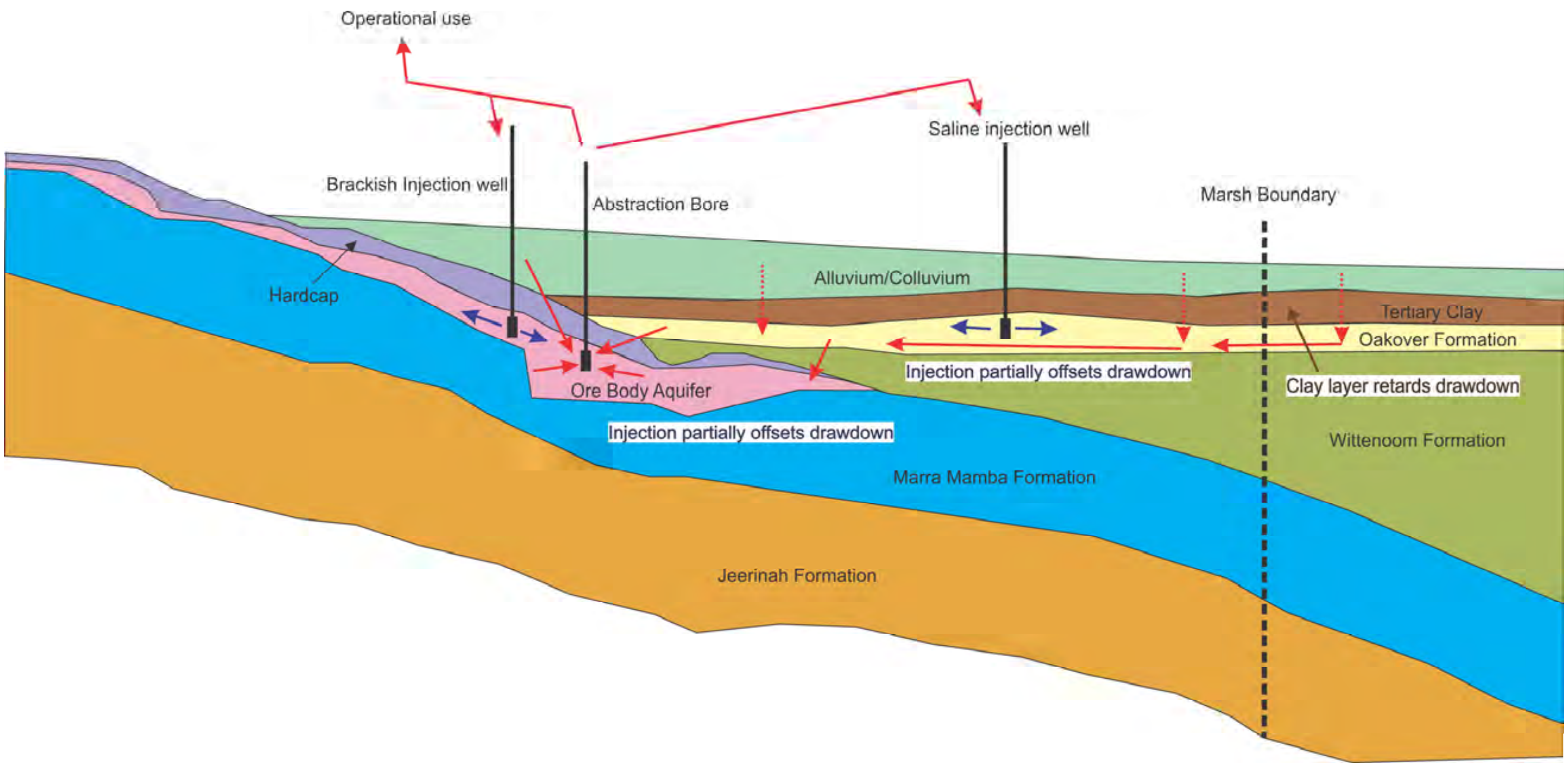


Figure 24 The mechanism of groundwater drawdown affecting the Fortescue Marsh associated with Fortescue's Christmas Creek mining operation

Appendix 1 Surface geology mapping codes

Surface geology mapping codes as per Thorne AM & Tyler IM 1997, Roy Hill, WA (2nd Edition): 1:250 000 Geological Series Explanatory Notes.

Code	Description
Qa	Alluvium unconsolidated silt, sand, and gravel; in drainage channels and on adjacent floodplains
Qc	Colluvium unconsolidated quartz and rock fragments in soil; locally derived soil, and scree, and talus deposits
Ql	Lacustrine deposits clay and silt; claypan (predominantly freshwater) deposits
Qs	Eolian deposit sand; in sheets and longitudinal dunes
Qw	Alluvium and colluviums red-brown sandy and clayey soil; on low slopes and sheetwash areas
Czc	Colluvium partly consolidated quartz and rock fragments in silt and sand matrix; old valley-fill deposits
Czk	Calcrete sheet carbonate; found along major drainage lines
Czp	ROBE PISOLITE: pisolitic limonite deposits developed along river channels
Czr	Hematite-goethite deposits on banded iron-formation and adjacent scree deposits
Czz	Brecciated siliceous caprock over dolomitic rock; angular chert fragments in a chert matrix; overlies WITTENOOM FORMATION
PLHb	BROCKMAN IRON FORMATION: banded iron-formation, chert, and mudstone
PLHj	WEELI WOLLI FORMATION: banded iron-formation (commonly jaspilitic), mudstone, and numerous metadolerite sills
PLHt	Medium- to coarse-grained metadolerite sills intruded into the Hamersley Group

AFj	JEERINAH FORMATION: mudstone, chert and thin-bedded meta-sandstone; intruded by meta-dolerite sills in the Hamersley Range
AFjd	Mudstone and thin-bedded meta-dolomite
AFjo	Woodiana Member: metamorphosed quartzitic sandstone, mudstone, and chert (locally stromatolitic)
AFm	MADDINA BASALT: amygdaloidal metabasaltic flows and breccia
AFmk	Kuruna Member: metamorphosed volcanic sandstone, mudstone, chert, and meta-dolomite; local accretionary lapilli and stromatolites
AFms	Musdtone, metamorphosed mafic to intermediate volcanic sandstone, and chert; local accretionary lapilli and stromatolites
AFt	TUMBIANA FORMATION: metamorphosed mafic to intermediate volcanic sandstone, mudstone, metabasaltic flows and breccia, chert, and meta-dolerite; local accretionary lapilli and stromatolites
AFtc	Meentheena Member: metamorphosed stromatolitic limestone and dolomite, mudstone, and volcanic sandstone
AHd	WITTENOOM FORMATION: dolomite and dolomitic argillite, with minor amounts of chert, carbonates, volcaniclastic rock and iron-formation
AHm	MARRA MAMBA IRON FORMATION: iron formation meso-bands, chert, shale and BIF
AHs	MOUNT SYLVIA FORMATION AND MOUNT MCRAE SHALE: the Mount Sylvia Formation consists of shale, dolomitic shale and three prominent BIF layers, two of which mark, respectively, the base and top of the unit. The Mount McRae Shale overlies the Mount Sylvia Formation and consists of argillite and dolomitic argillite, with minor amounts of chert.

Appendix 2 EPA Report 1429 - Cloudbreak LoM key environmental factors and their management with relevance to conservation of the Fortescue Marsh

Key environmental factor	EPA evaluation of significance	EPA evaluation of potential impacts	Relevant project implementation conditions (as per Ministerial Statement 899)
Flora and vegetation	The following vegetation communities occurring within the proposal impact footprint were considered to be of ecological importance: • **Samphire vegetation types** - significant due to their locally restricted distribution, regional uniqueness, and the presence of varying endemic and new to science species including *Eremophila spongiocarpa* (P1). • **Mulga vegetation** - significant due to: o it comprising the northern extent of the Mulga in WA o high morphologically variability o importance for landscape water and nutrient capture, and ecosystem function o supports a range of Priority	Direct disturbance (*i.e.* clearing for mine pits, stockpiles, and infrastructure): • Samphire vegetation types = 3 ha • Mulga vegetation = 5,829 ha • Creekline and drainage vegetation = 126 ha Indirect disturbance – groundwater drawdown and mounding, ponding and shadowing. The proponent considered that where mounding within Mulga vegetation and drawdown within Samphire and Creekline and drainage vegetation occurs for two or more consecutive years, and where there are changes to surface water such as ponding and shadow effects, the vegetation in these areas may be adversely impacted as follows: • Samphire vegetation = 763 ha • Mulga vegetation = 315 ha • Creekline and drainage vegetation = 3	**Condition 6: Conservation Significant Vegetation – Indirect Impacts** <u>Key aspects:</u> 1) No adverse impact to conservation significant vegetation outside the Mine Envelope resulting from the project greater than: • 763 hectares to Samphire vegetation; and • 315 hectares to Mulga vegetation; • 3 hectares a to Coolibah/River Red Gum creekline vegetation

Key environmental factor	EPA evaluation of significance	EPA evaluation of potential impacts	Relevant project implementation conditions (as per Ministerial Statement 899)
	Flora such as *Phyllanthus aridus, Eremophila youngii* subsp. *lepidota, Goodenia nuda* o highly susceptible to disturbance from fire, grazing and development of infrastructure • **Creekline and drainage vegetation** - vegetation dominated by Coolibah and River Red Gum, considered to have a partial dependence on groundwater.	ha The proponent predicted that no greater than 1 m of mounding and/or drawdown would occur within the Fortescue Marsh under an 'average' climate scenario. Overall impacts to significant vegetation types were evaluated as follows: • Samphire vegetation types = 2.4% of local extent • Mulga vegetation = 5.7% of local extent • Creekline and drainage vegetation = 5.4% of local extent. The EPA considered that although percentage impacts to the above significant vegetation communities may were relatively low, the disturbance would trigger an offset requirement (refer to page 25 for additional details)	2) Proponent required to prepare and implement a Vegetation Health Monitoring and Management Plan for the project area, to verify and ensure that the above requirements are met. This Plan must specifically address: flora and vegetation health and condition (potential impact zones and reference areas), species composition and habitat characteristics, trigger levels for additional management actions to prevent further impacts, and specific management and contingency actions beyond reporting or initiating assessment. **Conditions 15 & 16** - Offsets required for residual impacts to habitat (refer to page 25)

Key environmental factor	EPA evaluation of significance	EPA evaluation of potential impacts	Relevant project implementation conditions (as per Ministerial Statement 899)
Conservation significant fauna	The EPA considered the following habitat types have key values for the conservation of the Night Parrot, consistent with the findings of McDougall *et al.* (2009): • low halophytic samphire shrubland • hummock grassland on the fringe of the Fortescue Marsh • spinifex covered hills and ranges. However, the EPA also considered that the Night Parrot could potentially use a range of additional habitats within the project area (such as creek and drainage lines and through Mulga vegetation).	The maximum potential indirect disturbance to Night Parrot habitat was assessed to be approximately 776 ha, which equates to 1.5% of the mapped habitat extent for this species. The maximum potential indirect disturbance to Bilby habitat was assessed to be approximately 2% of the mapped habitat extent for this species. The maximum potential indirect disturbance to Mulgara habitat was assessed to be approximately 2.9% of the mapped habitat extent for this species. The EPA took the view that although the percentage impacts to the Night Parrot, the Mulgara and the Greater Bilby appear to be low, the potential cumulative residual impacts to these species, that are already considered to be threatened, should be offset.	**Condition 10** **Conditions 15 & 16** - Offsets required for residual impacts to habitat (refer to page 25)

Key environmental factor	EPA evaluation of significance	EPA evaluation of potential impacts	Relevant project implementation conditions (as per Ministerial Statement 899)
Surface water flows	The proposal has the potential to impact surface water as a result of interruption of the surface water flows, change in water quality and contingency discharge.	The effective reduction in the Fortescue Marsh catchment area under the proposal was evaluated to be less than 0.1% of the total catchment area, which was not considered to be significant. The EPA also considered the predicted to the catchments to be minimal and acceptable. The reduction in catchment areas for Yintas was estimated to be up to 7%. The EPA took the view that protection of the Yintas is a key consideration, notwithstanding the small reduction in Yinta catchments. Therefore, the commitment from the proponent to direct the flow from major creeklines that have been diverted, back into the same creeklines at the southern end of the mine area was considered to be important.	**Condition 11** Key aspect: Surface Water Management Plan to be updated to achieve outcomes similar to those predicted **Condition 13** Key aspect: Disturbance areas to be progressively closed and rehabilitated, and surface water flows reinstated, as soon as possible

Key environmental factor	EPA evaluation of significance	EPA evaluation of potential impacts	Relevant project implementation conditions (as per Ministerial Statement 899)
		The EPA noted that the cumulative impact to surface water flow into the Fortescue Marsh is 5.2% for the Northern Catchment and approximately 2% for the entire Fortescue Marsh. Although these proportions are small, the EPA was concerned that surface water flow to the Fortescue Marsh may be impeded; as approximately 75% along the northern boundary is likely to be cumulatively impacted by mining operations (Cloudbreak, Christmas Creek and Roy Hill projects) and may result in unacceptable changes to the ecology of the Marsh. The EPA therefore considered surface water management and progressive rehabilitation to be critical to the protection of the Fortescue Marsh. With respect to water quality, the EPA took the view that progressive closure is integral to soil stability and thereby managing the turbidity and sediment load to the Fortescue Marsh to mimic, as closely as possible, natural conditions.	

Key environmental factor	EPA evaluation of significance	EPA evaluation of potential impacts	Relevant project implementation conditions (as per Ministerial Statement 899)
Groundwater quantity and quality	The EPA considered that the injection of large volumes of saline water into areas with fresh or brackish water quality has the potential to increase salinity of groundwater in these areas. This is considered a concern as increasing the salinity above 6,000 mg/L limits the potential use of the water for stock drinking water and other beneficial uses. The EPA considered that the DoW can regulate the changes in groundwater salinity concentrations and proposed increase in dewatering/reinjection through licencing mechanisms. The EPA considered that leaching tests of ore/waste rocks was required to characterise the risk of acidic and metalliferous drainage (AMD) and inform appropriate management practices to ensure the protection of groundwater and the Fortescue Marsh.		**Condition 12** <u>Key aspect:</u> AMD risk assessment and management plans required.

Key environmental factor	EPA evaluation of significance	EPA evaluation of potential impacts	Relevant project implementation conditions (as per Ministerial Statement 899)
Residual impacts	The EPA noted that there will be approximately 83%, 96% and 43% of the Mulga vegetation, Samphire vegetation and the Coolibah/River Red Gum creekline vegetation, respectively, remaining after the Roy Hill, the Christmas Creek and the Cloudbreak Life of Mine projects have been developed. These percentages are based on the locally mapped extent and not the regional or pre-European extent.	The EPA considered that where there is a loss of conservation significant vegetation from either direct or indirect impacts, it should be offset. The EPA took the view that by offsetting the impacts to the significant vegetation types, the impacts to conservation significant fauna species habitat would also be addressed. The EPA stated that it had regard for other proposals in the Pilbara region in forming this view about offset requirements.	**Conditions 15 & 16** - Offsets required for residual impacts. Key aspect: Condition 15 stipulates the following offset requirements for direct and indirect vegetation impacts (outside existing Mine area): 1. $3,000 per hectare for direct and indirect impacts to Mulga vegetation in the proposed conservation reserve within the Project Area 2. $1,500 per hectare for direct and indirect impacts to Mulga vegetation outside of the proposed conservation reserve and within the Project Area 3. $3,000 per hectare for direct impacts to Samphire vegetation within the Project Area 4. $1,500 per hectare for direct impacts to Coolibah/River Red Gum creekline vegetation within the Project Area

Appendix 3 EPA Report 1402 – CCWMS key environmental factors and their management with relevance to conservation of the Fortescue Marsh

Key environmental factor	EPA evaluation of significance	EPA evaluation of potential impacts	Relevant project implementation conditions (as per Ministerial Statement 899)
Flora and vegetation	The EPA made the following statement with respect to the conservation significance of vegetation types in the project area: *"Three vegetation types in the proposal area are associated with locally significant Mulga, which are sheetflow dependent vegetation communities. One vegetation type is associated with the partially groundwater dependent species Coolibah (Eucalyptus victrix) and River Red Gum. A further seven vegetation types are associated with Samphire vegetation. Six vegetation types are locally significant and are associated with the Fortescue Marsh."*	The EPA considered that impacts to samphire communities would not be expected to occur if modified watertables remained within the limits if natural variation, and hence by implication within natural tolerance limits of samphire communities. The EPA also noted that samphire communities at the marsh are unlikely to be largely dependent on groundwater, as the Fortescue Marsh is predominantly a surface water feature. The EPA considered that the predicted indirect impact to River Red Gum and Coolibah vegetation resulting from drawdown of 82 ha (equating to 3.6% of the mapped community) was not significant.	**Condition 6 – Groundwater Mounding** <u>Key aspect:</u> Mounding should not result in the groundwater rising to be within 2 m of the surface where baseline levels allow this in Mulga dominated communities. **Condition 7 – Fortescue Marsh** <u>Key aspect:</u> Injection of surplus water to be managed to ensure that groundwater levels do not rise by more than 1 to 1.5 m, at selected bore locations near the Fortescue Marsh boundary.

Key environmental factor	EPA evaluation of significance	EPA evaluation of potential impacts	Relevant project implementation conditions (as per Ministerial Statement 899)
		The EPA took the view that mounding should not result in the groundwater rising to be within 2 m of the surface where baseline levels allow this in Mulga dominated communities. The design of the water conveyance infrastructure, management and monitoring proposed by Fortescue to minimise impacts to Mulga from changes in sheetflow was considered acceptable by the EPA. The EPA considered that the proponent should undertake vegetation monitoring in combination with groundwater and surface water monitoring to validate the vegetation impact predictions.	**Condition 8 – Vegetation Monitoring** <u>Key aspect:</u> A Vegetation Health Monitoring and Management Plan to be developed and implemented that addresses: • identification of keystone plant species and habitat characteristics and limits of acceptable change in health and/or condition of these to be used as the basis for monitoring • suitably selected locations for predicted impact and reference monitoring sites (outside the predicted impact areas) for baseline and ongoing monitoring, • Results of baseline monitoring (species composition &habitat characteristics) at both predicted impact and reference monitoring sites, and groundwater levels and groundwater quality at agreed sites in proximity to the vegetation monitoring sites

Key environmental factor	EPA evaluation of significance	EPA evaluation of potential impacts	Relevant project implementation conditions (as per Ministerial Statement 899)
			• specifications for the monitoring program for vegetation health, species composition and habitat characteristics, including trigger levels for additional management actions • specific management and contingency actions beyond reporting or initiating assessment.
Fauna and habitat	The EPA recognised the potential for a number of fauna species with conservation significance to occur in the project area including: • Australian Bustard • Night Parrot • Northern Quoll • Short-tailed Mouse • Rainbow Bee-eater • Peregrine Falcon • Bush Stone-curlew • Western Pebble-mound Mouse • White-bellied Sea-eagle, • Wood Sandpiper • Common Greenshank • Great Egret	The EPA considered that impacts to fauna and habitat were unlikely to be significant on the basis that: • potential loss of habitat to threatened, specially protected and priority fauna would be minor in scale • species attributes such as nomadism, overall distribution and particular habitat requirements mitigated against the potential for significant impacts • stygofauna assemblages are widespread outside the project area	

Key environmental factor	EPA evaluation of significance	EPA evaluation of potential impacts	Relevant project implementation conditions (as per Ministerial Statement 899)
	The EPA also recognised the occurrence of stygofauna assemblages in the project area, and potential occurrence of troglofauna assemblages.	• troglofauna habitat is widespread outside the proposal area.	
Cumulative impacts of future Chichester mine expansions[27]	In its advice to the Minister, the EPA outlined its expectation that the proponent identify the cumulative impacts of its future proposals to the maximum extent practicable. Key aspects that the EPA identified as being necessary to investigate/address to demonstrate that the Fortescue Marsh will not be unacceptably impacted included: • Impacts from dewatering and reinjection. • Proposed management, including detailed information on mine planning, backfilling, the recreation of landforms, rehabilitation measures, and completion criteria	The EPA stated its expectation that the proponent will provide timely, robust and comprehensive information that demonstrates that the local and regional impacts to flora, vegetation, fauna, and groundwater, in particular those associated with the Fortescue Marsh, can be managed in association with future mine expansion proposals.	N/A

[27] Not identified by the EPA as a key environmental factor, but mentioned in the EPA assessment.

Key environmental factor	EPA evaluation of significance	EPA evaluation of potential impacts	Relevant project implementation conditions (as per Ministerial Statement 899)
	The EPA also stated it's awareness of other in-progress studies regarding the Fortescue Marsh being uindertaken by Fortescue, and advised that the results of these studies should be considered and included in the proponent's environmental review of its expansion project(s). Key aspects that the EPA identified as being necessary to investigate/address to demonstrate that the Proposed Conservation Reserve (PCR) will not be unacceptably impacted included: • Provision of comprehensive information to demonstrate that mining has avoided and minimised impacts on the PCR to the greatest extent practical. • Provision of detailed rehabilitation and closure measures including objectives, actions, timing, and completion criteria		

Key environmental factor	EPA evaluation of significance	EPA evaluation of potential impacts	Relevant project implementation conditions (as per Ministerial Statement 899)
	• Provision of regional information on the cumulative impacts, in particular in relation to mulga woodland but also to significant flora, vegetation and fauna. The EPA also stated it's expectation that the proponent will have early discussions with the DEC to establish mitigating strategies in relation to the PCR from any expanded proposal.		
Groundwater[28]	The EPA accepted that there is a low risk that water quality will be significantly impacted by saline injection, due to low permeability clay layers separating the Tertiary Detrital and Oakover Formation aquifer systems and inherent hydrogeological attributes of the Tertiary Detritals (low permeability and high water storage properties).		N/A

[28] Not identified by the EPA as a key environmental factor, but mentioned in the EPA assessment.

Key environmental factor	EPA evaluation of significance	EPA evaluation of potential impacts	Relevant project implementation conditions (as per Ministerial Statement 899)
	The EPA noted that groundwater quality could be effectively managed by the Department of Water through regulation of the Proponent's approved Groundwater Operating Strategy.		

Interim Project Report

Ecophysiology of stem succulent halophytes subject to changes in salinity and water availability: distinguishing natural dynamics from potential mine related impacts

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School of Plant Biology

The University of Western Australia

Introduction

Fortescue Metals Group Ltd (FMG) are industry partners in an Australian Research Council (ARC) research project entitled "Ecophysiology of stem succulent halophytes subject to changes in salinity and water availability: distinguishing natural dynamics from potential mine related impacts", led by the School of Plant Biology at The University of Western Australia (UWA), in collaboration with the WA Herbarium. FMG commissioned the UWA research team to provide an interim report, in addition to the annual reporting to ARC, with the broad scope/purpose to summarise the state of knowledge of samphire vegetation water use dynamics and taxonomic status in the Fortescue Marsh (based on the project results). This information will inform FMG's environmental impact assessment process associated with its operational activities. This interim report provides an update on results from field work at Fortescue Marsh, and glasshouse experiments on selected species to evaluate responses to specific stress conditions.

Background

In mid-2008, The University of Western Australia (E.J. Veneklaas & T.D. Colmer), in collaboration with the WA Herbarium (K.A. Shepherd), commenced an ARC-Linkage research project on samphires at Fortescue Marsh, in partnership with FMG Ltd. The project was initiated by FMG approaching the School of Plant Biology (a group with expertise and track record for samphire and related research in south-western Australia), as FMG recognised the importance of an improved understanding of the marsh vegetation, especially given the proximity of the FMG operations to Fortescue Marsh.

A consultative process established the broad aims to explore samphire diversity and functioning at the Fortescue Marsh, a wetland in north-western Australia of national significance. The improved knowledge on these fascinating plants, and on plant stress tolerance and recovery more generally, will likely have applications to underpin future management of these areas. Understanding the vegetation at the Fortescue Marsh will provide vital base-information for future monitoring and management. Improvement of the publicly available Herbarium database on samphire species will also enable improved species identifications for conservation and/or rehabilitation efforts. The project will also train a PhD student in an industry-relevant research area that is currently in high demand.

The project is also of wider significance. Australia is a centre of diversity for stem succulent halophytic samphires (Chenopodiaceae), yet knowledge about these plants and their salt lake habitats is limited to one or two species and sites in southern Australia. Samphires have a unique ability to grow where salinity and episodic flooding combine to create an extremely stressful habitat for most other plants. Several of these habitats are under threat from climate- or land use-induced hydrological changes. There is a need for information on the ecological conditions in which different species of samphire grow, as well as on their tolerance to changes in these conditions. Thus, the specific aims of the research project are:

(i) To identify which samphire species are present and which environmental factors explain their distribution pattern;

(ii) To relate samphire population dynamics with the dynamics of water availability (flooding and water deficit) and salinity, as related to weather conditions (rainfall, air temperature, and evaporative demand);

(iii) To relate key plant health indicators, including transpiration, water status, ionic relations, organic osmolytes, pigment composition (chlorophyll and photoprotective carotenoids) and chlorophyll fluorescence, with varying levels and combinations of stress factors (salinity, drought, flooding) as these occur in the field;

(iv) To rigorously test, in controlled environments with defined treatments, hypotheses developed during the field work regarding physiological processes contributing to resistance of salinity, drought, and flooding, and also to ascertain reliable early-warning stress indicators.

Taxonomy and conservation values

An outcome of the taxonomic component of this project has been the resolution of *Tecticornia* sp. Fortescue Marsh (K.A. Shepherd *et al*. KS 1055) and *Tecticornia* sp. Roy Hill (H. Pringle 62), which have been confirmed as distinct new species. These species will be named as *Tecticornia globulifera* ms and *Tecticornia medusa* ms, respectively, and described in a peer-reviewed paper to be published in 2010 (Shepherd & van Leeuwen, in press).

A report by K.A. Shepherd entitled "Preliminary taxonomic assessment of halophytic samphires on the Fortescue Marsh, Western Australia" has been submitted to FMG.

Experiments and field monitoring in the present report have focused on three samphire (i.e. *Tecticornia*) species: *T. indica*, *T. auriculata* and *T. medusa* ms. *T. indica* is a C4 species and occurs at the highest elevations, *T. auriculata* (C3 species) at middle elevations and *T. medusa* ms (C3 species) at the lowest elevations, at Fortescue Marsh (described in the next section).

Field sites

Observations on samphires, soils and weather are being made at two locations in the Fortescue Marsh. The first location is immediately south of the Cloudbreak mine, where the probability of a hydrological impact of dewatering is greatest. The second location is approximately 20 km west of the first location, more distant from any influence of the Cloudbreak mine. The locations are similar in plant community composition, soils and topography, but detailed information on plant species and abundance as well as soil features still needs to be collected. This will be done along two transects, roughly oriented north-south, i.e. perpendicular to the marsh fringe, that were established by the UWA team and which have recently been surveyed for elevation by FMG surveyors (Figure 1).

At both locations, the main samphire (i.e. *Tecticornia*) species are *T. indica*, *T. auriculata* and *T. medusa* ms. *T. indica* occurs at the highest elevations, *T. auriculata* at middle elevations and *T. medusa* ms at the lowest elevations, but the distributions of *T. indica* and *T. auriculata* overlap, as do those of *T. auriculata* and *T. medusa* ms. The elevation difference along the transects, which are over 1.5 km long, is only about 1.5 m (Figure 1); however, this 1.5 m change in elevation can be ecologically very significant in an environment prone to flooding and with shallow water tables.

Along each transect, two 20 m x 20 m plots were established, fenced to exclude cattle, in each of the three vegetation zones, dominated by each of the three species. The position and elevation of each plot is shown in Figure 1.

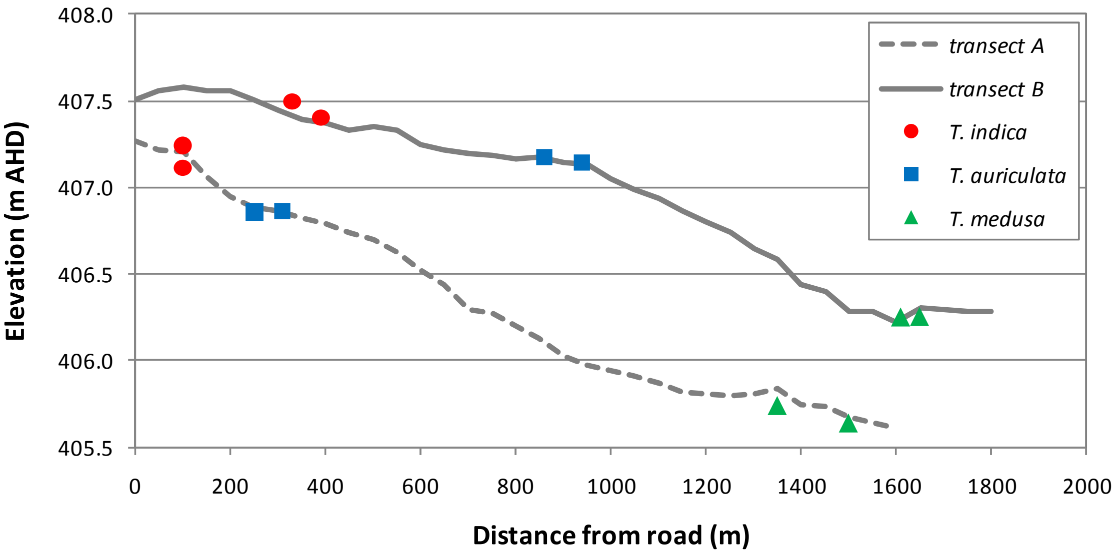


Figure 1. Positions and elevations of the twelve plots, four per species, along the two transects into the Fortescue Marsh. Elevation data courtesy of FMG. Transect A is located immediately south of the Cloudbreak mine site, and transect B is approximately 20 km west from transect A.

Weather conditions

At the start of the project, a weather station was installed near the *T. indica* plots on transect A. The station records rainfall, shortwave radiation, temperature, relative humidity, wind speed and wind direction. Selected data are shown in Figure 2. Unfortunately there are two large data gaps between February and August 2009, owing to equipment failure; records since August 2009, however, have been good. It is expected that interpolation from regional weather stations will be useful if data are needed to fill the gaps. This is explored in Figure 2a for rainfall, showing reasonable correspondence between data recorded with the tipping-bucket gauge at the transect A weather station, data recorded using a pluviometer at the Cloudbreak mine, and an average of records from official Bureau of Meteorology stations at Wittenoom, Marble Bar and Newman. The apparently large discrepancies between the regional average and the Cloudbreak mine in February and March 2009 are due to a very large storm that was recorded on the 28th of February at Cloudbreak mine but on the 1st of March at two of the other stations.

Strong seasonality is observed in temperature and radiation, which has important consequences for potential evapotranspiration. Typical daily rates of potential evapotranspiration are 8-10 mm in mid-summer and 3-5 mm in winter.

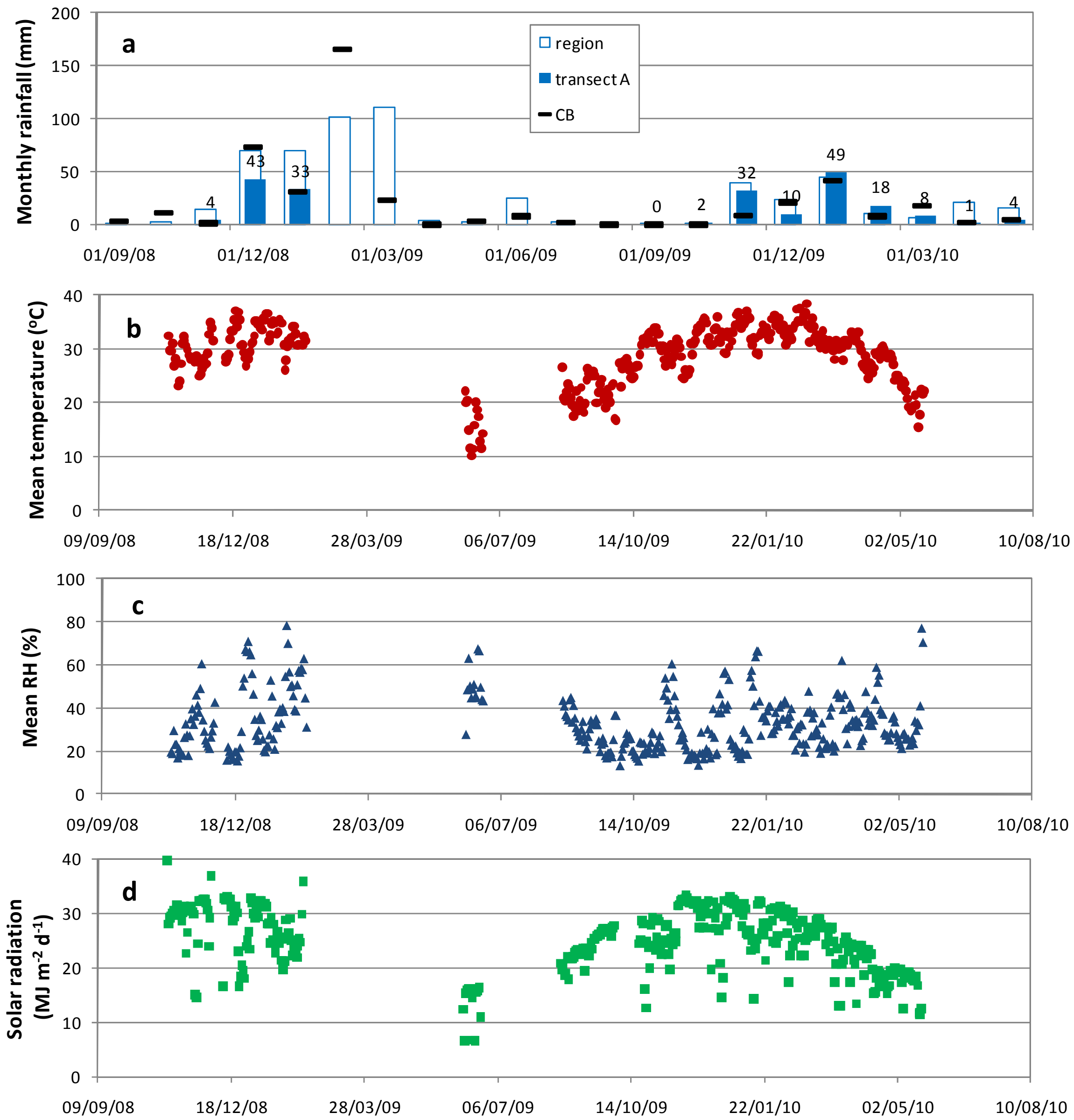


Figure 2. Selected weather data observed at the transect A weather station: a. Monthly rainfall (solid blue columns and numbers; where no number is shown, data are not available), as compared with a regional average (open columns, mean for stations Wittenoom, Marble Bar and Newman) and data from Cloudbreak mine site (black horizontal bars); b. Daily mean temperature; c. Daily mean relative humidity (RH); d. Daily total shortwave radiation.

Soil parameters

Soil profile, pH and electrical conductivity

Soils at the Fortescue Marsh transects are clayey, highly saline and with a gypsum content of approximately 5%. Comprehensive soil descriptions have not yet been made. Pedological characterizations are planned to be carried out by a consultant. The UWA team will assess a small number of key soil characteristics at fixed intervals along the transects. In this interim report, patterns in soil water content, salinity, and pH, are summarized, based on regular sampling from the plots along the transects.

Soil samples are being collected at 3-monthly intervals in all plots, duplicated, at depths of 0-1 cm, 1-10 cm, 10-20 cm 20-30 cm and 30-50 cm. These are used to measure soil moisture content (see section below), pH and electrical conductivity (EC). The measurements of pH and EC are done in 1:5 soil:water extracts. Many researchers and land managers routinely measure salinity as $EC_{1:5}$ values, as these are quicker measurements than ECe, and are useful to identify trends as they represent a standardised measure of salinity. $EC_{1:5}$ values can also be converted to ECe values (described below).

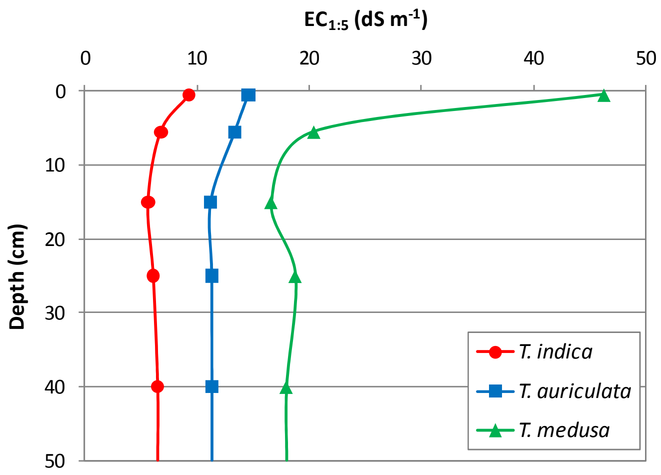


Figure 3. Electrical conductivity of 1:5 soil:water extracts (i.e. $EC_{1:5}$) for sites sampled containing the three species, for depths between 0 and 50 cm. Mean values for all plots over the period October 2008 - February 2010. Sampling intervals are 0-1 cm, 1-10 cm, 10-20 cm, 20-30 cm and 30-50 cm, and values for these intervals are plotted at their mid-point depths.

Figure 3 shows that levels of salinity are greater at lower positions in the marsh: below 10 cm depth, $EC_{1:5}$ stabilises at about 7, 11 and 17 dS m^{-1}, respectively, for *T. indica*, *T. auriculata* and *T. medusa* ms. $EC_{1:5}$ is higher near the soil surface, due to evaporative concentration of salts. Again, this process seems most important at the *T. medusa* ms sites, presumably because soil moisture is closer to the surface and capillarity to the surface means evaporation would invariably be higher at these sites.

Summarised for the top 20 cm of the soil, $EC_{1:5}$ has decreased in the first half of 2009, presumably due to rainfall exceeding 200 mm, and has slowly increased since then, probably due to mass transport driven by evaporation from the soil surface (Figure 4). The largest increases were observed in the *T. medusa* ms sites, which had the highest soil moisture content (see below, Figure 9). In contrast, increases were small for *T. indica*, which may point to a lack of upward transport of salt in dry soils (i.e. less or general lack of capillarity to the soil surface). At depths greater than 20 cm, changes in $EC_{1:5}$ are smaller than in the top 20 cm.

Salinity close to that experienced by plant roots is best assessed using “saturated pastes” (i.e. ECe), as the large volume of water in 1:5 extracts dilutes the salt concentration and potentially shifts solubility equilibria. Our results for the routine 1:5 extracts ($EC_{1:5}$) will be calibrated with saturated paste measurements (ECe), but this calibration is not available at present. In the meantime, a standard conversion factor of 8 can be used for the ratio $ECe/EC_{1:5}$ in clayey soils (George and Wren, 1985) to estimate approximate ECe values. Conversion to ECe indicates that even the lower salinity environment of *T. indica* with the lowest $EC_{1:5}$ of 6 (equivalent to ECe of 48 dS m^{-1}) exceeds the level of 32 dS m^{-1} above which salinity is described as “extreme” in salt affected agricultural lands (Bennett et al., 2009) and is already roughly similar to sea water. Thus, the soil salinity in *T. auriculata* and *T. medusa* ms zones greatly exceeds that of sea water.

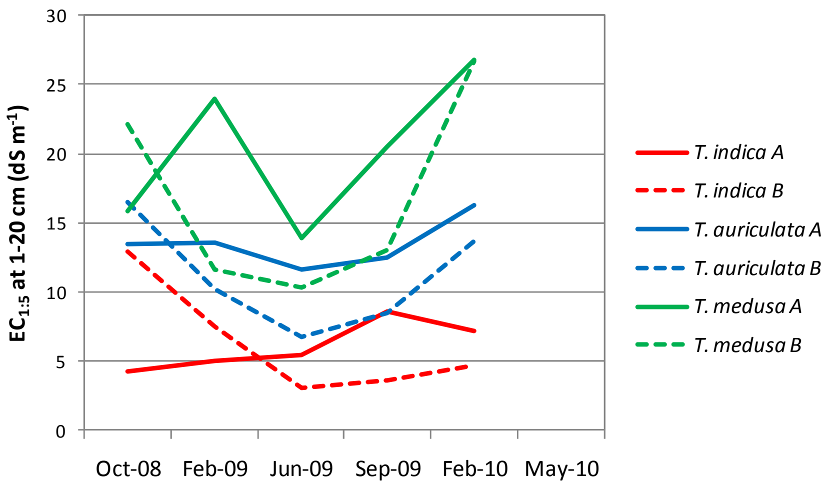


Figure 4. Electrical conductivity of 1:5 soil:water extracts ($EC_{1:5}$) for sites sampled containing the three species, average for depths between 1 and 20 cm, during the period October 2008 - February 2010.

Soils at the Fortescue Marsh are neutral to moderately alkaline. At depth, *T. indica* sites have higher pH than *T. auriculata* sites, while *T. medusa* ms sites tend to be lower again. At *T. indica* sites pH increases with depth, whereas the opposite happens at *T. auriculata* and *T. medusa* ms sites (Figure 5). During the wet first half of 2009, soil pH in the upper 20 cm of the profile tended to decrease, whereas it increased in drying soils since mid 2009, converging towards a pH of 7.5-8.0 (Figure 6).

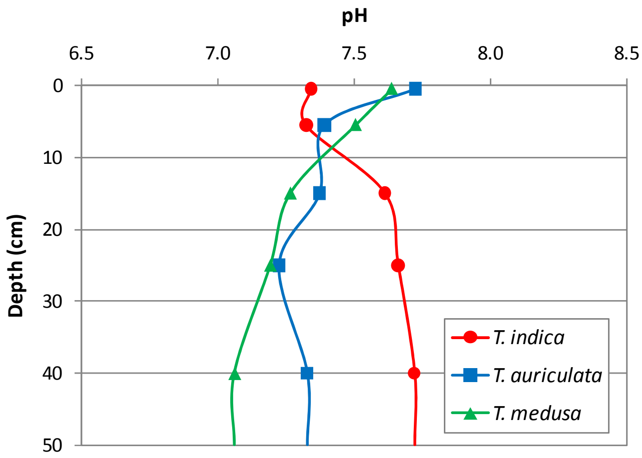


Figure 5. pH of 1:5 soil:water extracts for sites sampled containing the three species, for depths between 0 and 50 cm. Mean values for all plots over the period October 2008 - February 2010. Sampling intervals are 0-1 cm, 1-10 cm, 10-20 cm, 20-30 cm and 30-50 cm, and values for these intervals are plotted at their mid-point depths.

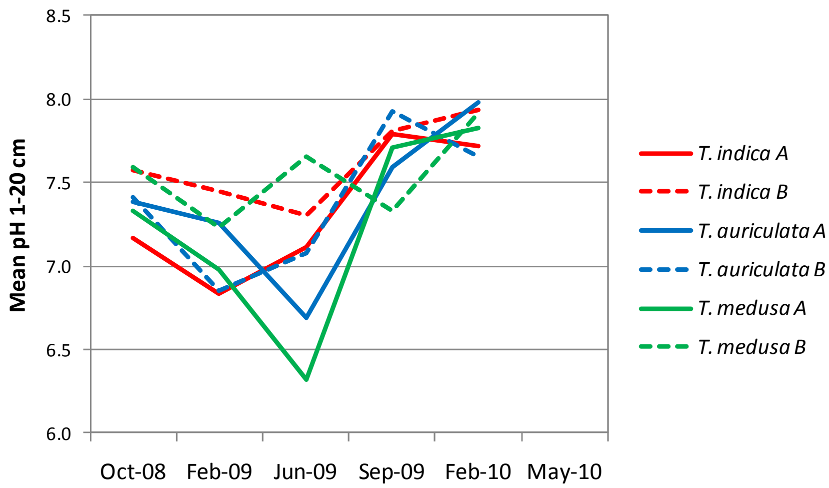


Figure 6. pH of 1:5 soil:water extracts for sites sampled containing the three species, averaged for depths between 1 and 20 cm, during the period October 2008 - February 2010.

Chemical and physical analysis of the soil profiles will help interpret differences in pH between plots, as well as changes over time. Modelling of soil water content, and movement of water and solutes in the soil, is needed to further understand trends in soil EC. Observations of species abundances along the transects, along with patterns in soil pH and EC will, in addition to the data presented here, help identify species preferences for certain conditions.

Water table dynamics

Piezometers were installed in all plots of both transects (Table 1). Presence of a hardpan limited the depth of some of the piezometers. In all *T. medusa* ms plots, being further out on the marsh, permanent water tables were measured (Figure 7). As expected, following high rainfall events, water tables rose above the surface in the lower-lying *T. medusa* ms plots, but after the long absence of large rainfall events the water remained at about 1 m depth below the soil surface.

Table 1. Elevation of all plots, depth to which piezometers were installed, and depth at which hardpan was detected. Where no hardpan was detected, it may be present below 1.5 m depth. The thickness of the hardpan is approximately 3 cm. Hardpan was penetrated using the hand auger only in one case, despite considerable effort.

Transect	**Species**	**Plot**	**Elevation** (m AHD)	**Piezometer depth** (m)	**Hardpan depth** (m)
A	*T. indica*	5	407.24	1.50	0.8*
		6	407.11	0.80	0.8
	T. auriculata	3	406.86	0.73	0.7
		4	406.87	0.78	0.8
	T. medusa ms	1	405.74	1.50	not detected
		2	405.64	1.50	not detected
B	*T. indica*	5	407.50	1.50	not detected
		6	407.40	1.53	not detected
	T. auriculata	3	407.14	1.50	not detected
		4	407.17	1.50	not detected
	T. medusa ms	1	406.25	1.50	not detected
		2	406.25	1.58	not detected

Comparison of piezometers at the *T. medusa* ms plots at transects A and B shows some interesting results. Although transect B is further west, i.e. “downstream” in the Fortescue River floodplain, it lies at slightly higher elevation than transect A (Figure 1). This suggests that it is not simply part of the same sub-catchment area and therefore not necessarily subject to the same flooding regimes. Water tables rose in transect B in late December 2008 and January 2009, whereas water tables in transect A did not respond. Rainfall measured at transect A on those days was approximately 30 and 15 mm, but the possibility that these events were larger at transect B cannot be excluded. The large storms of late February to early March 2009 caused flooding to 20 cm depth in plots of *T. medusa* ms at transect A but to 50 cm in transect B. These water levels also fell faster in transect A than transect B. Possible differences between the two locations may be differences in run-on and run-off (connectivity with other parts of the marsh), and differences in soil hydraulic properties, affecting infiltration, storage and drainage. The flooding events at transect A between April and July 2009 were due to discharge of excess water from the Cloudbreak mine into a creek feeding the marsh near this transect. Interestingly, water levels during these prolonged events did not exceed 10 cm depth, suggesting that at that point water may start flowing off into other areas of the marsh.

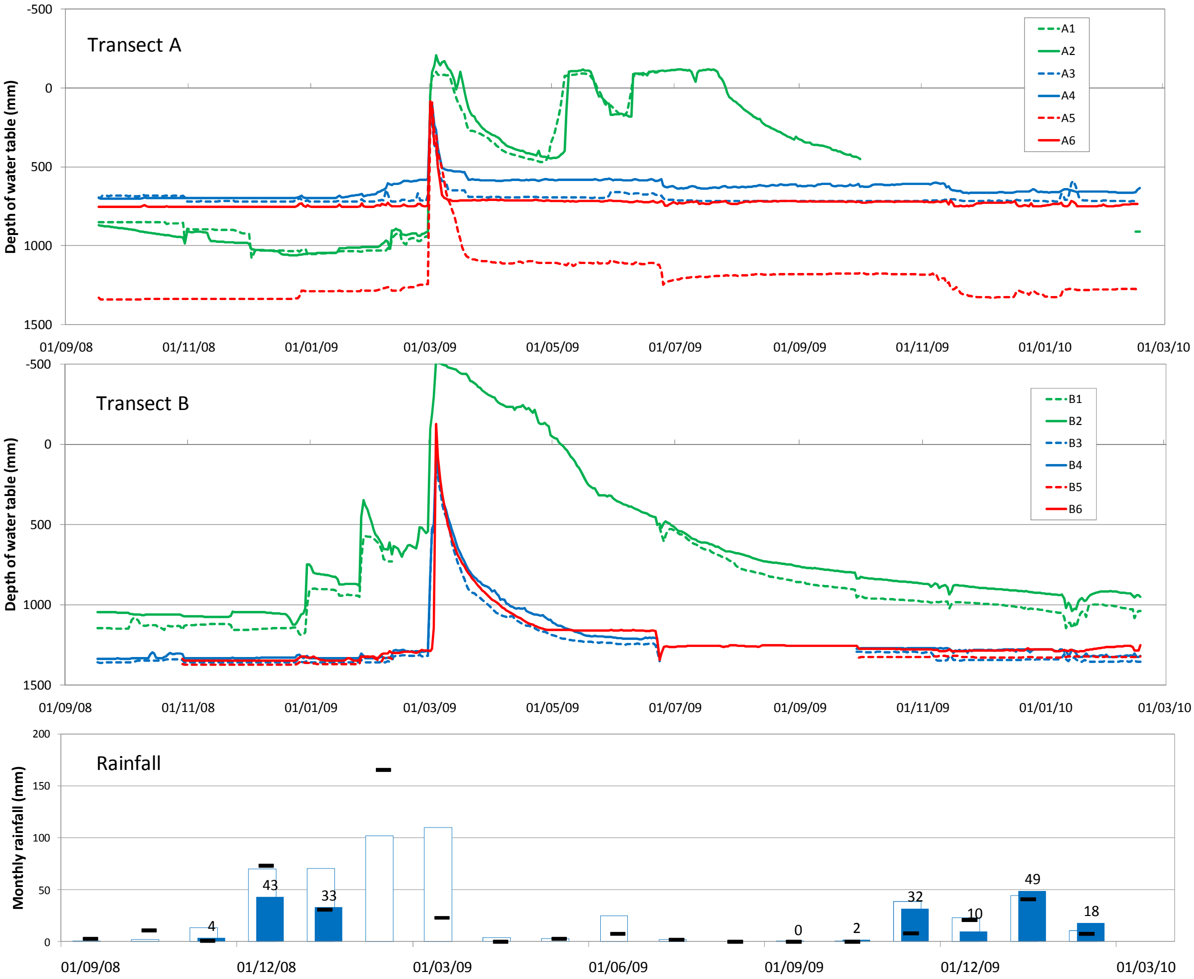


Figure 7. Water table depth measured at all plots of transects A and B. Note that the depth scale is shown in reverse and that negative values indicate flooding. Plots A1, A2, B1, B2 are *T. medusa* ms (green lines); plots A3, A4, B3, B4 are *T. auriculata* (blue lines); plots A5, A6, B5, B6 are *T. indica* (red lines). Also, importantly, flat lines in piezometers A3-A6 and B3-B6 indicate water at or below the maximum depth of the piezometer. Monthly rainfall data are supplemented with an estimated regional average (white bars), calculated as the mean monthly rainfall for the weather stations at Marble Bar, Wittenoom and Newman. Blue bars are records from the weather station at transect A. Amounts are shown in mm, above the bars, to indicate for which months the records are complete.

Soil moisture dynamics

Soil moisture is monitored in two ways. Samples are taken every 3 months for gravimetric determination of water content, and soil moisture probes (using standing wave principle and dielectric constant) record volumetric soil water content continuously at transect A. Here we focus on the gravimetric results, as this dataset is longer, uninterrupted, and available for both transects. Moisture probe data still need to be calibrated and processed.

Detailed results for all plots and all transects between October 2008 and May 2010 are shown in Figure 8. It is clear that soils at sites of *T. medusa* ms are always wetter than those of the two other species, and soils of *T. indica* are generally driest, although *T. auriculata* at transect B is at least as dry as the *T. indica* sites. Peak moisture contents were associated with the rainfall of early 2009, and soils dried slowly since then, in the absence of large storms. Soils are drier near the surface than at depth, which presumably reflects evaporation from the surface.

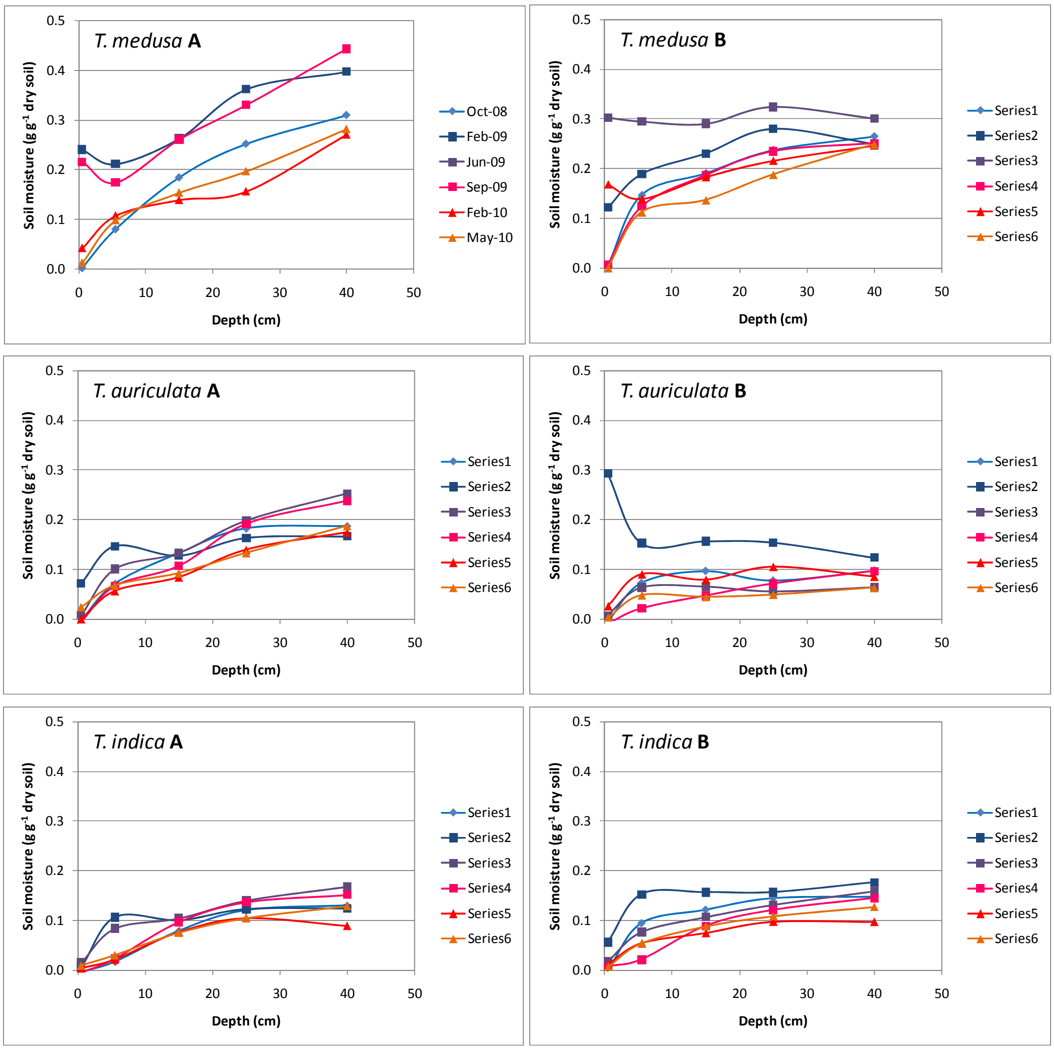


Figure 8. Soil moisture profiles for the top 50 cm of the soil at transects A and B for all three species. Means are shown for both plots of each species. Sampling intervals are 0-1 cm, 1-10 cm, 10-20 cm, 20-30 cm and 30-50 cm, and values for these intervals are plotted at their mid-point depths.

The soil moisture data are further summarised in Figure 9, showing trends over time for the amount of water contained in the top 50 cm of the soil. Net water loss from this top 50 cm in the non-flooded plots of *T. indica* and *T. auriculata* in the year between mid-2009 and mid-2010 has not exceeded 50 mm. As rainfall during this year was approximately 130 mm, the apparent loss of water from the top 50 cm was less than 200 mm. Given that annual potential evapotranspiration is in excess of 3000 mm, it is highly unlikely that actual evapotranspiration, i.e. all plant transpiration and soil evaporation, was less than 200 mm. As shown in the section about plant water use, there was little evidence that *T. indica* and *T. auriculata* in mid-2010 had reduced their transpiration due to limited soil water availability. It is tentatively concluded that plants must have access to water from depths beyond 0.5 m.

Two mechanisms are hypothesised to be responsible: the presence of deep roots and/or the capillary rise of water from depths >0.5 m toward the surface. Samphire plants are very likely to have roots at depths exceeding 0.5 m, but no data are available, and quantitative studies using soil pits are essential for enhanced understanding of rooting depths. In addition, soil hydraulic studies are recommended to parameterise models of soil water transport and ecosystem water balance.

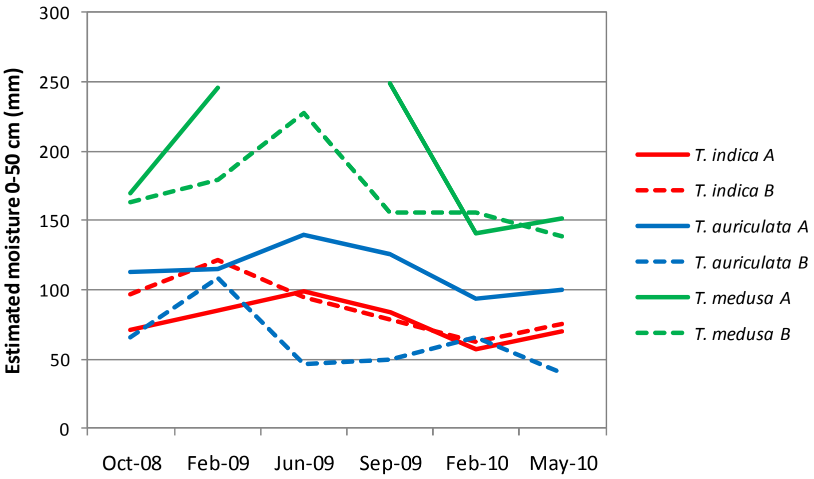


Figure 9. Total soil moisture contained in the top 50 cm of the profile, expressed in mm depth, between October 2008 and May 2010.

Selected results from the soil moisture probes, which sense soil moisture content continuously, are shown in Figure 10. These results are preliminary because the probes have not been calibrated or corrected for salinity. Nevertheless, certain trends can be discerned. The most significant rainfall in the first half of 2010 was 42 mm that fell mostly on 15 and 16 January. It can be inferred from the gravimetric samples (Figure 8) that soil moisture contents at these depths under *T. indica* and *T. auriculata* were between 0.07 and 0.17 g g^{-1}, presumably far below field capacity. Nevertheless, the 42 mm of rain reached depths of 0.5 m under both species. This may indicate that hydraulic conductivity is not as low as might be expected of clayey soils. Further calibration and confirmation of these data is required, and experimental determination of hydraulic parameters would be a useful addition to the research program.

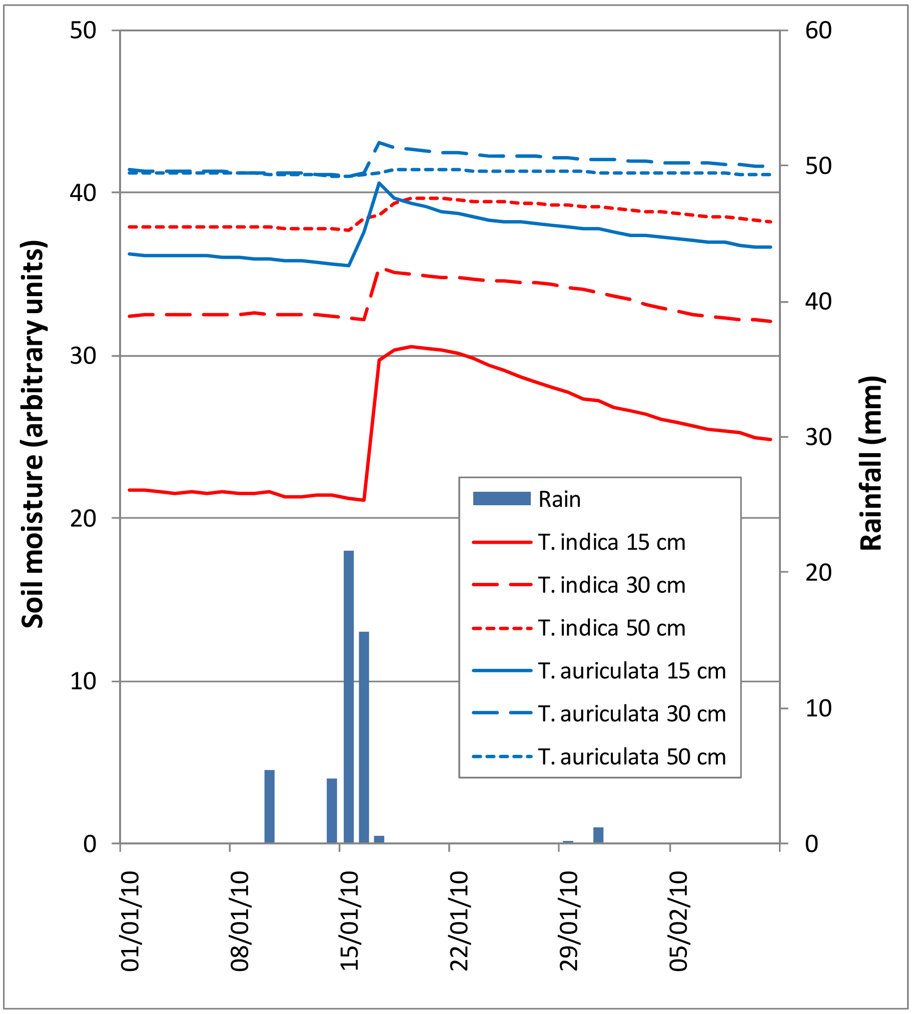


Figure 10. Soil wetting after rainfall in mid-January 2010, as measured by soil moisture probes placed at three depths in plots of T. indica and T. auriculata. Traces are means for two plots per species.

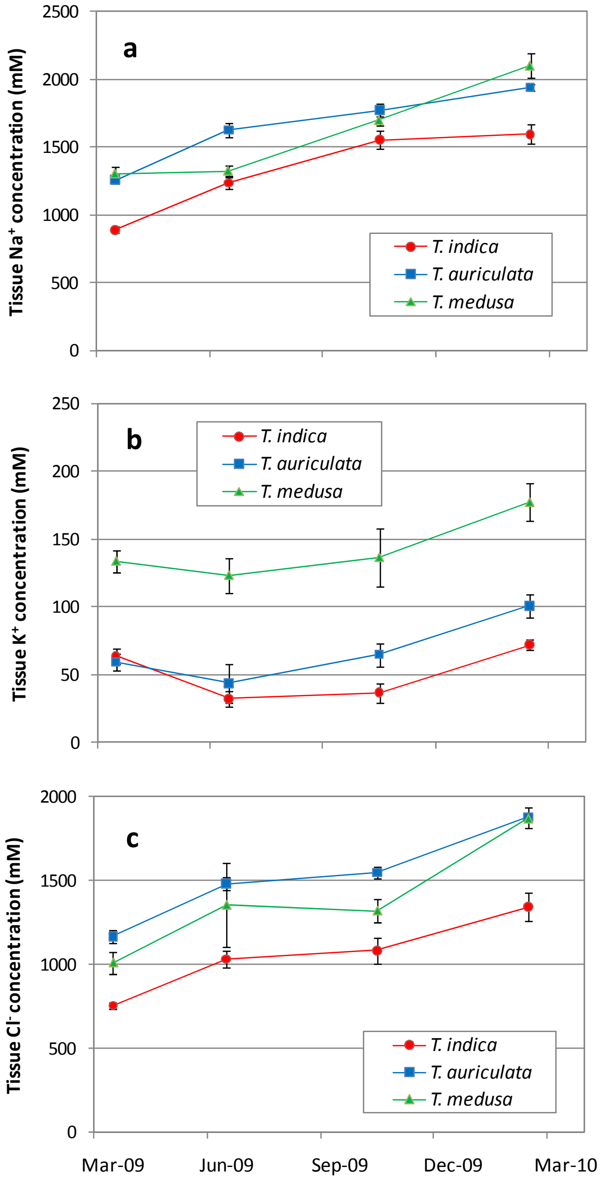
Plant solutes

Halophytes require high concentrations of solutes in their tissues to "osmotically adjust" and thus maintain their tissue water content when faced with the dehydrating influence of a highly saline environment. This adaptation to saline environments requires a tolerance to high concentrations of Na and Cl in the tissues. These ions are stored in large vacuoles, explaining the succulent nature of samphires. In the cytoplasm, where high NaCl concentrations are not tolerated, organic solutes make a significant contribution to the osmotic value, and so would K. The compound glycinebetaine has been found to occur at high concentrations in samphires, and also in many other halophytes, and is a "compatible solute", which may either be synthesized in response to salinity stress, or transported from vacuoles to the cytoplasm. Maintaining adequate concentrations of the important nutrient K is also one of the challenges for plants in highly saline environments.

Plant samples are being collected every 3 months for several analyses that relate to the environmental stresses that the samphires can likely experience. Tissue water content reflects the hydration status as influenced by soil moisture, soil salinity and evaporative demand of the atmosphere. Osmotic potential is the chemical potential of water in a solution – more negative values indicate higher concentrations of solutes in the tissue. Freeze-dried tissue samples are analysed for the inorganic ions Na, K and Cl, as well as the organic solutes sucrose, glucose and fructose (sugars) and glycinebetaine. All solute concentrations are here reported on a tissue water basis, in molar units, as this relates directly to the osmotic potential and is physiologically most relevant for tissues of succulent halophytes.

Plant samples are routinely collected from live, succulent stems, taking separate samples for fully matured stem articles, as well as the younger growing articles at tips of stems. All results reported here are for mature succulent stem articles. Apart from the solute analyses mentioned above, these samples will also be analysed for pigments, which are potential indicators of stress.

Tissues of all three species lost water between March 2009 and February 2010, a year with little rain (Figure 11a). As expected, osmotic potential became more negative over that period (Figure 11b), and concentrations of Na and Cl increased (Figure 12a,c). Concentrations of K were relatively stable initially, but later increased (Figure 12b). Most, but not all, of the increase in Na and Cl concentrations is explained by the concentration effect of dehydration. It is commonly observed that these salts accumulate in halophytes. The trends in K are probably explained by a combination of the concentration effect and difficulty of the plant to maintain K concentrations in the presence of Na concentrations. It is striking that *T. medusa* ms. has considerably higher K concentrations than the other two species, perhaps due to exceptional adaptation to salinity, in agreement with the conditions it grows in (Figure 4).



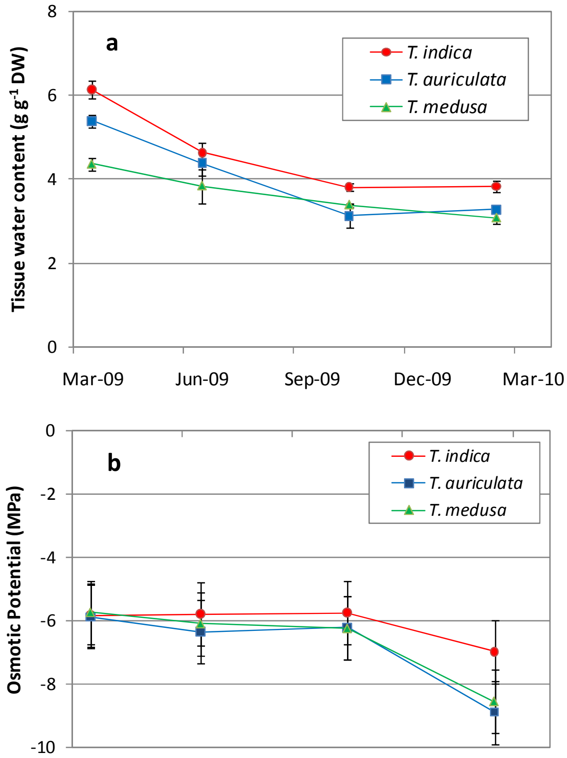


Figure 11. Water content (a) and osmotic potential (b) of fully-grown succulent stem articles of the three species between March 2009 and February 2010. Means for two plots (three samples each) at transect A.

Figure 12. Concentrations of Na (a), K (b) and Cl (c) in fully-grown succulent stem articles of the three species between March 2009 and February 2010. Means for two plots (three samples each) at transect A.

Concentrations of sugars (sucrose, glucose and fructose) and glycinebetaine have thus far been analysed in selected samples only. The relative proportions of sucrose, glucose and fructose were reasonably constant (approximately 19, 36 and 45% of total sugars, in molar units), so only the combined total concentration of sugars is reported here. From March 2009, when soil moisture was high, to February 2010, when soil moisture had significantly decreased, there were decreases in tissue sugar concentrations, possibly not statistically significant, and an increase in glycinebetaine concentration for one species (Figure 13). Glycinebetaine concentrations were not different between the three species, but sugar concentrations were consistently higher in *T. indica* than *T. auriculata*, but higher still in *T. medusa* ms.

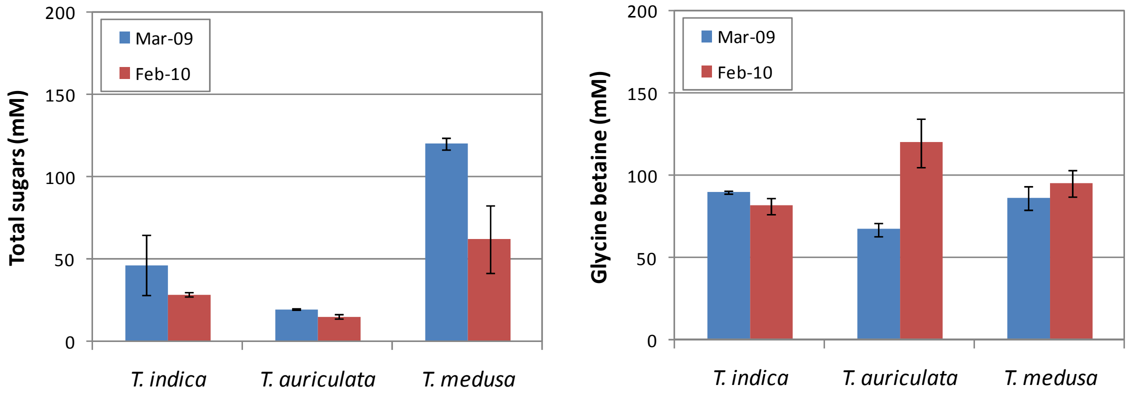


Figure 13. Sugars and glycinebetaine concentrations in fully-grown succulent stem articles of the three species. Data are for March 2009 (soon after significant rainfall) and February 2010 (after a year with very little rainfall). Means for two plots (three samples each) at transect A.

Another group of samples presented here is that of *T. medusa* ms sampled at the time of an artificial flooding event at transect A. Data for the same species at transect B, where natural flooding had receded, are shown for comparison (Figure 14). The flooded plants at transect A had much higher concentrations of sugars and somewhat lower concentrations of glycinebetaine. Three months earlier, in March 2009, when *T. medusa* ms sites were experiencing natural flooding or waterlogging, sugar levels were also high, but by June 2009 sugar concentrations had decreased substantially at transect B, whereas they increased somewhat at transect A, presumably due to prolonged flooding (Figure 14). Interestingly, glycinebetaine in *T. medusa* ms at both transects had decreased by about 50% in the June sampling (Figure 14), relative to the summer samplings (Figure 13); the possibility that glycinebetaine increases during the higher temperatures in summer months deserves to be tested experimentally.

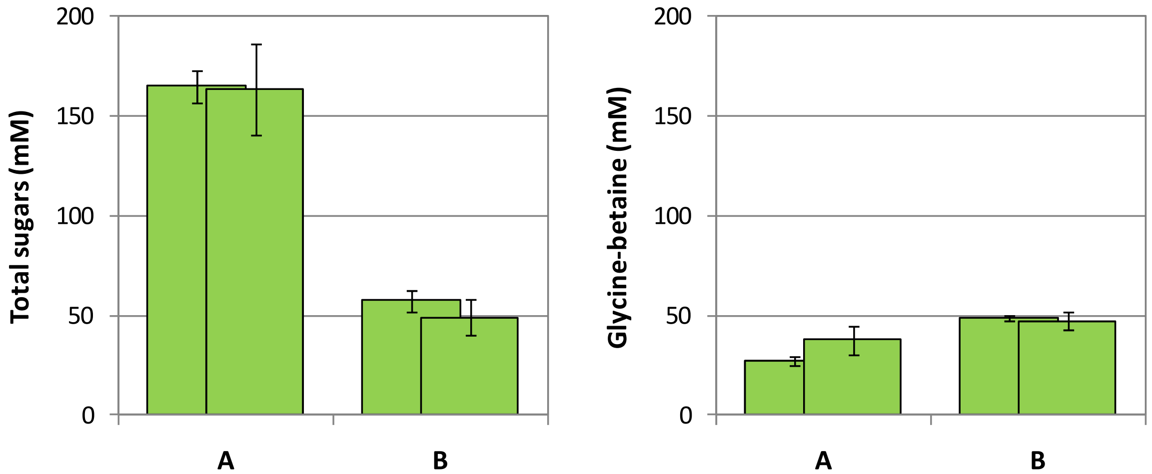


Figure 14. Sugars and glycinebetaine concentrations in fully-grown succulent stem articles of *T. medusa* ms collected June 2009 in the field, when plots at transect A were flooded due to discharge from Cloudbreak mine-site, while plots at transect B had only experienced natural flooding. The two bars for each transect represent the two plots (each with three samples).

A batch of samples for June 2009 showed that sugar concentrations (on a dry mass basis) were 40% less in growing tissue, glycinebetaine were 40% more. This is consistent with the idea that sugar concentrations are low when demands are high (e.g. demands for growth and energy in young tissue). The higher glycinebetaine concentrations in younger tissues may be explained by the higher ratio of cytoplasm:vacuolar volumes (i.e. lower degree of vacuolization).

Plant growth

Growth of plants in the field is assessed in the project in two ways. Firstly, changes in plant size over the duration of the project are quantified by measuring plant height and crown dimensions at the start and end of the project. Secondly, gains and losses of green succulent articles are assessed 3-monthly by measuring shoot extension and lignification on tagged branches. The branch-level measurements have not been processed yet for presentation and so can not be reported. Plant dimensions were measured at the start of the project (late 2008), and are presented here as these data also provide insight into plant morphology and in the population structure, and hence, recruitment ecology.

Data are based on 3 m x 10 m quadrats in all plots. For each plant, total height as well as length and width of the crown were measured. For *T. auriculata*, height of the lowest green branch was also measured as this species posesses a real stem that lifts the crown above the ground. Crown volume was estimated assuming an ellipsoid shape, using length, width and depth (height).

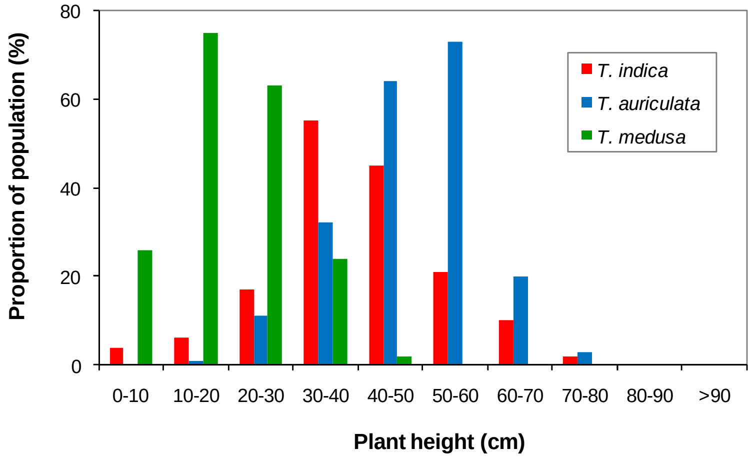


Figure 15. Population structure of the three *Tecticornia* species in late 2008. Data pooled for 2 quadrats at each transect (i.e. 4 quadrats per species in total).

Sizes of all three species are approximately normally distributed (Figure 15), with average heights of 40, 49 and 20 cm for the species *T. indica*, *T auriculata* and *T. medusa* ms, respectively. The greater height of *T. auriculata* is due to its tree-like growth form, with a crown elevated on a single main stem of about 20 cm. It only has green succulent articles on the main stem when a juvenile. The elevated crown may offer protection from inundation. *T. medusa* ms, which is found at lower elevations in the marsh, does not have this elevated crown, and must therefore have other adaptations to submergence. Submergence tolerance of juvenile individuals is unknown but is being investigated in a glasshouse experiment.

A striking result for all three species is the prominence of mid-sized plants. Populations that are continuously rejuvenating would have a much larger number of small plants. This observation suggests that the current populations are likely the result of large recruitment events in the past for each species. Samphires are known to recruit massively after floods. Some recruitment of *T. medusa* ms was observed in the field after the floods of early 2009, but few of the seedlings seem to have survived. The 2011 measurement of the population will show if this event was significant.

A plot of crown volume against plant height (Figure 16) shows the key differences in plant morphology of the three species. It must be noted that apart from the study plots, insufficient populations of *T. medusa* ms have been observed to tell if the smaller size of this species is partly due to a younger age. A few larger individuals were observed outside the plots, but nowhere did these seem to attain the heights that *T. auriculata* attains. *T. auriculata* has smaller crown volumes at a given height compared to *T. indica*, due to the absence of a stem that elevates the crowns of the latter species. Both *T. indica* and *T. medusa* ms branch profusely from ground level, and the height-volume relationship is thus much more similar for these two species.

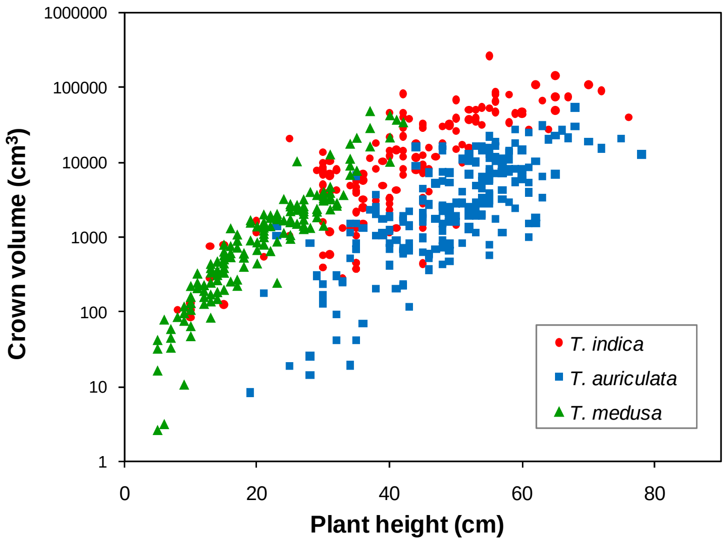


Figure 16. Plant dimensions of the three *Tecticornia* species, showing a good relationship between plant height and crown volume.

Plant water use dynamics

Information on plant water use of the three *Tecticornia* species is being collected using sapflow techniques and gas exchange techniques. Sapflow measures the velocity at which water flows through the xylem in a plant stem. It therefore relates to the entire crown if the sapflow probes are inserted in the main stem, and velocities can be scaled to volumes of water by taking into account the cross-sectional area of active sapwood. Sapflow is recorded at 30-min intervals and logged automatically. Data currently available are from three plants each of *T. indica* and *T. auriculata* at transect A, measured from October 2009 to May 2010. Measurements are ongoing and will be expanded with greater replication to capture the transition from winter to summer and the response to rainfall events. *T. medusa* ms plants are not being measured due to the likeliness of flooding which would damage the equipment. Data presented here have not been fully calibrated and should be interpreted with caution, however identification of trends over time and correlation with weather conditions is valid.

Gas exchange techniques measure the uptake of CO_2 (photosynthesis) and loss of water vapour (transpiration) at the scale of leaves or small branches. These measurements are carried out at 3-monthly intervals on all three species. While limited to a single time of day and four days per year, these measurements provide additional insights into the physiological condition of the species, and can be related directly with the water status and chemical properties that are assessed for those same points in time. Gas exchange measurements will not be presented in the current report. One observation is worth mentioning, however, namely that gas exchange measurements confirm that *T. indica* is a species with C4 photosynthesis. Due to biochemical differences, C4 plants can achieve a higher rate of photosynthesis at a given stomatal conductance (or the same rate of photosynthesis at a lower conductance) than C3 plants. As stomatal conductance is directly linked with transpiration rates, this means that C4 plants have a greater water use efficiency than C3 plants in the same environment. C4 plants are often found in warm climates prone to drought. *T. indica* is therefore expected to be more tolerant of dry soil than *T. auriculata* and *T. medusa* ms.

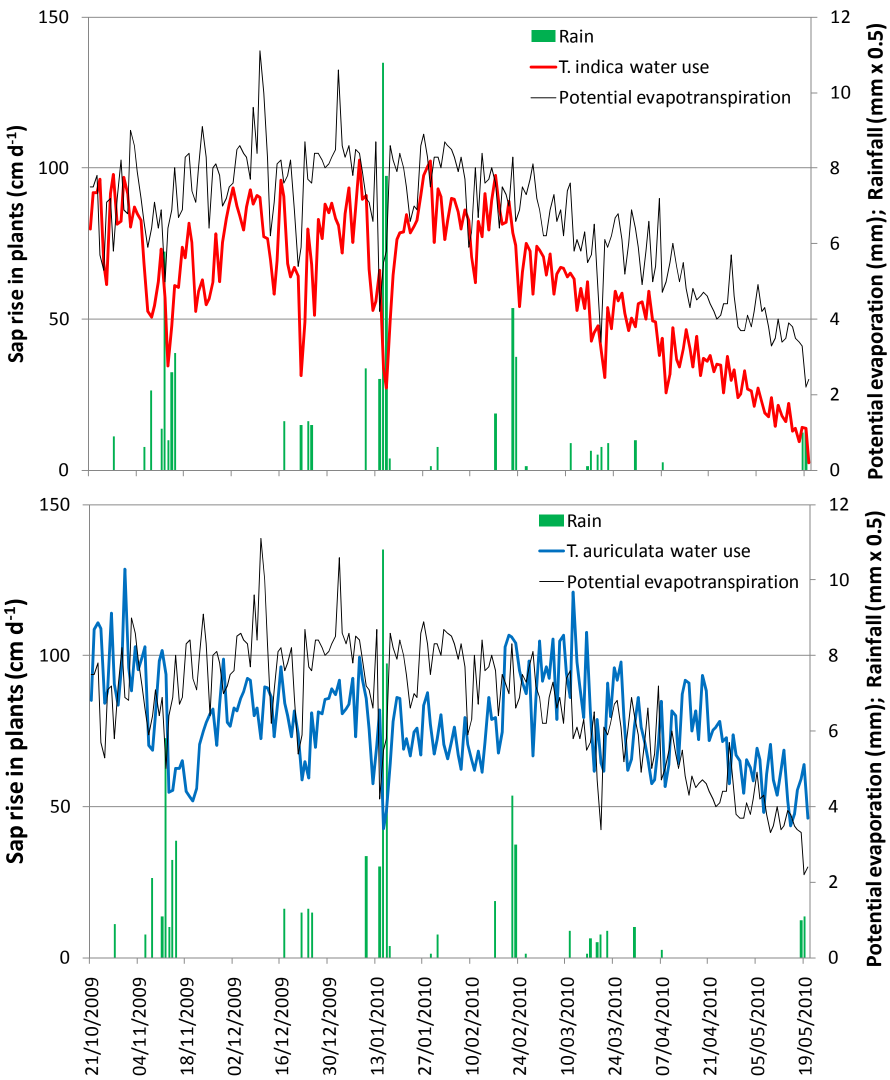


Figure 17. Sapflow (daily rise of water in stem xylem) of *T. indica* and *T. medusa* ms between October 2009 and May 2010 at transect A. Data are means for three plants per species. Potential evapotranspiration and rainfall are shown for comparison.

Sapflow of both *T. indica* and *T. auriculata* suggests good access to soil moisture between October 2009 and May 2010, despite the fact that rainfall over this period was only 124 mm, and that there had been no significant rainfall in the 7 months prior to that. Figure 17 shows that *T. indica* sapflow rates remained high until February 2010, and declined gradually after that month, which is consistent with the decline in evaporative demand. The importance of weather as a driver of transpiration is supported by a good correlation with potential evapotranspiration (Figure 18). Sapflow velocities of *T. auriculata* were similar to those of *T. indica* and only started to decrease in March/April 2010, when potential evapotranspiration had already started do decline. In accordance with this, the correlation with evapotranspiration was poorer for this species. Neither *T. indica* nor *T. auriculata* responded to rainfall events by increasing rates of sapflow, indicating that some or all of their roots were in soil that was moist enough to allow stable uptake. Moreover, comparison of diurnal patterns of water use (Figure 19) suggests that drought stress was not more severe in April 2010 than October 2009. Drought-stressed plants usually show midday and/or afternoon stomatal closure. Based on this evidence, we tentatively conclude that both species had adequate access to soil moisture, and that even after a relatively dry year, water uptake and transpiration were driven by weather conditions rather than soil moisture. Given that soil moisture content in the top 0.5 m of the profile at these sites actually increased rather than decreased between February and May 2010 (Figure 9), it is likely that the majority of the water used by these plants is taken up at depths below 0.5 m.

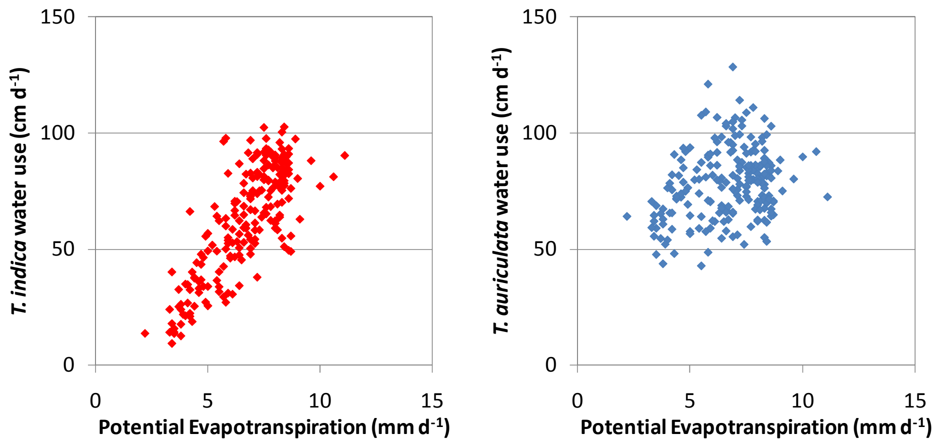


Figure 18. Relationship between sapflow and potential evapotranspiration for days between October 2009 and May 2010. The correlation is tighter for *T. indica* than for *T. auriculata*. Non-zero intercepts are most likely due to baseline (zero-flow) corrections which still need to be carried out.

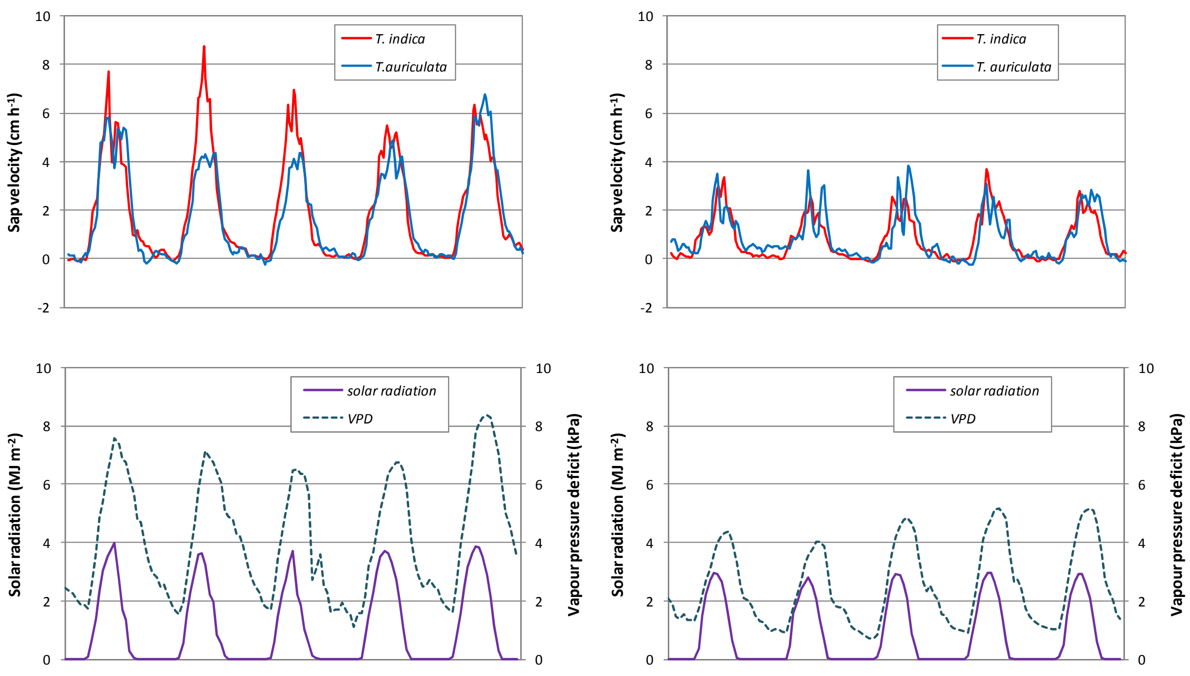


Figure 19. Diurnal courses of sapflow in *T. indica* and *T. medusa* ms for 26-30 October 2009 (left panels) and 27 April-1 May 2010 (right panels) at transect A. Data are means for three plants per species. Solar radiation and vapour pressure deficit (lower panels) show that the

days were quite similar during each 5-day period shown, but energy available for transpiration and evaporative demand were less in April than in October.

General conclusions and implications of the field observations are presented at the end of this report.

Controlled exposure to drought and salinity

Description of approach

Experimental studies under controlled conditions enable comparisons of species responses to imposed environmental conditions (e.g. salinity, water deficit, flooding) without confounding factors often present in field situations. Controlled experiments help identify physiological mechanisms underlying responses observed in the more complex field environments. The project has completed several glasshouse experiments on responses to salinity and drought, with flooding experiments still in progress. These experiments have compared three species of interest (*T. indica, T. auriculata*, and *T. medusa* ms) using seed collected from Fortescue Marsh.

As germination and seedling survival of these species is variable, the approach involves: (i) germination of seeds on filter papers soaked with nutrient solution (composition given below), (ii) transplanting of seedlings into white sand in tube stocks, with this irrigated frequently with nutrient solution, (iii) transplantation of uniform seedlings into larger pots in which the plants are then allowed to establish further, after which defined treatments are imposed. These larger pots contained white sand over gravel (salinity and flooding experiments) or a mixture of white sand:perlite (1:3, v/v) so as to increase initial water-holding capacity for the draw-down experiments to impose water deficits (i.e. “drought”).

The nutrient solution composition was as used previously in earlier species of *Tecticornia pergranulata* (e.g. Colmer et al., 2009), and contained (in mM): K_2SO_4, 4.7; $CaCl_2•2H_2O$, 9.3; Na_2SO_4, 5.0; $MgSO_4•7H_2O$, 1.0; $Ca(NO_3)_2•4H_2O$, 0.7; K_2HPO_4, 0.3; $NH_4H_2PO_4$, 0.2; Fe-EDTA, 0.05; H_3BO_3, 6.25 x 10^{-3}; $MnSO_4•H_2O$, 5.0 x 10^{-4}; $ZnSO_4•7H_2O$, 5.0 x 10^{-4}; $CuSO_4•5H_2O$, 1.25 x 10^{-4}; $Na_2MoO_4•2H_2O$, 1.25 x 10^{-4}. pH was adjusted to 6.5 using KOH. This solution provides all essential mineral nutrients for plant growth, and also contains the high background concentrations of Ca and K typical for saline environments such as salt lakes and salt marshes (i.e. marine-based salinity), so that NaCl treatments across a large range can then be imposed within this “basal nutrient solution”. All experiments were conducted in glasshouses located at UWA, Crawley (Perth), Western Australia.

Destructive harvests of plants were taken at the commencement and end of treatment periods (details given in figure captions), so that growth rates during the imposed conditions could be calculated. Growth was expressed at the relative growth rate, RGR (i.e. increments in mass per unit of existing mass per unit time), using the formula: RGR = (ln W2 – ln W1)/time ; where ln is the natural log, W2 and W1 are plant weights at the final and initial samplings, respectively, and time is the number of days between samplings.

At samplings, shoots were excised and separated into fractions (e.g. sub-samples of recently fully-expanded succulent stem articles were taken for chemical analyses), fresh mass determined, and samples were either snap-frozen in liquid N_2 and then freeze-dried or oven dried (60°C), and dry mass determined. Tissue water content was calculated from the fresh and dry mass values. Sub-samples of succulent stem articles were placed into cryovials, frozen in liquid N_2, and then expressed sap was analysed for osmotic potential using an osmometer. Freeze-dried tissues were used for chemical analyses. These were pulverised in a ball mill prior to sub-samples being used for the various assays.

Sugars were extracted in 80% ethanol boiled with reflux for 20 min, twice. Total sugars in the extracts were measured using anthrone (Yemm and Willis, 1954). Ethanol-insoluble dry mass was determined by weighing the dried pellet left after the sugar extraction. Glycinebetaine and proline in these extracts was determined using high performance liquid chromatography (HPLC) (Naidu, 1998) equipped with a Sugar-Pak column (300 mm length, 6.5 mm diameter; Waters Corporation) housed in a column heater at 90^{o}C. Reliability of these methods was confirmed by recovery checks of glycinebetaine, sugars, and proline spiked into a sub-set of tissue samples at the time of extractions.

Ions were extracted by shaking in 5 ml of 0.5 M nitric acid for 2 days. Na and K were measured in dilutions of extracts using a flame photometer (Model PFP7, Jenway/Barloworld Scientific, Essex, England). Cl was measured using a Buchler-Cotlove Chloridometer (Buchler Instruments, Model 4-2000, New Jersey, USA). Reliability of these methods was confirmed by analyses of a reference tissue taken through the same procedures.

Salinity dose response

As described in the section containing field data, *Tecticornia* species at Fortescue Marsh grow in highly saline soils, but with gradients in salinity across the marsh and temporal changes also occur owing to differences in soil water status with time (salts diluted in wet periods and concentrated during dry periods. Thus, growth responses to NaCl of the three *Tecticornia* species were evaluated under controlled conditions in well-drained sand cultures (Figure 20).

The lowest NaCl treatment used was 10 mM NaCl, as succulent halophytes have previously been shown to require some NaCl otherwise growth is severely inhibited (summarized in Flowers & Colmer, 2008). All three *Tecticornia* species showed enhanced growth as NaCl was increased from the basal 10 mM upto 600 mM NaCl, and growth was only reduced when exposed to 1200 mM NaCl (Figure 20). The impressive levels of salt tolerance are put into some context by considering that seawater typically contains ~ 500 mM Na, so these plants can grow at levels of salinity well above 2-times seawater and *T. auriculata* and *T. medusa* ms even survived the extreme salinity of 2000 mM (4-times seawater), but *T. indica* died at 2000 mM.

Soil salinity imposes stress onto plants via three main mechanisms: (i) toxicity of Na and Cl when these exceed tolerable levels in tissues, (ii) the dehydrating effect of the very negative osmotic potential owing to dissolved salts, causing “physiological drought”, and (iii) possible nutrient deficiencies that can develop if high NaCl interferes with nutrient uptake, for example depressed K absorption by roots (Munns & Tester, 2008). The high tolerance of succulent stem tissues of *Tecticornia* species is discussed in the next section, in which tissue solute data are presented (data on solutes in this dose-response experiment will also become available during the current project). Here we consider the capacity of succulent stems to generate the negative osmotic potentials required to maintain favourable gradients, relative to the external medium, for tissue water retention (Figure 20). The decline in osmotic potential of the external medium as salinity increases is shown for the NaCl treatments used. All three *Tecticornia* species generate negative tissue osmotic potentials by accumulation of ions when grown at low salinity, and although the difference between external and tissue osmotic potential declines as salinity is increased, the tissues still maintain a lower tissue osmotic potential (i.e. a favourable gradient for water retention) at 1200 mM NaCl. Halophytes achieve such a lowering of tissue osmotic potential relative to the external medium by regulation of Na and Cl uptake (e.g. *T. pergranulata*, Short & Colmer, 1999), and compartmentation of these ions into vacuoles, so that these are kept away from sensitive metabolic sites (Flowers & Colmer, 2008). Compatible organic solutes are accumulated in the cytoplasm and organelles. For the three *Tecticornia* species from Fortescue Marsh, when salinity was extreme (2000 mM NaCl), however, the osmotic gradient appears no longer to be maintained. Failure to maintain tissue water, possibly also in combination with tissue ions exceeding tolerable levels, can then lead to death when extreme salinity occurs. Nevertheless, the levels of salt tolerance shown in the present project for these three *Tecticornia* species would rank these plants amongst the most salt tolerant vascular plants documented world-wide.

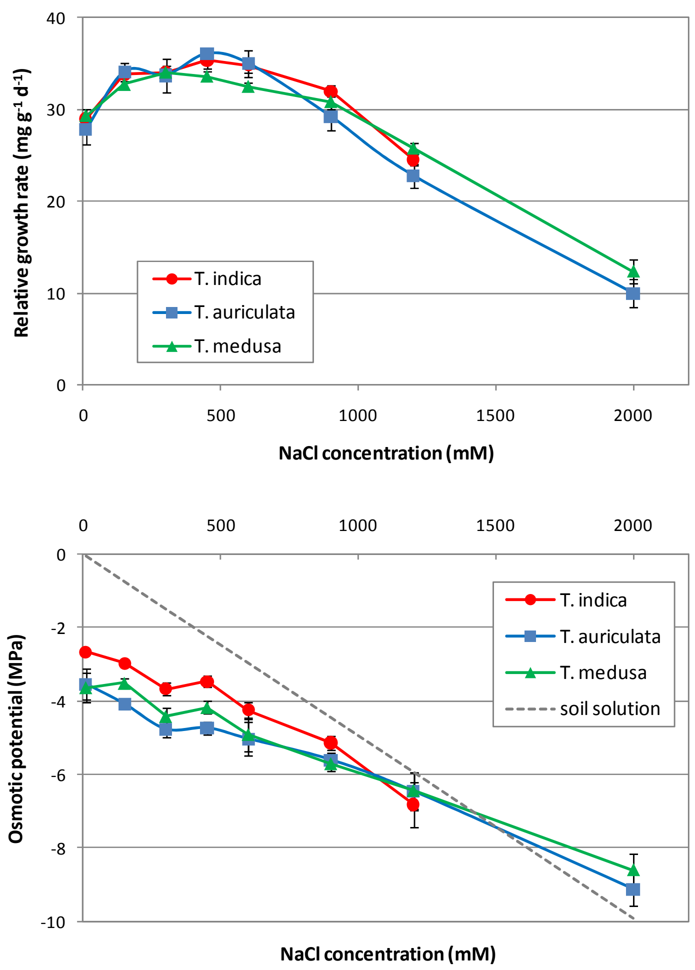


Figure 20. Shoot relative growth rate (increase in dry mass per unit of dry mass present per day), and osmotic potential of sap expressed from recently fully-expanded succulent stem articles, for plants exposed to NaCl salinity ranging from 10 to 2000 mM in a complete nutrient solution. Plants were in pots containing white sand regularly flushed with the treatment solutions.

Drought, salinity, and their interaction

Declines in soil moisture will eventually expose plants to potential dehydration, and in addition for saline soils the concentrations of ions also increase as soil water is depleted. Two companion glasshouse experiments were conducted to evaluate the influence of water deficits (soil drying), and also the effects of progressive increases in soil salinity at different rates over time, on the three *Tecticornia* species.

All three species survived a 7-week period of withholding water that resulted in soil water contents decreasing from 0.36 to approximately 0.14-0.25, depending on species and treatment, as the rate of water consumption depends on plant size and transpiration rate (Table 2). The experiment was conducted at two starting levels of salinity (10 and 200 mM NaCl) which would have increased to ~14-18 mM and ~ 320-420 mM NaCl, respectively, as the soil dried (Table 2). All three species survived the drying event, but growth of *T. indica* was reduced less than that of the two other species (Figure 21). The growth data cover the entire drying period, so that most growth presumably occurred during the earlier periods when water was available. A major aim of the experiment conducted was to also assess recovery upon re-watering, so the threshold level causing death was not determined in the present work, but important information on the capacity to recover was obtained. Upon re-watering for an additional 7-week period, growth rates returned to the levels observed in well-watered plants in all three species (data not shown). These results support the notion that *T. indica* (with C4 photosynthesis and a higher Water Use Efficiency, data not shown) performs better than *T. auriculata* and *T. medusa* ms (both C3 species) when water supply is restricted, but that even these species from further out on the marsh can withstand short periods of moderate water deficit.

Table 2. Soil water content and its estimated NaCl concentration at the end of the drought experiment. Initial soil water content was 0.36 g g^{-1} DW. Initial salinity was as listed under the heading 'Treatment'.

	Treatment	**Soil water (g g^{-1} DW) day 54**	**Estimated concentration of NaCl in soil moisture (mM) day 54**
T. indica	10 mM	0.203	18
	200 mM	0.211	342
T. auriculata	10 mM	0.135	27
	200 mM	0.171	422
T. medusa ms	10 mM	0.251	14
	200 mM	0.224	321

An experiment to investigate root morphological and anatomical adaptations to drying of the upper soil layers is currently in progress to add more information on how these *Tecticornia* species acclimate to drying soils. Future work will be needed to determine the threshold levels of soil water content for survival (including the lower limit for water extraction), and should also test responses to soil drying with higher commencing levels of salinity.

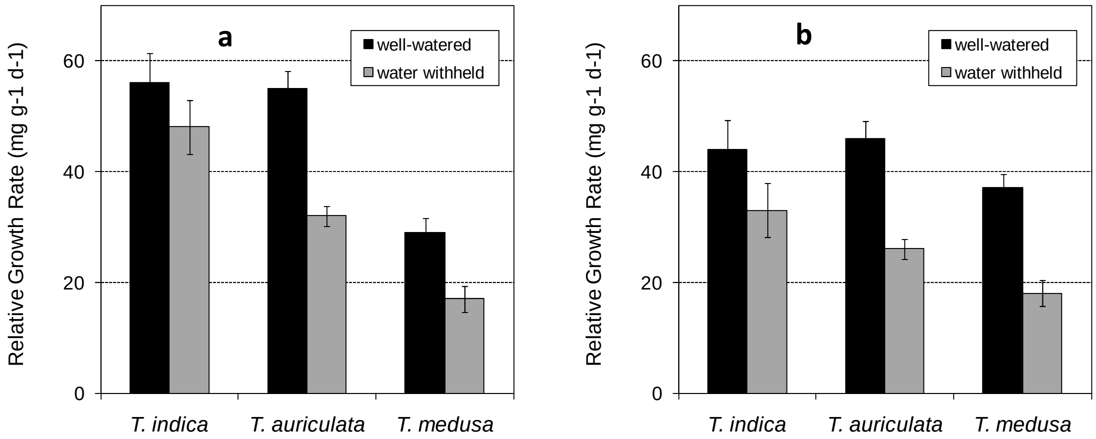


Figure 21. Relative growth rate (increase in shoot dry mass per unit of dry mass present per day) during a 7-week period that plants were either watered or had water withheld, at two starting salinity levels: a.10 mM NaCl; b. 200 mM NaCl.

In a second experiment, plants were also exposed to gradual increases in soil salinity, but in well-watered pots (thus mimicking the effect on increasing salinity in a drying soil, but without the drying). Salinity was either maintained at an optimal level for growth (viz. 200 mM NaCl), or was increased 30, 60 or 90 mM NaCl per week to result in final levels of 710, 1200, or 1710 mM, respectively. The results confirmed the earlier dose-response response experiment (described above), that the three *Tecticornia* species are very salt tolerant, as all plants survived even the highest NaCl level imposed. Interestingly, *T. indica* showed no significant impact of salinity on growth rate, up to the highest concentration of 1710 mM NaCl, whereas growth of *T. auriculata* and *T. medusa* ms were both reduced by approximately 50% at that highest level. Although the present experiment did not reach 2000 mM NaCl, the greater tolerance of *T. indica* in the present experiment at 1710 mM contrasts with death of this species only in the earlier dose-response experiment (Figure 20). This could be due to the threshold for tolerance not yet being reached, or more likely the longer step up time to reach high NaCl levels could have enabled plants to acclimate more fully than the more rapid increases in salinity used in the dose-response experiment. Future experiments should be conducted to resolve this issue, but clearly the conclusion that all three *Tecticornia* species are all highly salt tolerant is further supported by these data.

The lack of, or only small, declines in growth of all three species as NaCl was increased to 1200 mM (Figure 22) indicates that the growth reductions in the soil drying experiment conducted with 10 mM NaCl (Figure 21a) were caused by soil water deficits, rather than the effect of concentrating NaCl which on a bulk soil basis would have reached less than 30 mM (Table 2). Even in the drying soil that commenced with 200 mM NaCl, bulk soil NaCl was only estimated at 320-420 mM, so again the changes observed in the drying soils were most likely the impact of water deficits, as salinity only approached these high levels as the soil became very dry in the final weeks. Moreover, the dose-response experiment (Figure 20) demonstrated little effect of salinity on growth below NaCl concentrations of 600 mM.

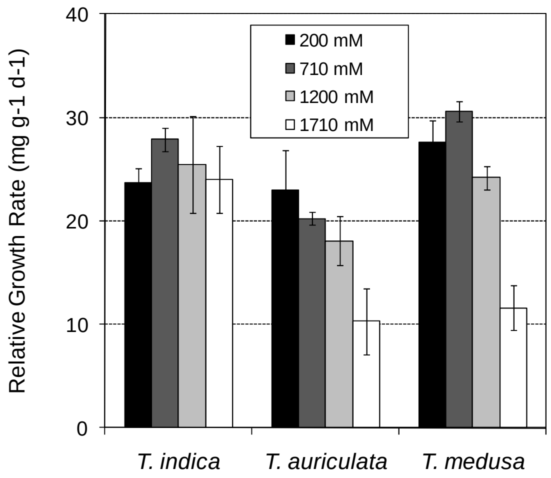


Figure 22. Relative growth rate (increase in shoot dry mass per unit of dry mass present per day) during an 8-week period for well-watered plants where salinity was gradually increased by 0, 30, 60 or 90 mM NaCl per week to the final levels indicated in the legend.

In addition to growth responses to soil drying and increasing soil salinity, tissue physiological parameters were also assessed. Plants grown at 10 mM NaCl had lower tissue water contents than those at 200 mM NaCl, but in both cases when water was withheld tissue water content decreased. These decreases in tissue water content would have increased the concentrations of solutes in the tissues, contributing to declines in tissue osmotic potential. The solutes contributing to osmotic potential differed markedly between plants at 10 and 200 mM NaCl, with K being much higher in tissues of plants at the low salinity, and tissue K declined as tissue Na increased in plants at 200 mM NaCl (Figure 23).

The drought treatment caused a doubling of tissue sugar concentrations in all three species (Figure 24), but had smaller effects on tissue Na and Cl concentrations (Figure 23). During recovery from drought, sugar concentrations returned to “normal” levels as seen in the well-watered control plants. Glycinebetaine was present at osmotically-significant concentrations, especially if this solute is compartmentalized into the cytoplasm during high salinity, although the levels of this well-known compatible organic solute did not increase in response to the drought treatment (Figure 24).

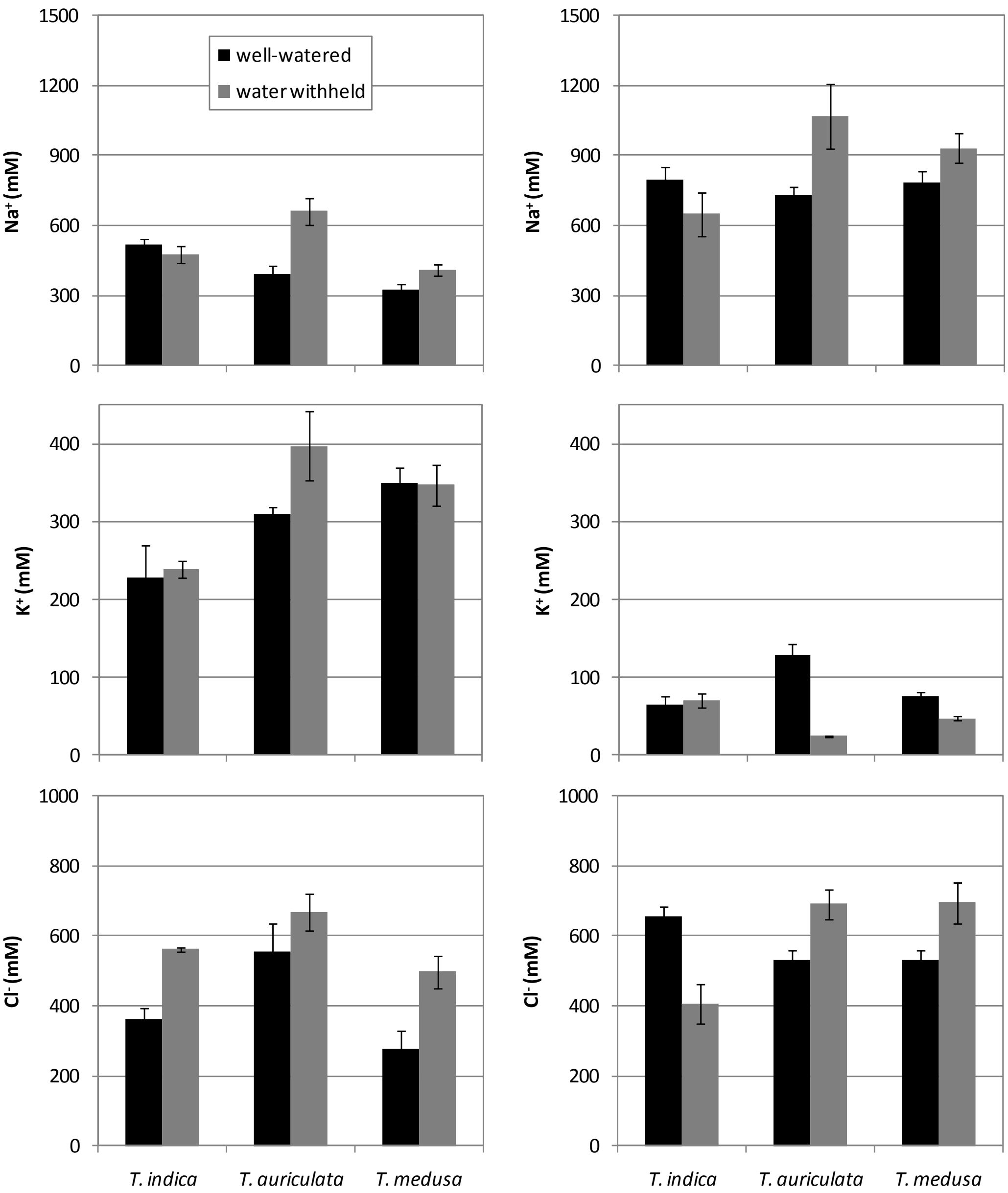


Figure 23. Concentrations of Na (a,d), K (b,e) and Cl (c,f) in fully-grown succulent stem articles of plants that were either watered or had water withheld, at starting salinity levels of 10 mM NaCl (a-c; left) or 200 mM NaCl (d-f; right).

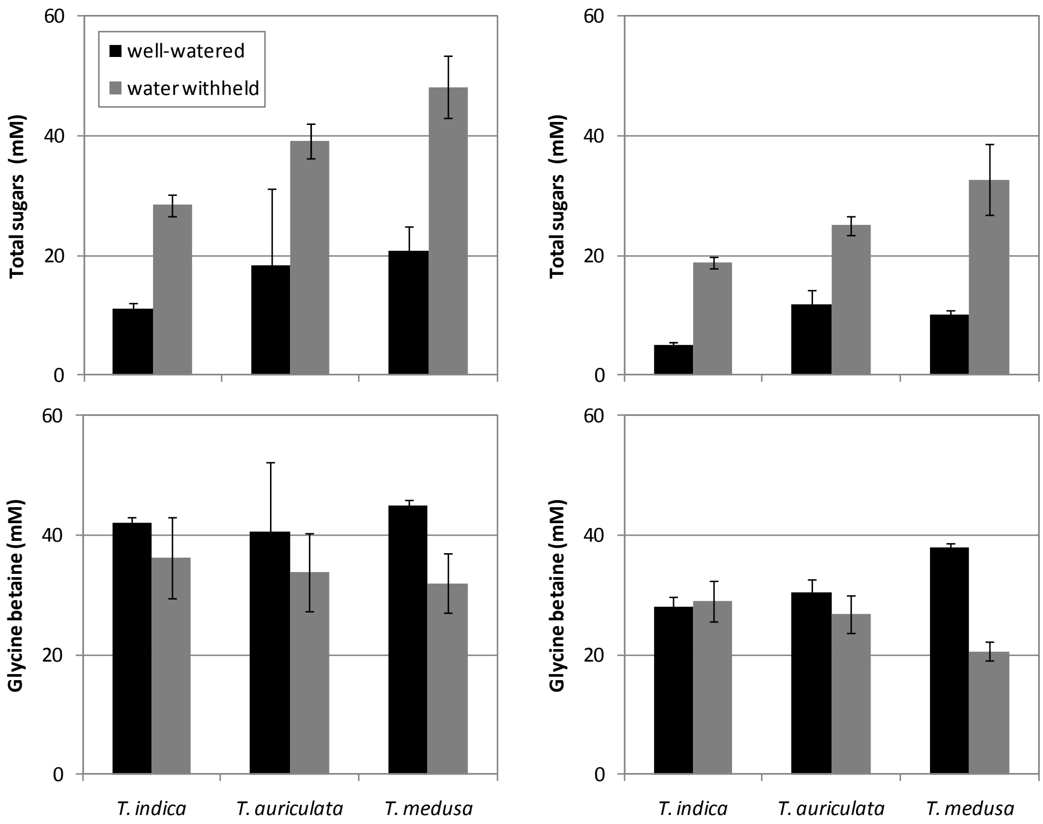


Figure 24. Concentrations of total sugars (glucose, fructose and sucrose; a,c) and glycinebetaine (b,d) in fully-grown succulent stem articles of plants that were either watered or had water withheld, at starting salinity levels of 10 mM NaCl (a-b; left) or 200 mM NaCl (c-d; right).

Conclusions from controlled experimental research

- Three *Tecticornia* species from Fortescue Marsh studied in the present work are highly salt tolerant. *T. auriculata* and *T. medusa* ms survived 2000 mM NaCl (~ 4-times seawater), but *T. indica* did not. *T. indica*, however, was most tolerant when high salinity was imposed gradually. These plants are amongst the most salt tolerant recorded world-wide.
- Growth of all three species is optimal over a wide salinity range, only decreasing at low salinity (10 mM and below) and also above 800 mM. Extreme salinity (e.g. 2000 mM NaCl) impedes growth and even caused death of *T. indica*, resulting from failure to cope with the high osmotic stress causing tissue water content to decline and possibly also in combination with tissue ions exceeding tolerable levels.
- *T. indica* (with C4 photosynthesis) has higher Water Use Efficiency and performs better than *T. auriculata* and *T. medusa* ms (both C3 species) when water supply is restricted.
- The three *Tecticornia* species tolerated the combined effects of water deficit and increasing salinity in remaining water, but higher salt levels combined with soil

drying need to be tested to establish threshold levels causing death. Tissue solute regulation for osmotic adjustment is one tolerance mechanism common to both salinity and drought stress.

Priorities for future work under controlled conditions

- Salinity tolerance thresholds (i.e. levels causing death) should be investigated for the various species, but with different rates of increases in salinity so that full acclimation to increasing salinity can be assessed, and so that threshold levels might better resemble responses to soil conditions in which salinity is expected to increase gradually. Recovery from periods at extreme salinity, with salts decreased again, should be included in these assessments. Survival, growth, water use and tissue-level physiological responses should be measured.
- Thresholds for tolerance of water deficits should be determined, at a range of starting levels of soil salinity. Responses should be assessed under moderate and high temperatures, also with moderate and high humidity (i.e. vapor pressure deficits). Survival, growth, water use, and tissue-level physiological responses should be measured. The lower threshold for water extraction from soil, including that from Fortescue Marsh, should be determined.
- Experiments are currently underway to assess flooding tolerance of the three *Tecticornia* species. Depending on the outcomes of current work, follow up experiments on this aspect might also be warranted.
- Measurements of whole plant water use, using sap flow sensors installed into plants grown in deep PVC columns (e.g. 1.5 m columns), with and without a perched water table at depth, would provide valuable data on patterns of water use by plants with or without access to a watertable. Data on root biomass and lengths at various depths in these deep pots would also be highly valuable to understanding root traits of the species studied.

Monitoring indicators

All variables and properties measured and derived in the field and/or glasshouse are potentially valuable as indicators of stress. They are proving useful for interpreting the functioning and health of individual plants and the population, however many of these indicators are difficult to observe or collect, and their interpretation can be complex. Table 3 summarises advantages and disadvantages.

Table 3. List of potential stress indicators for *Tecticornia* species, with advantages and disadvantages of each also given. * indicates part of the present study, but data not yet available. ** indicates not part of the present study, but listed as this indicator could be evaluated as part of future work.

Potential indicator	Comments	Advantages	Disadvantages
Na and Cl	Responds to large changes in salinity, but also changes during		Salinity increases in drying soils, so impossible to unravel

	drought. If expressed on a tissue dry mass basis, perceived responses to drought would likely diminish		the two effects
K	Responds strongly at low levels of salinity		Low salinity is not a key stress condition likely to require monitoring
Osmotic potential	Responds to salinity and drought		Alone can not distinguish between salinity and drought
Water content	Responds to salinity and drought		Alone can not distinguish between salinity and drought
Sugars	Responds to salinity and drought, but in opposite directions, unless extreme salinity is reached	A responsive component, expected to change within days	Potentially useful, but without additional information might be difficult to interpret.
Glycinebetaine	Not very responsive on a whole tissue level to salinity or drought		Not responsive, but seasonally variable.
Proline	Not responsive to salinity (below detection in these *Tecticornia* species), response to drought needs to be checked		Below detection in these *Tecticornia* species
Pigments*	To be evaluated as part of the present project (data not yet available)	Potentially easy to measure as spectral changes detected by affordable hand-held devices. May correlate with remotely sensed hyperspectal data	Requires species-specific calibrations for threshold levels. No knowledge presently available for *Tecticornia* species. Monitoring frequency would need to be determined, otherwise only “snap shots” available
Shoot gas-exchange	Measurements of net photosynthesis (CO2 uptake) and transpiration (tissue water loss)		Time-consuming measurements requiring specialized equipment. Only “snap shots” available
Sap-flow (heat pulse)	Measurements of water flow in xylem along stems and branches of plants	Continuous monitoring of whole plant water use. Direct assessment	Requires expensive equipment, including weather station, so

		of an indicator of key importance	that plant water use can be benchmarked against evaporative demand. Equipment on samphires is at risk of being destroyed by floods, needs regular checks and downloading of data (minimum 3-monthly). Expertise required for data processing and interpretation
Shoot growth and senescence	Growth only occurs when conditions are favourable. Lignification of articles (conversion from green succulent to dry woody) is a natural process that may be accelerated by stress, causing net loss of green tissue	Relatively quick to measure. Processing the results can be time-consuming but a simplification of our method may be possible	No data processed yet to judge the merits of this approach
Canopy or shoot temperature**	A surrogate for transpiration losses by plants, based on the cooling effect of evaporation of water from shoots, when measured relative to air temperature	Potentially easy to measure by some affordable hand-held devices; precedents established in crop physiology.	Requires species-specific calibrations for threshold levels. No knowledge presently available for *Tecticornia* species. Monitoring frequency would need to be determined, otherwise only “snap shots” available.

Environmental gradients

An overview of gradients in soil properties and species distribution along the two transects will be completed for Phase 2 of the report.

Overall synthesis of results

ARC Linkage Project Objectives:

There is good progress regarding the objectives formulated for this UWA-DEC-FMG project:

(1) *Identify samphire species and environmental factors influencing distribution patterns.* New samphire species have been described and will be published soon (Shepherd and van Leeuwen, in press), as described in the companion report (Shepherd, 2010). Transects have been surveyed and relationships between species and topography and soils will be assessed within the next few months. Data on conditions within plots in different species zones along the transect are presented in this report.

(2) *Relate samphire dynamics with changes in water (flooding and water deficit) and salinity.* These measurements are ongoing and preliminary summaries are presented in this report.

(3) *Assess plant health indicators, including transpiration, water status, ion relations, with varying stress levels (salinity, drought, flooding).* Preliminary summaries are presented in this report, as well as an evaluation of the value of these indicators.

(4) *Evaluate physiological processes contributing to resistance of salinity, drought, and flooding.* These processes are being observed in detail in experiments under controlled environments, and current status is presented in this report.

Update of the Fortescue Marsh eco-hydrology conceptual model

The ARC Linkage project provides vital information about plant water use that allows better understanding of the ecohydrology of samphire habitats at the Fortescue Marsh. The ARC Linkage project was not designed as an ecohydrological project, so important questions in the realms of hydrology and soil physics have not been addressed; this key priority has emerged since the initial project design. The conceptual model identifies key processes and structures in the landscape that need to be understood and quantified in order to be able to predict hydrological impacts from the mine site or other activities. Such knowledge would not only be useful for environmental management, but also be of great value as a description of a unique ecosystem. There will be important synergies between the ecophysiological work and the ecohydrological work.

Piezometer data and soil moisture measurements, summarised in this report, represent the only quantitative data available to support claims about the dynamics of water in the Fortescue Marsh soils. There are no direct measurements of flows, apart from rainfall, into the Marsh. Measurements of transpiration may be able to be scaled up from individual plants to the ecosystem level, however a more extensive deployment of equipment is required, as current measurements are limited to three plants each of two species of *Tecticornia*. Evaporation from the soil, or from soil covered with small plants, is possible using ventilated chambers, available at UWA, but such measurements are not planned within the current project.

Both ecohydrological and ecophysiological studies will benefit enormously from soil trenching studies that allow the quantification of root distribution and soil hydraulic parameters. Following this, simulation modelling would be very helpful in describing soil moisture dynamics, and analysing potential impacts.

Based on the information in the current report, there is evidence that samphires, in particularly the two species nearest to the fringes where a hydrological impact might be expected, are very tolerant to salinity and low rainfall in terms of growth and survival. In the field, this tolerance appears to be partly owing to deep rooting (inferred based on plants accessing water when the top 0.5 m of soil was not the likely source; actual rooting depth data not available – waiting on permissions for excavations to ascertain rooting patterns). Key questions therefore relate to soil moisture availability within reach of the roots, in particular whether or not the roots reach the water table or if the unsaturated zone is recharged from the water table through capillary rise. It is essential that the influence of the hardpan on root distribution and water movement is considered in this context. If there is any evidence that the maintenance of soil moisture within the rooting zone of samphires is partly dependent on the depth of groundwater, it is to be expected that a lowering of groundwater levels would reduce plant health, growth and survival.

Groundwater dependency of samphires

The current ARC-Linkage research was not specifically designed to identify or quantify groundwater dependency of Fortescue Marsh vegetation. However, the observations regarding patterns of water use and water status in the field, combined with experiments under controlled conditions, are starting to show trends that can be interpreted in terms of the species' likely response to changes in water availability. These new data on the three species of *Tecticornia* are unique as very little is known about them to date.

Plant water use data, as assessed by sap flow techniques, indicate that *T. indica* and *T. auriculata* continued to take up water during a hot and largely dry summer, and that transpiration was only reduced by decreased evaporative demand towards winter. During this period, rainfall events which were small but significant enough to wet the topsoil, had little or no effect on water uptake, and decreases in soil moisture content of the top 0.5 m seemed much too small to account for transpiration and soil evaporation. These observations suggest that these two samphire species take up an important fraction of their water from depths below 0.5 m, and are likely to be affected in their growth and condition if soil moisture reserves at depth were decreased. While it is clear that soil moisture at depth is partly determined by rainfall and evapotranspiration, and may be depleted considerably in a sequence of dry years under natural circumstances, it is not known at present if capillary rise of groundwater also plays a significant role in recharging the unsaturated zone from which samphires take up water. Studies of root depth distribution and soil moisture dynamics are essential for a better understanding of groundwater dependency.

The following table lists questions raised regarding groundwater dependency in the Fortescue Marsh, based on criteria explained by Eamus et al. (2006), and comments on these criteria based on the results of the current project. It is important to note that the project investigates three samphire species, and that conclusions for these three species do not necessarily apply to all samphire species, and that other plant species may have other requirements.

Table 4. Are the samphire vegetation communities in the Fortescue Marsh dependent on groundwater for key ecological functions? Questions derived from Eamus *et al.* (2006), adapted by Dan Huxtable.

Questions/actions	**Response based on current knowledge**
Is groundwater, or the capillary fringe above the water table, present within the rooting depth of any of the vegetation?	Yes, definitely true for *T. medusa* ms, likely for *T. auriculata*, not known for *T. indica*. Rooting depths, water table depth, and capillary zone need to be determined.
Does a proportion of the vegetation remain green and physiologically active (principally transpiring and fixing carbon, although stem-diameter growth or leaf growth are also good indicators) during extended dry periods of the year?	All samphires are evergreen and need to be physiologically active throughout the year. Data show continued plant water use during extended dry periods
Is the vegetation associated with shallow watertables different (in terms of species composition, phenological pattern, LAI or vegetation structure) from vegetation close-by but which is not associated with (i.e. accessing) this groundwater	There is clear species zonation associated with topography and groundwater depth. It is important to note that there are probably interactions between groundwater dependence and salinity tolerance, and that alterations in groundwater will affect salinity
Is the annual rate of water use by the vegetation significantly larger than annual rainfall plus storage created by run-on?	Unknown, but quite likely, as rainfall is low, potential evapotranspiration very high, and outflow from the catchment probably negligible. Scaling up of transpiration from plant to ecosystem needs additional work. Soil evaporation has not been measured but is likely to be significant. Landscape-level flux estimates using micrometeorology or alternative methods may be appropriate.

Table 5. What is the nature of the groundwater dependency? Questions derived from Eamus *et al.* (2006), adapted by Dan Huxtable.

Questions/actions	**Response based on current knowledge**
Estimate (quantify) the proportion of annual water use that is derived from groundwater and then assume that this is a measure of the degree of dependency	Current data would allow a very coarse estimate. It is likely that most uptake from groundwater happens after capillary rise into the unsaturated zone, and that capillary rise is substantial
Conduct groundwater drawdown experiments and measure short term responses in vegetation	Permits may be problematic. Vegetation response likely to be slow. Rate of drawdown likely to influence result
Infer the degree of groundwater dependency by examining temporal patterns in soil moisture availability, rainfall and vegetation variables known to be influenced by soil moisture content (e.g., leaf area index and vegetation water use).	Current data suggest that moisture in unsaturated zone can last long periods and rooting is likely to be deep (inferred only from water use data; rooting depths need to be determined). Long-term observations are required due to episodic nature of rainfall and slow growth of plants
Is groundwater required to sustain samphire communities through to the end of a particularly long cycle of below-average rainfall?	Unknown – no research has been done during an extended dry period. Historic imagery (aerial or satellite) may yield some insights

Recommendations for further work

Recommendations for future glasshouse work were presented in that section. Recommendations for further field research will be presented in Phase 2 of the report.

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Pigment concentrations and spectral signals of samphires

Internal Research Report for the period October 2011-February 2012

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Introduction

The University of Western Australia (Professors Erik Veneklaas and Tim Colmer) in partnership with Fortescue Metals Group Ltd (FMG) commenced a research project in 2008 on the stem succulent halophytes (samphires) at Fortescue Marsh in the Pilbara. The project during 2008-2011 covered different aspects of the ecophysiology of three main species (*Tecticornia indica*, *T. medusa* and *T. auriculata*) to changes in salinity and water availability as experienced in the Fortescue Marsh. The information obtained from this earlier project provided a starting point for understanding the samphire vegetation dynamics as related to environmental conditions in Fortescue Marsh, as well as to provide a baseline for future analyses of possible impacts associated with FMG operational activities. The current research project commenced in October 2011 as an additional activity, with the objective to determine if shifts in pigment concentrations due to stress (natural dynamics) can be detected spectrally in *Tecticornia* species at the Fortescue Marsh. The information gained is an important step to evaluate whether a remote sensing approach might be useful as a method for the future assessment of samphire vegetation stress/health in the field.

The main aims of this 5-month project were:

1. To review the available scientific literature on the use of satellite remote sensing and on-site spectrometry for characterisation of vegetation in ecosystems similar to the Fortescue Marsh (e.g. coastal marshes, salt lakes, other wetlands, other sparse vegetation).
2. To determine relationships between pigment concentrations and field spectroradiometer readings for *T. indica.*
3. To correlate plant pigment concentrations (mainly betalains and chlorophylls) with measured physiological plant stress indicators and climatic variables.

A literature review on remote sensing and on-site spectrometry was produced (Marchesini 2012). The review included some of the most common methods to identify and quantify plant pigments using spectrometry at different scales, from hand-held spectrometers (at leaf and plant scale) to satellite remote sensing (at landscape and regional scale). The review also presented a section on monitoring succulent vegetation with special attention to salt marshes and wetlands, areas of relevance to possible applications at the Fortescue Marsh. As a conclusion, this review indicated that spectrometry potentially offers a rapid and reliable method to describe different aspects of natural ecosystems, as well as a tool for evaluating and predicting the impact of human activities. For example, through the use of spectral indices it is possible to analyse the relationship between vegetation condition, pigments and spectral signatures providing a promising approach for improving knowledge of vegetation in marshes and other wetlands ecosystems.

In addition to the literature review, experimental work during this 5 month project involved the quantification and evaluation of pigments and their dynamics in three *Tecticornia* species at Fortescue Marsh, by analyses of field samples taken during 2008-2011. Additionally, a visit to the Fortescue Marsh was made in December 2011 with the purpose of identifying and describing vegetation heterogeneity at patch/plot scale to define areas to perform spectral measurements to eventually correlate with plant pigments. Furthermore, a pilot study on spectrometry and pigments in *Tecticornia* species at Yenyening Lakes, which is an analogous system to the Fortescue Marsh, but of greater convenience for this initial test as the instrument used was only available on a short loan and this site is located only 200 km from Perth, WA. The results from these experimental activities are presented in this report.

Pigment analyses: three *Tecticornia* species from the Fortescue Marsh (samples taken 2008-2011)

Results from the ARC Linkage project showed that the samphires at Fortescue Marsh grow in highly variable and stressful environments, which affect plant growth and condition. *Tecticornia* species are green during favourable conditions but can develop pink/orange colouration during unfavourable periods. The changes in colouration could be due to changes in chlorophylls as well as betalains (a diverse group of water-soluble pigments analogous to anthocyanins that accumulate in flowers, fruits and vegetative tissues (Strack et al. 2003)). Betalain pigments comprise the violet betacyanins (visible absorption maximum between 535 and 541 nm) and the yellow betaxanthins (visible absorption maximum between 460 and 480 nm). Preliminary analyses indicated that *T. Indica*, *T. auriculata* and *T. medusa*, three species at Fortescue Marsh, differ in their pigment compositions (Fig. 1).

Since betalain analyses had not been previously been done for *Tecticornia* species, a number of tests were performed to ensure that the extraction and quantification of these pigments was satisfactory. Then, all samples of all three *Tecticornia* species collected during the ARC Linkage project that had been freeze-dried and stored to preserve pigments, were analysed. This section describes the temporal (different seasons during 2008-2011) dynamics of these pigments from 250 samples taken in two transects (A and B) located in the Fortescue Marsh. Samples consisted of representative fully-grown succulent stem articles of *T. medusa, T. auriculata* and *T. indica*.

First results of the spectral absorbance of *Tecticornia* pigment extracts showed that the absorption spectra of the three species had different absorption peaks (Fig. 1). Published equations for betacyanins and betaxanthins assume peak absorptions at 538 nm and 480 nm respectively, which do not exactly coincide with the observed *Tecticornia* peaks. An additional problem is that due to overlap of absorption spectra, betacyanin presence may lead to overestimation of betaxanthin concentration, and *vice versa*. To investigate these potential issues, the pigment spectral absorbances of extracts from flowers of two reference species containing known betalains were checked: *Bougainvillea glabra* (purple colour, owing to betacyanins) and *Portulaca grandiflora* (yellow colour, owing to betaxanthins) for which absorption spectra and pigment concentrations had been previously studied (Strack et al. 2003).

Extraction and quantification methods were as follows. Betalain pigments were extracted in water buffered using 100 mM MES with pH adjusted to 5.5 using NaOH. Prior to extraction, tissues had been freeze-dried and stored dry at -20^{o}C to preserve the samples. Betacyanin quantification was based on absorbance at 538 nm while betaxanthin quantification was based on absorbance at 480 nm (Strack et al. 2003). Measurements were performed using a UV/Vis spectrophotometer (Cary 3-Varian) with a spectral bandwidth range of 0.2 to 4 nm. Wavelength accuracy is ± 0.2 nm. Each betalain concentration (BC) was expressed as mg L^{-1} and was calculated using the following equation.

$$BC\ (mg\ L^{-1}) = A \times DF \times MW \times 1000/\varepsilon \times L_c$$

Where BC is the total betacyanin or betaxanthin concentration; A is the absorption at 538 nm (betacyanin) or 480 nm (betaxanthin); DF is the dilution factor and L_c the path length of the 1 cm cuvette; MW is the molecular weight (550 and 339 g mol^{-1} for betacyanin and betaxanthin, respectively); and ε is the molar extinction coefficient (60 and 48 L mol cm^{-1} for betacyanin and betaxanthin, respectively). Concentrations were then expressed on a dry weight basis by taking into account the amount of dry tissue extracted and the extraction volume.

Chlorophyll and carotenoid pigments were extracted using cold methanol according to Sims and Gamon (2002). Absorbance was measured in the same spectrophotometer as described above, at 470, 652.4 and 665 nm. Chlorophylls and carotenoids were estimated using the following equations (Sims and Gamon 2002).

$$Chl\ (a) = 16.72 \cdot A_{665.2} - 9.16 \cdot A_{652.4}$$

$$Chl\ (b) = 34.09 \cdot A_{652.4} - 15.28 \cdot A_{665.2}$$

$$Carotenoids = (1000 \cdot A_{470} - 1.63 \cdot Chla - 104.96 \cdot Chlb) / 221$$

Concentrations of chlorophylls and total carotenoids were expressed as µg g^{-1} of tissue dry weight.

As plant tissue samples had been taken across about two years, the dynamics in plant pigments were correlated with different climatic parameters and changes in soil water contents. Climatic data were obtained from a weather station located at Fortescue Marsh, close to the plots from where plants had been sampled.

Results and Discussion

<u>Pigments absorbance spectrum</u>

The spectral absorbance obtained from the reference species with flowers known to contain particular betalains showed maximum (i.e. peak) absorption between the wavelengths 533-540 nm for *B. glabra* (violet flowers; betacyanins) and between 475-477 nm for *P. grandiflora* (yellow flowers; betaxanthins) (Fig 2). These absorption maxima are within the range of values for betacyanins and betaxanthins pigments found in other species such as *Beta vulgaris* (red beet), *Schulumbergera buckleyi* (Christmas cactus) and in *Celosia argentea* (cockscomb) (Strack et al. 2003). The spectrum obtained through mixing *B. glabra* and *P. grandiflora* samples showed, as expected, two absorption peaks, one corresponding to betacyanins at 537 nm and the other to betaxanthins at 480 nm (Fig. 2). Unfortunately, as betacyanins showed considerable absorption at 480 nm (Fig. 2), which is the peak used to estimate betaxanthins, a combination of the two pigments in one sample can lead to overestimation of the total betalain concentration.

The spectra of the *Tecticornia* extracts compared to those obtained from the reference samples showed a peak at 539 nm for *T. indica* indicating putative betacyanins, whereas in the other two *Tecticornia* species no clear peak was evident (Fig . 1). The absorbance spectra of *Tecticonia* extracts also showed high absorptions between 400-500 nm which in turn could mask any smaller peaks possible for betaxanthins (expected near 480 nm). Although the absorption observed at 538-540 nm for *T. indica* is likely due to the presence of betacyanins, confirmed identification would require additional analyses and characterisation of the exact compounds involved (e.g. chromatographic analysis for compound separation or structural analyses using NMR spectroscopy). Uncertainty of the identity of the compounds does not, however, diminish the objective of this study to analyse and compare the temporal dynamics of pigmentation between species and sites, and to test for correlations of plant tissue changes with environmental conditions.

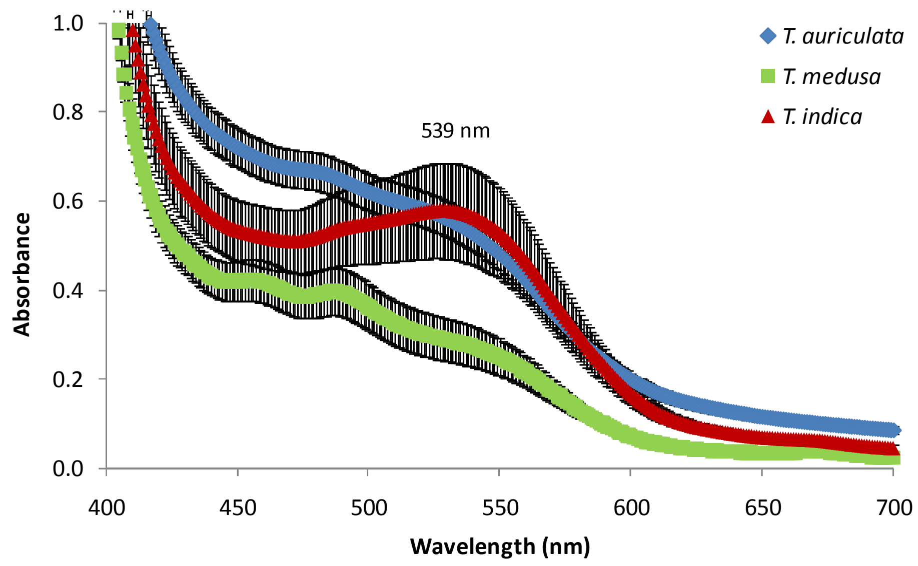


Figure 1: Visible spectra for extracts from three species of *Tecticornia*. Samples were taken in September 2010 from Fortescue Marsh. The peak absorption wavelength (λmax) for betacyanins at 539 nm is indicated, with the peak in *T. indica* indicating putative betalains in this species. Mean values and standard errors are shown for each species (n=10 per species).

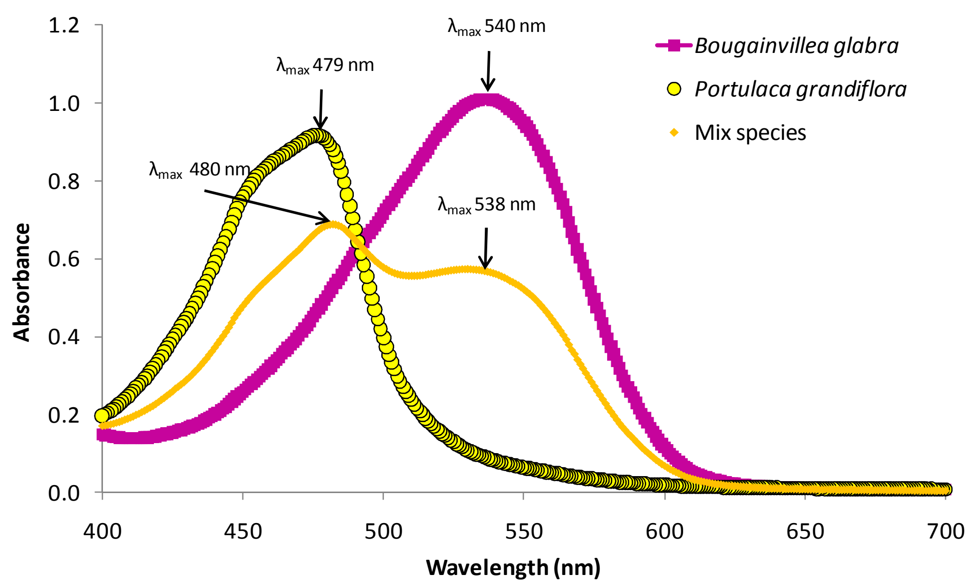
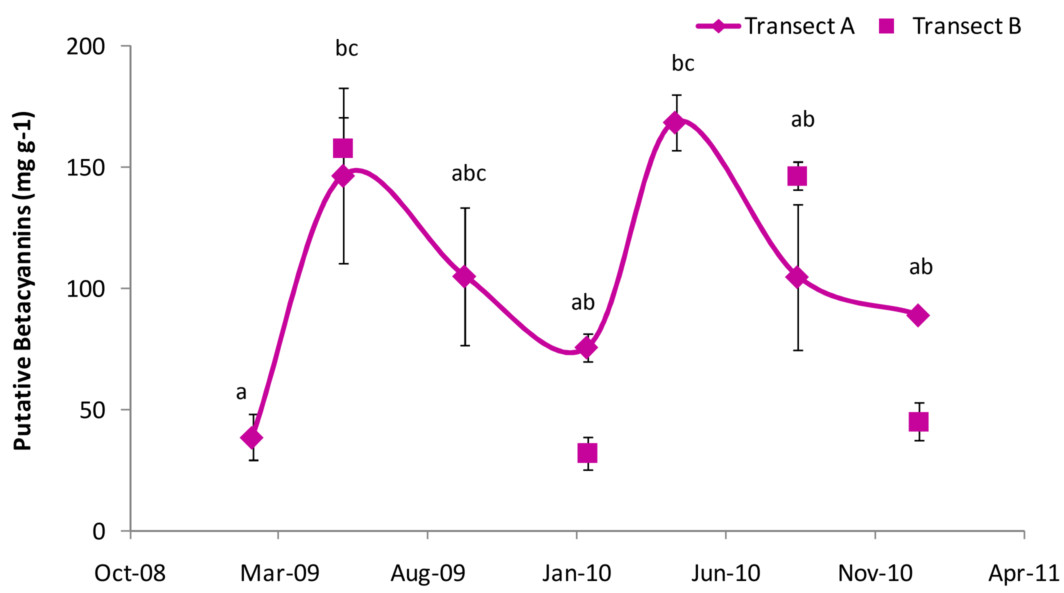


Figure 2: Visible spectra for extracts from flowers of reference species and a mixed sample (*B. glabra* + *P. grandiflora*). Peak absorption wavelength λmax for the various extracts are indicated.

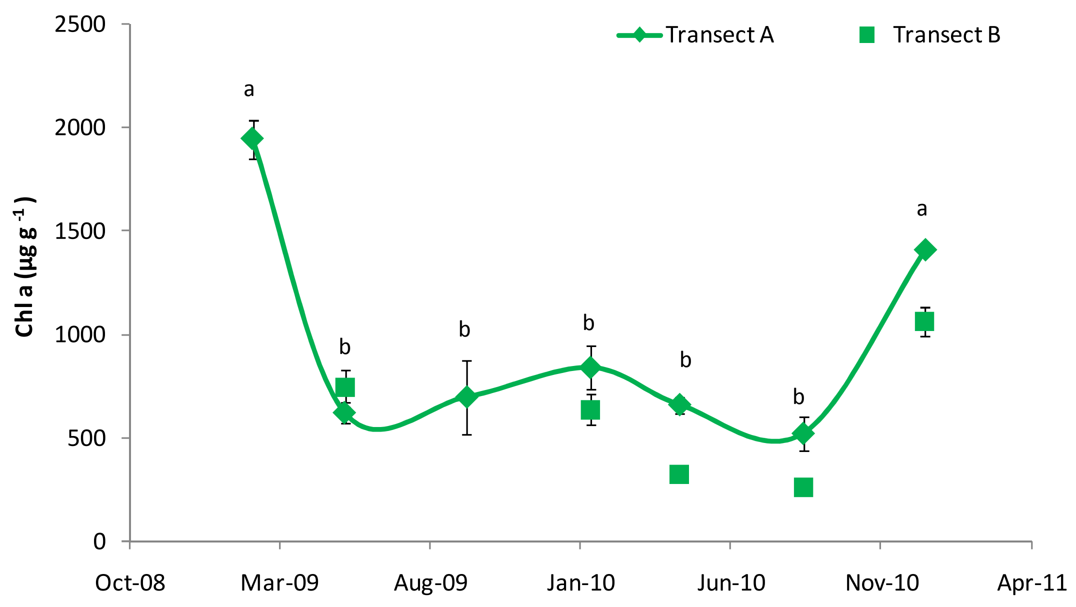
<u>*Tecticornia indica* pigments: temporal and spatial trends</u>

Concentrations of putative betacyanins in *Tecticornia indica* succulent stems showed strong temporal dynamics with higher values during March-May and lower values during December-February ($p<0.001$) (Fig. 3). Chlorophyll a concentration was variable between species (compare Figs. 3 and 4) but in *T. indica* the concentration decreased after autumn and then showed an increase again in Spring-Summer in accordance with the beginning of the rainy season. Carotenoids concentration also varied considerably between species (Figs. 3 c, 4 b and d) but did not change systematically along seasons for *T. medusa* and *T. auriculata.* May, June and September (before the rains) were the months when the highest concentration of putative betacyanins was recorded. Betacyanins in succulent stems of *T. indica* slightly varied between transects A and B. Despite there being fewer sampling times for transect B, comparison between transects showed that at both locations the concentrations of putative betacyanins were dynamic over time (Fig. 3 a).

a)

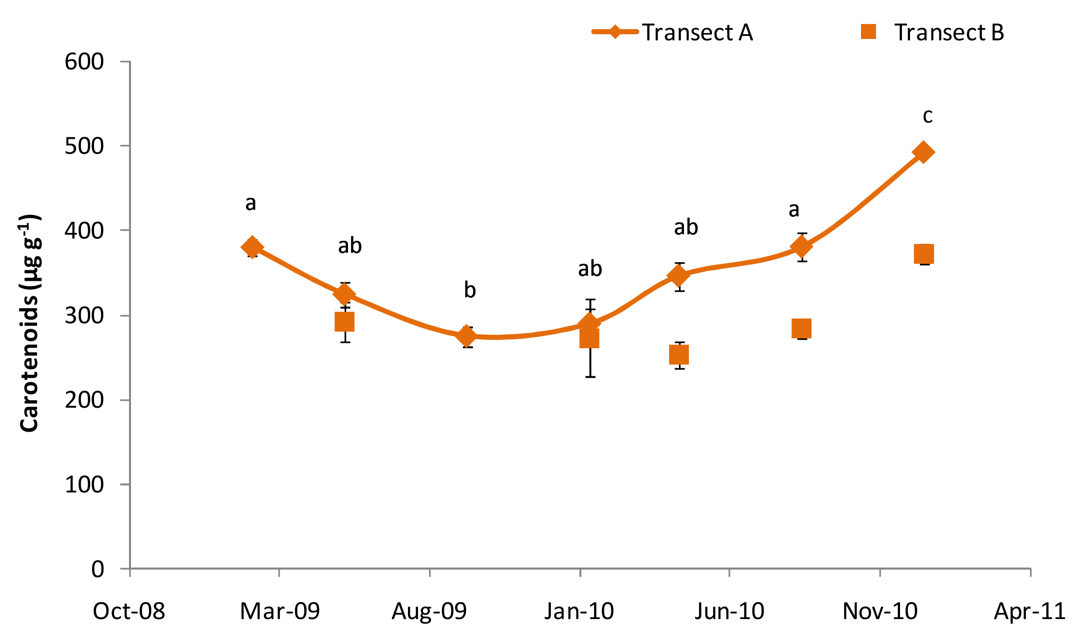


b)



Transect A
Transect B
2500
2000
1500
1000
500
0
Chl a (µg g-1)
Oct-08
Mar-09
Aug-09
Jan-10
Jun-10
Nov-10
Apr-11
a
b
b
b
b
b
a

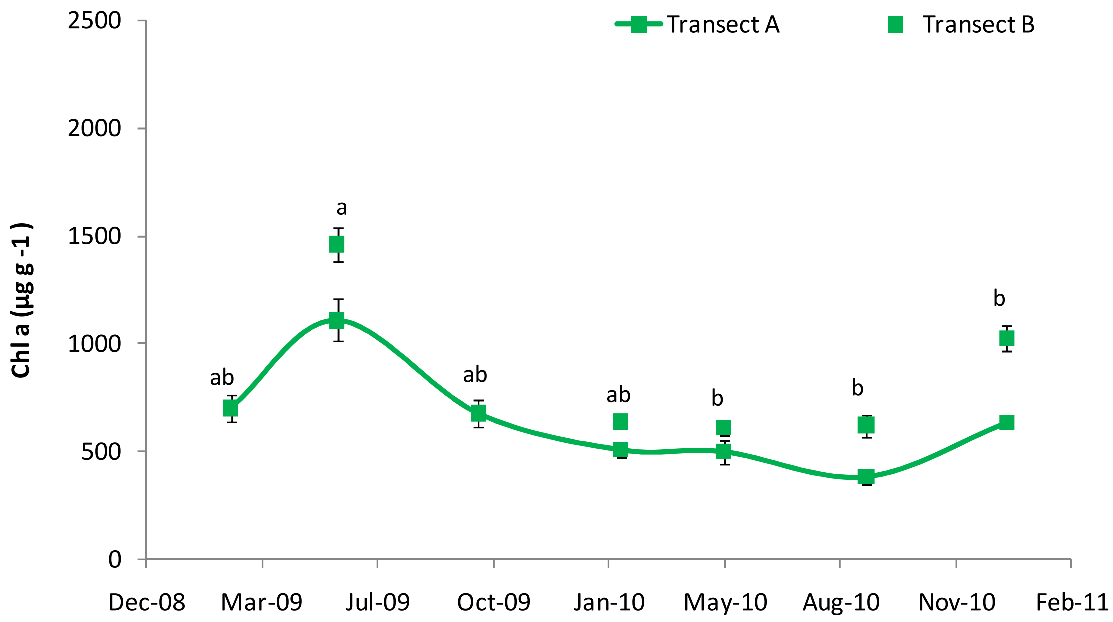
c)



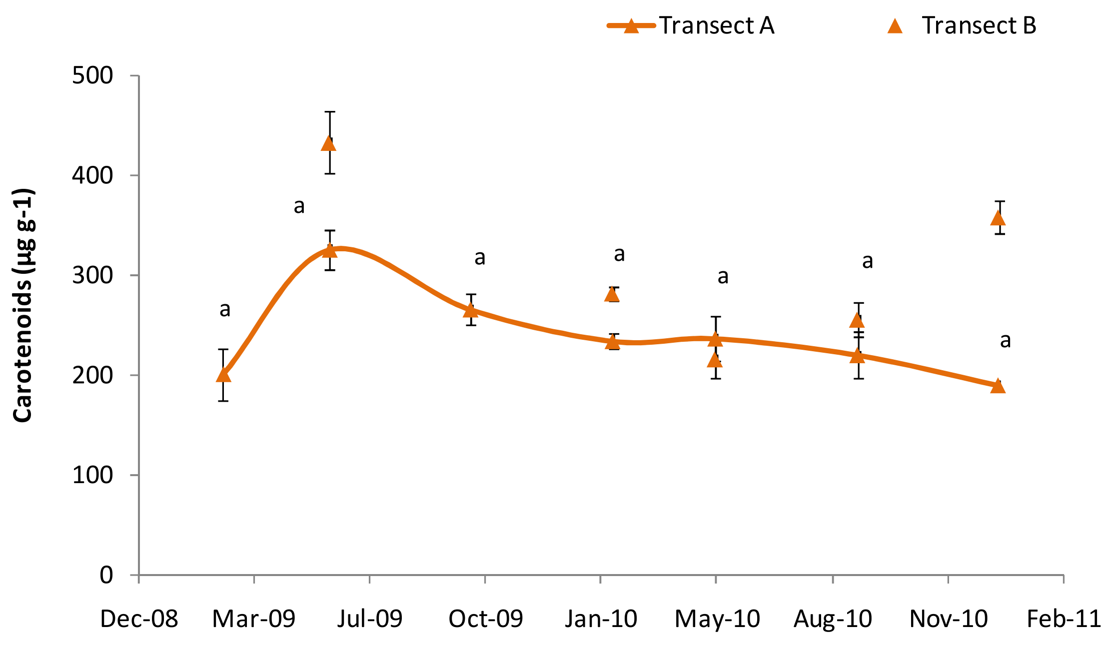
Transect A
Transect B
600
500
400
300
200
100
0
Carotenoids (µg g-1)
Oct-08
Mar-09
Aug-09
Jan-10
Jun-10
Nov-10
Apr-11
a
ab
b
ab
ab
a
c

Figure 3: Concentrations of putative betacyanins, chlorophyll a and carotenoids in succulent stems of *Tecticornia indica*. Mean values are shown for samples taken in transect A (solid line) and B (no line) from January 2009 to January 2011. Different letters indicate temporal changes that are statistically different at p<0.05 for data from transect A.

a)

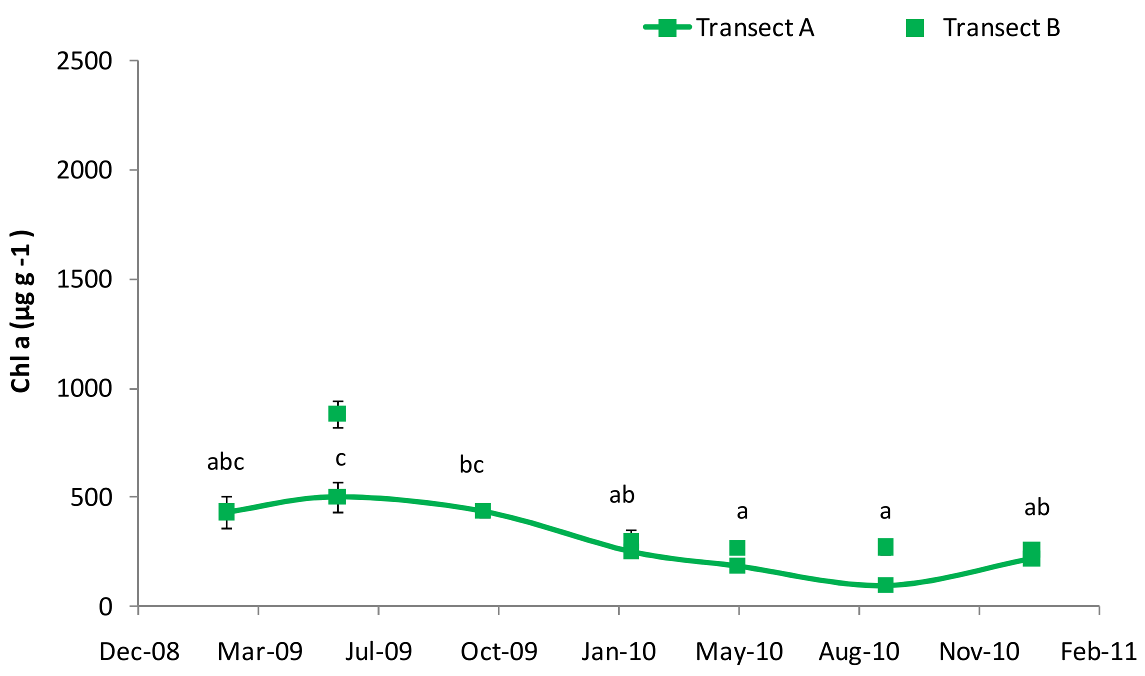


b)



Transect A
Transect B
Carotenoids (µg g-1)
500
400
300
200
100
0
a
a
a
a
a
a
a
Dec-08
Mar-09
Jul-09
Oct-09
Jan-10
May-10
Aug-10
Nov-10
Feb-11

c)



Transect A
Transect B
Chl a (µg g -1)
2500
2000
1500
1000
500
0
abc
c
bc
ab
a
a
ab
Dec-08
Mar-09
Jul-09
Oct-09
Jan-10
May-10
Aug-10
Nov-10
Feb-11

d)

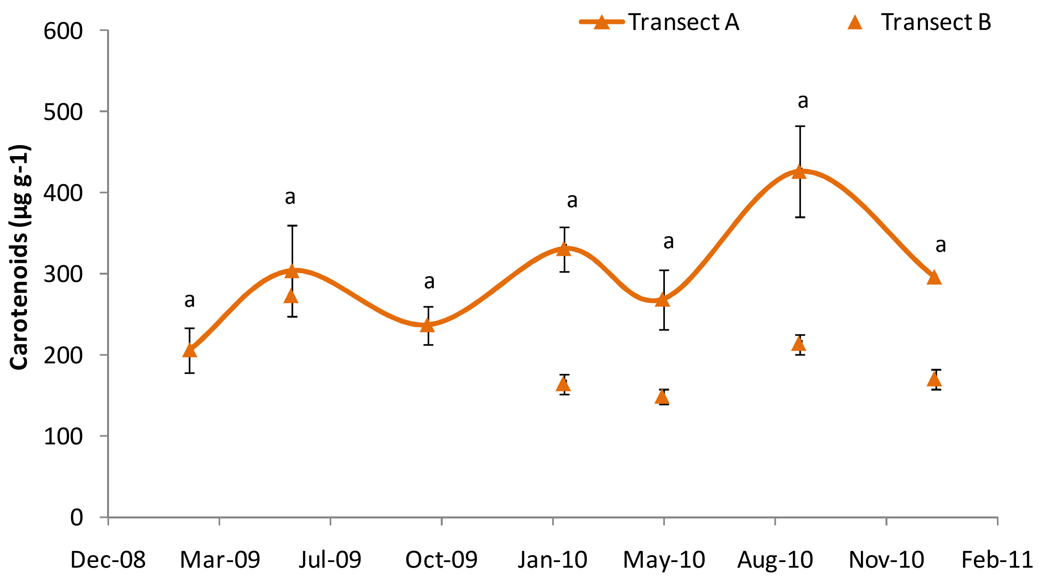


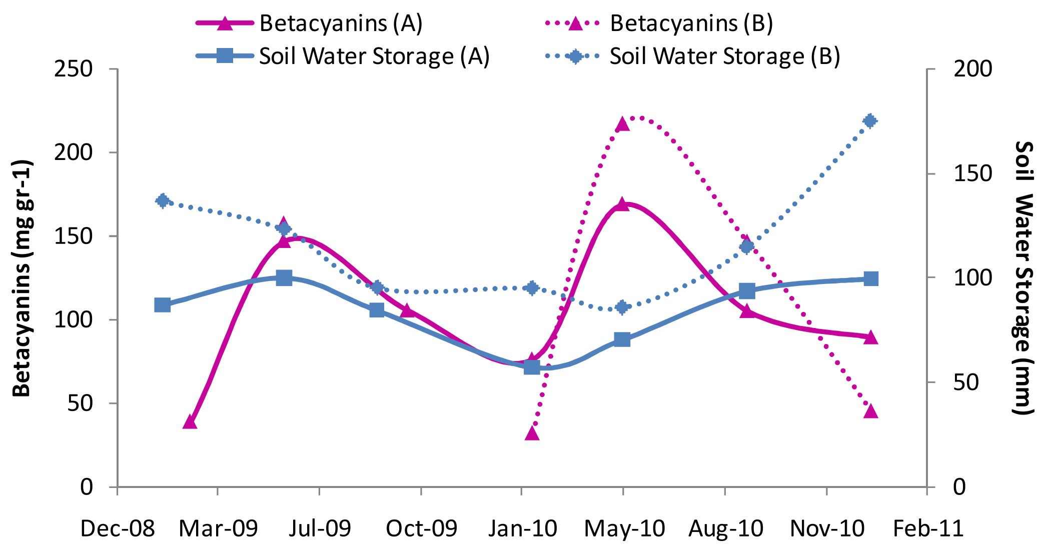
Figure 4: Concentrations of chlorophyll a and carotenoids in succulent stems of *T. auriculata* (a, b) and *T. medusa* (c, d). Mean values are shown for samples taken in transect A (solid line) and B (no line) from January 2009 to January 2011. Different letters indicate temporal changes that are statistically different at $p<0.05$ for data from transect A.

Correlations between putative betacyanins and chlorophylls, and climatic parameters

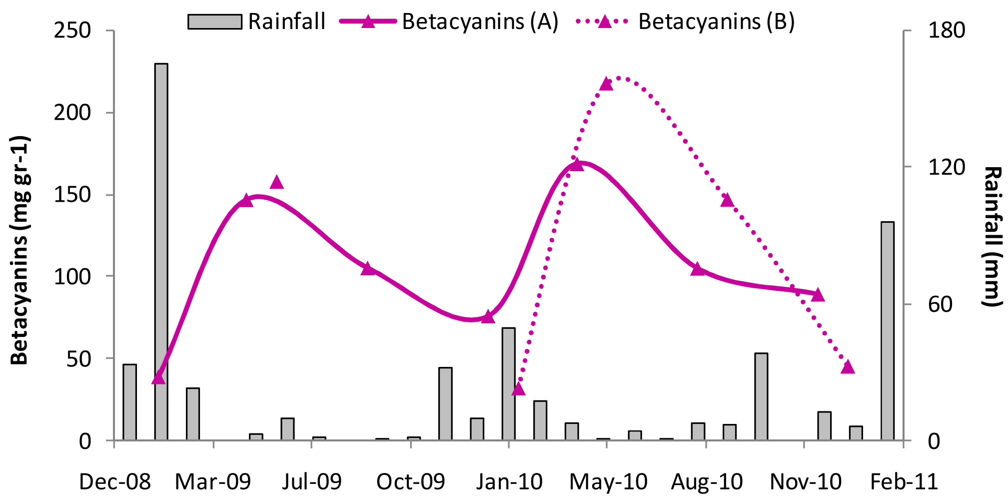
T. indica, the species that exhibited a putative betacyanin absorption peak, showed large changes in tissue concentrations of apparent betacyanins with time of samplings, so correlations between environmental variables and pigment concentrations were investigated using this species. Correlations between pigments (putative betacyanins and chlorophyll a) and four environmental variables were examined: a) Soil water storage, b) cumulative monthly precipitation of the month before the sampling date, c) mean daily radiation and d) mean daily air temperature. Soil water storage was estimated considering the gravimetric soil water content in each soil layer at 10 cm intervals from 0.1 to 0.5 m and assuming a soil dry bulk density of 1.5 g cm^3.

Soil water storage did not correlate with betacyanins, neither in transect A (R^2 0.01) nor transect B (R^2 0.11) (Table 1). Soil water storage was less variable in transect B than in transect A, but betacyanins were equally dynamic in both transects (Fig. 5a). Concentrations of betacyanins for each sampling date correlated negatively and significantly with the amount of rainfall accumulated in the previous month before sampling (R^2 0.6 for transect A) (Table 1). High monthly precipitation during October-January matched with lower pigment concentration while rain deficiency during March-August in 2009 and 2010 coincided with a peak in betacyanins (Fig. 5b). In the same way, a negative and significant relationship was observed for betacyanins and solar radiation (R^2 0.69 and R^2 0.76 for transects A and B, respectively) and between betacyanins and mean air temperature (Fig. 5c and 5d) (R^2 0.60 and R^2 0.84 for transects A and B, respectively). The negative relationship between betacyanins and solar radiation and mean air temperature could be explained considering that increments in solar radiation and air temperature (summer) coincide with the rainy season. Chlorophyll a concentration also did not show a clear correlation with soil water storage, but did show a strong positive relationship with the cumulative rainfall in the previous month (R^2 0.67) (Fig. 5e, Table 1). This was especially evident in transect A where a peak in rainfall during January 2008 was followed by a peak in Chlorophyll (Fig. 5 e). Absence of data in transect B during this wet period may be responsible for the poor correlation between rainfall and Chlorophyll in that transect.

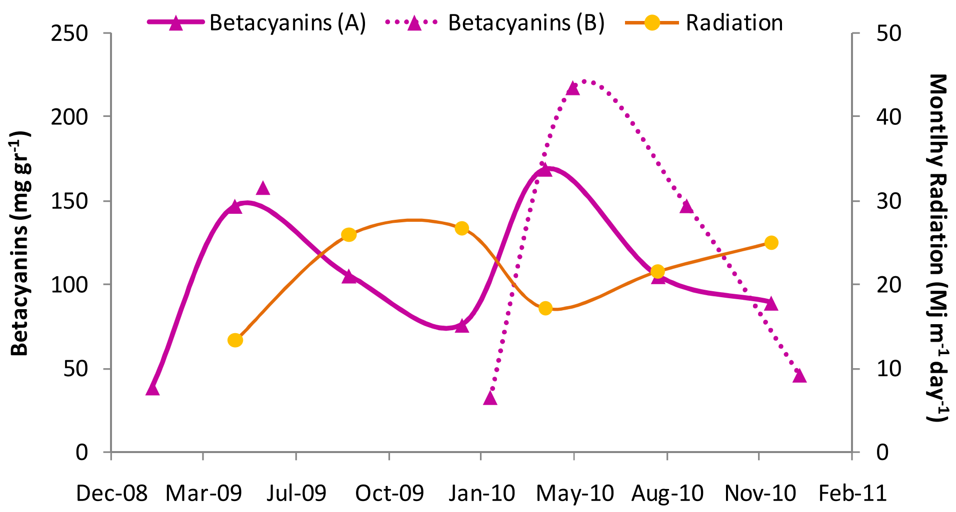
a)



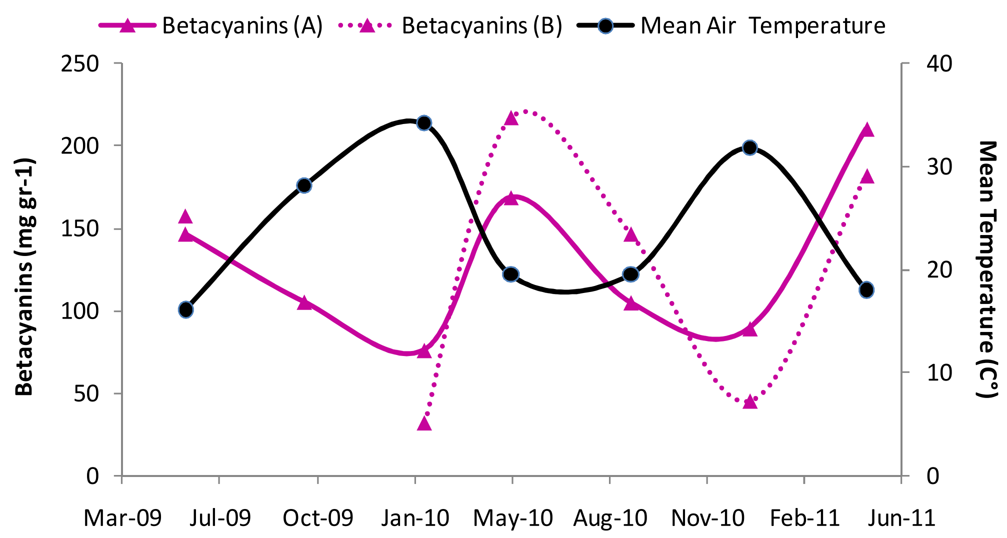
b)


Rainfall
Betacyanins (A)
Betacyanins (B)
Betacyanins (mg gr-1)
Rainfall (mm)
250
200
150
100
50
0
180
120
60
0
Dec-08
Mar-09
Jul-09
Oct-09
Jan-10
May-10
Aug-10
Nov-10
Feb-11

c)


Betacyanins (A)
Betacyanins (B)
Radiation
Betacyanins (mg gr-1)
Montlhy Radiation (Mj m-1 day-1)
250
200
150
100
50
0
50
40
30
20
10
0
Dec-08
Mar-09
Jul-09
Oct-09
Jan-10
May-10
Aug-10
Nov-10
Feb-11

d)



e)

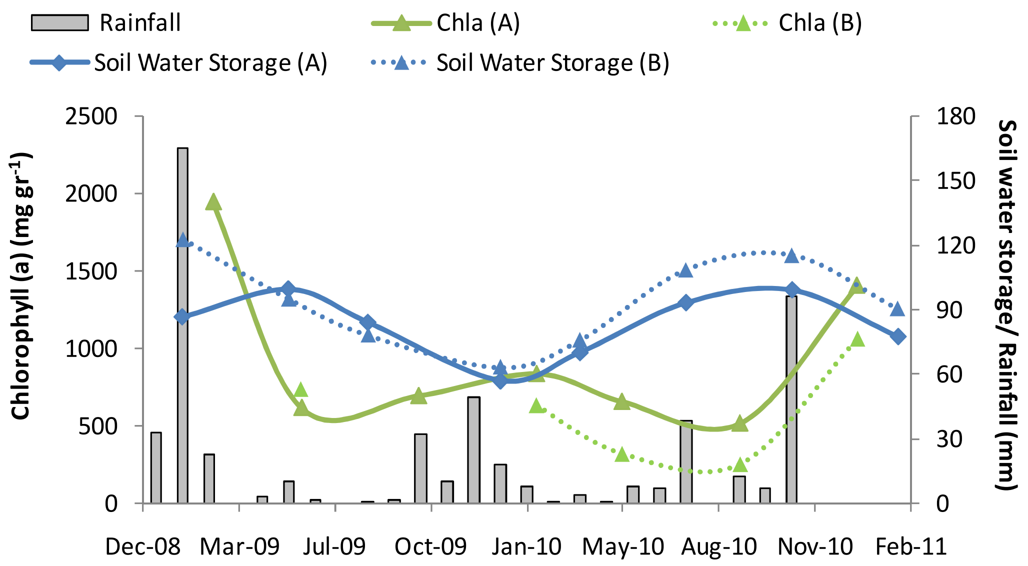


Figure 5: Patterns in pigment dynamics (putative betacyanins and chlorophyll a concentrations) in tissues of *T. indica,* in comparison with patterns of soil water storage (a), cumulative precipitation (b, e), daily radiation (c) and mean air temperature. Mean values for samples taken in transect A (solid line) and B (dotted line) from January 2009 to January 2011.

Table 1: Linear regressions between pigment concentrations (betacyanins and chlorophylls) in *T. indica* and four environmental variables. Equations, R^2 and P-statistic values for transects A and B. *ns = relationship between variables not significantly different to 0.

Variables correlated	Transect A	Transect B
Betacyanins (mg g^{-1}) against Soil water storage (mm) (Fig. 5a)	Bcy = -0.32* SWS + 144.48 R^2 = 0.015 (P= ns)*	Bcy= -0.794 SWS + 227.03 R^2 = 0.12 (P= ns)
Betacyanins (mg g^{-1}) against Cumulative rainfall in the previous month (mm) (Fig. 5b)	Bcy = -0.55* Rainfall + 122.46 R^2 = 0.59 (P= 0.04)	Bcy = -2.71 rainfall + 156.05 R^2 = 0.49 (P= ns)
Betacyanins (mg g^{-1}) against Mean radiation (MJ m^{-2} day^{-1}) (Fig. 5c)	Bcy = -5.7*Rad + 239.18 R^2 = 0.76 (P= 0.02)	Bcy = -11.79 rad + 364.76 R^2 = 0.69 (P= 0.08)
Betacyanins (mg g^{-1}) against air temperature (C°) (Fig. 5d)	Bcy= -5.14* Temp + 251.58 R^2 = 0.60 (P= 0.04)	Bcy = -8.86 temp + 335.76 R^2 = 0.84 (P= 0.01)
Chlorophyll a - Cumulative rainfall (mm) (Fig. 5e)	Chl (a) = 7.06*Rainfall + 721.48 R^2 = 0.67 (P= 0.02)	Chl (b) = 1.55 rainfall + 583.79 R^2 = 0.01 (P= ns)

Discussion and Conclusions

The analyses of pigment concentrations in tissues of *T. indica* for 2008-2011 indicated strong temporal dynamics associated to seasonal changes. This analysis also highlights strong differences between species in pigment concentrations (chlorophylls and carotenoids) and pigment dynamics (Fig. 3 and 4). In general, chlorophylls and putative betacyanins showed opposite patterns in concentrations in *T. indica*: increases in putative betacyanins coincided with decreases in chlorophyll (Fig. 3). Correlations of pigments in succulent stems of *T. indica* with environmental variables indicated that putative betacyanins concentrations were highest in winter when radiation intensity and air temperature were lowest. At that time of year, rainfall is low but stored soil moisture can still be fairly high due to recharge during the previous months. The negative and robust correlation observed between putative betacyanins and climatic variables such as rainfall, net radiation and air temperature reveals a strong coupling between the presence of these pigments and the occurrence of the dry season. Despite this association of pigment changes during the period of low rainfall, use of these pigments as indicators exclusively of drought stress is not recommended, since other factors and/or variables (not included in this analysis) might influence the concentrations of these pigments. The direct response of these pigments to drought should be tested in future work.

Of the three study species, *T. indica* showed the highest concentrations and the greatest temporal dynamics. This may be due to its habitat which is more elevated than that of *T. medusa* and *T. auriculata.* The higher elevation may be associated with larger seasonal fluctuations in soil moisture (possibly beyond depths measured in this study) and groundwater, which in turn may lead to more intense drought stress and stronger changes in colouration (putative betacyanins and carotenoids) compared with the other two species.

Spectrometry and pigment concentrations: method test at Yenyening Lakes

This section describes the results of a pilot project carried out on samphires in Yenyening Nature Reserve, a series of salt lakes with marsh areas located approximately 200 km east from Perth (32° 14´ 35.47 S, 117° 10' 53.14 E). The area was selected considering its proximity to Perth and also the occurrence of *Tecticornia indica*, as this species also occurs at the Fortescue Marsh. The objective of this pilot project was to perform reflectance measurements at the plant scale of specimens that visually differed in colours (green or pinkish-red individuals) to determine if shifts in pigment concentrations could be detected using the hand-held spectrometer. The methodology applied in this project will guide measurements of samphires at Fortescue Marsh. Specific wavelengths were also investigated in order to calculate spectral indices to correlate with pigment concentrations.

Methodology to measure spectral reflectance on *Tecticornia indica* at Yenyening Lakes

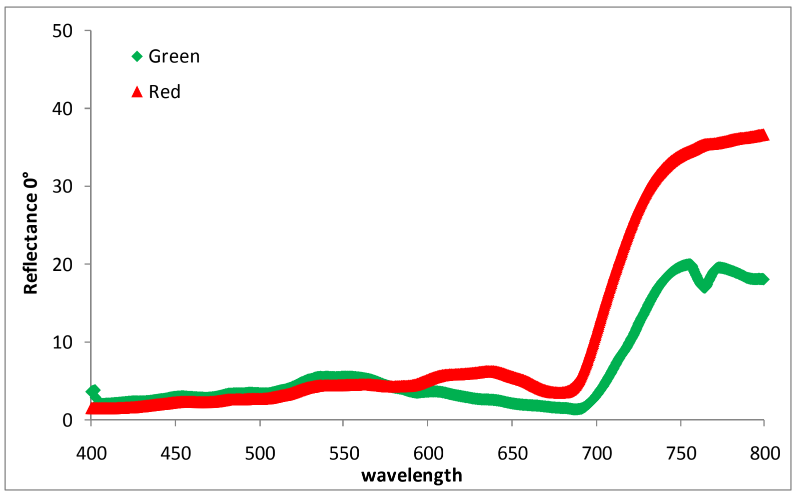
Spectral measurements were performed using a hand held spectrometer (JAZ, Ocean Optics) from 11:00 am to 1:30 pm (when sun is close to zenith) during a clear sky day in November 2011. The device consists of a fiber optic attached to a spectrometer designed to measure reflectance between 400 to 1200 nm (visible and near infrared wavelengths). Reflectance is estimated as a percentage between a maximum (solar radiation) and a minimum (a "dark" value obtained by blocking the fiber optic) reference value. Measurements were taken on 10 plants of similar size of *Tecticornia indica* selected according to a range of colours given the presence of putative betacyanins in the tissues, from green plants (with low betacyanins) to pinkish-red plants (with high betacyanins) (Fig. 14, Appendix 1). Measurements were also performed holding the device at several angles: 0°, 45°, 90°, 135° and 180° determined by a clinometer. The distance between the sensor (optical fiber) and the target branch was 10 cm. After measurements, representative parts of the plant were sampled for pigment extraction: one branch from each angle side was kept on ice and in darkness to transport back to the laboratory for subsequent pigment and tissue water measurements. Samples were washed, weighed, freeze dried and stored at -20 C° before pigment extraction (methods as described in the previous section of this report).

Results and Discussion

Spectral reflectance from the individual *T. indica* plants differed according to plant appearance, red plants reflected more light between 580-750 nm than the green ones (Fig. 6) and differences between plants were marked at 550 and 640 nm (Fig. 7). The differences in reflectance were evident at all the angles measured (i.e. angle of instrument when measurements were taken), providing confidence that the hand-held technique is not overly sensitive to differences in operator angles. Above 700 nm wavelengths, reflectance from pinkish-red plants was always higher compared to that from green plants. In accordance with these results, the analysis of tissue extracts showed putative betacyanins absorbance by samples from pinkish-red plants (i.e. a peak in absorbance at 538 nm). Absorbance by extracts from green plants by contrast, did not show any significant changes (i.e. no peak) along the spectrum between 500-700 nm. These plants however, showed greater absorbance between 410-470 nm than the red plants (Fig. 8).

Average chlorophyll concentration in green plants was 16% higher than in pinkish-red plants while the concentration of putative betacyanins in pinkish-red plants was 50% higher than in green plants, although these differences were not statistically significant (Fig. 9, Table 2). Nevertheless, both the reflectance data obtained by the hand-held spectrometer and the data from pigment extracts indicated detection of colour changes thought to be due to differences in concentrations of putative betacyanins in the tissues.

a)



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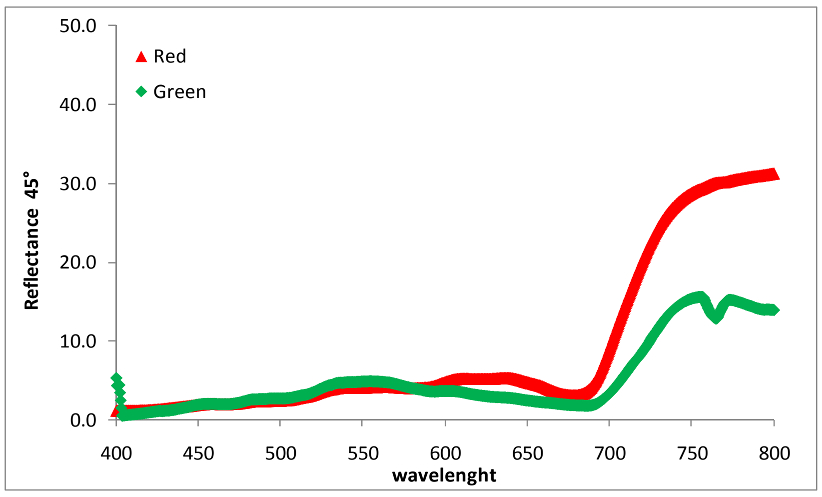

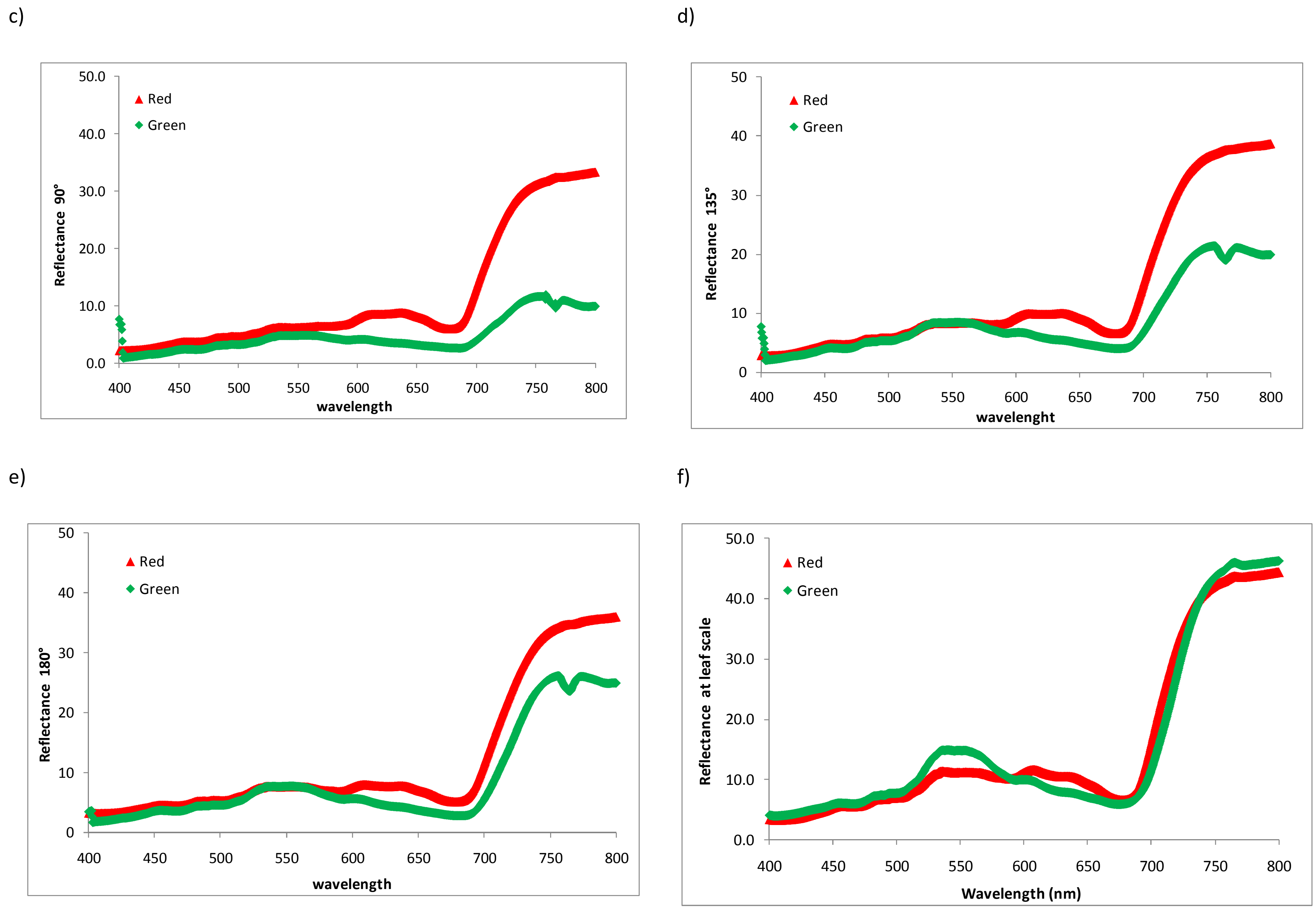

Figure 6: Visible spectra for pinkish-red (n=5) and green plants (n=4) of *T. indica* at plant (a, b, c, d, e) and succulent stem article scale (f). Measurements at plant level were performed in the field at different angles from 0° to 180 ° during November 2011.

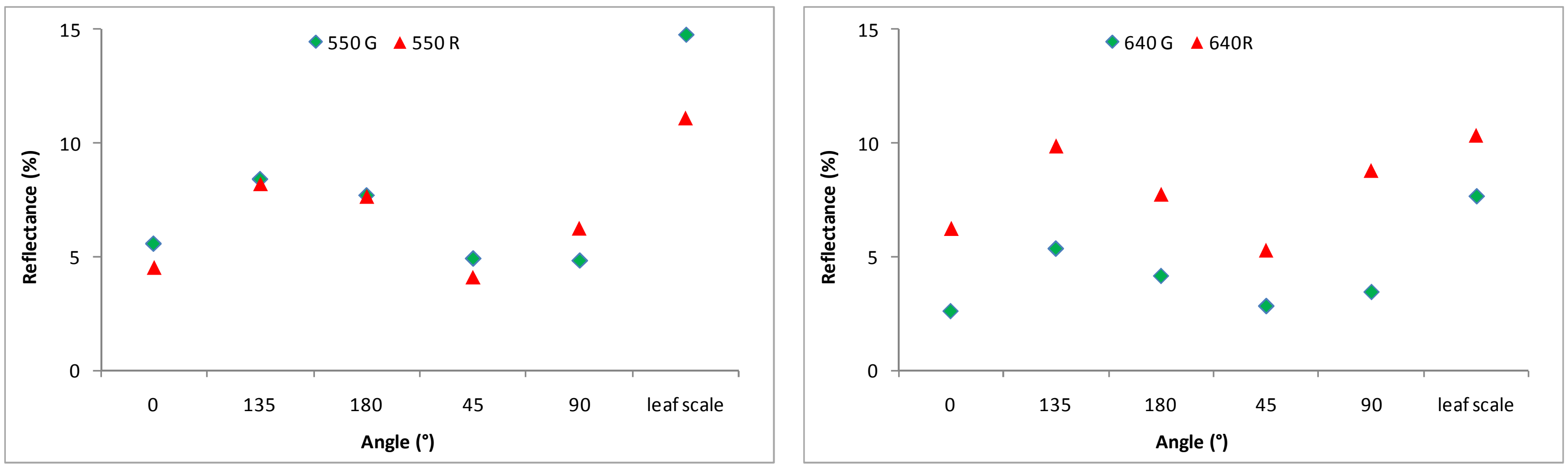

Figure 7: Relationship between light reflectance (%) at 550 and 640 nm and different measured angles for green (G) and pinkish-red (R) plants. Measurements performed in the field during November 2011.

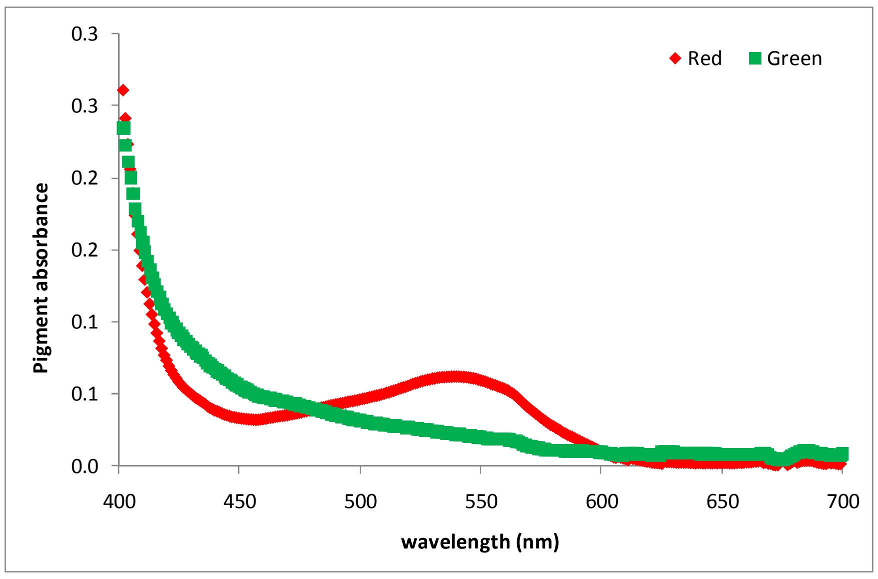

Figure 8: Visible absorbance spectra for extracts of *T. indica*. Mean values for plants of pinkish-red (n=5) or green appearance (n=4) sampled at Yenyening Lakes during November 2011.

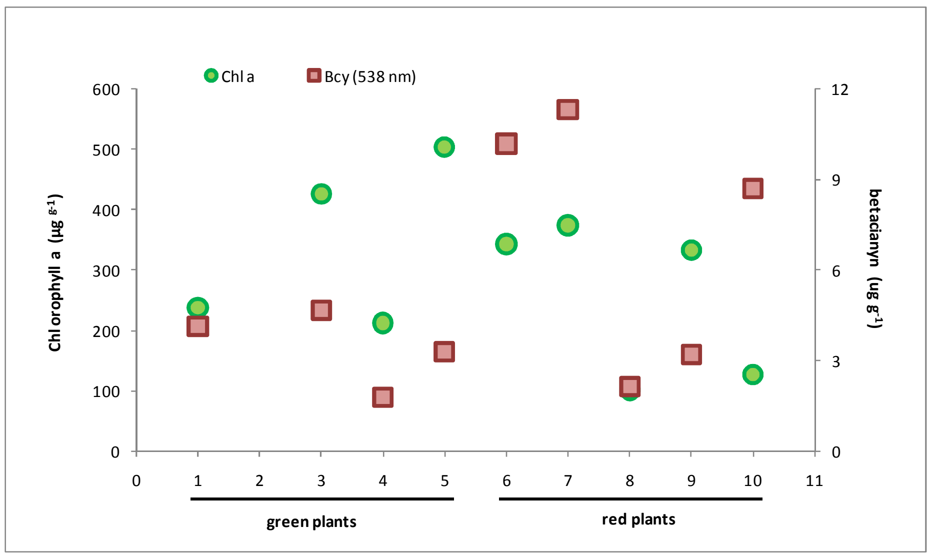

Figure 9: Concentrations of chlorophyll a (O) and putative betacyanins (☐) in tissues of green (#1, 3, 4 &5) and pinkish-red (# 6, 7, 8, 9 & 10) plants of T. *indica*. Samples were taken from Yenyening Lakes in November 2011.

Table 2: Mean values and standard errors for chlorophylls (a) and putative betacyanins concentration for pinkish-red and green appearance plants.

	Chlorophylls (a) (µg g-1)	Putative Betacyanins (µg g-1)	P-value
Pinkish-red plants	256 (±58)	7.1 (±1.9)	0.1
Green plants	345 (±71)	3.5 (±0.6)	0.7

Spectral indices and pigment concentration correlation in *T. indica* at Yenyening Lakes

Spectral detection of pigments and their expression as spectral indices has been widely used to identify changes in plant pigments, as well as other changes in vegetation status produced by different stress drivers (drought, salinity, temperature, etc.) (Sims and Gamon 2002; Ustin et al. 2009). Spectral indices combine the reflectance in bands located mainly in the visible and in the near infrared regions to estimate the occurrence of pigments such as chlorophylls, carotenoids and anthocyanins. For example, since changes in the ratio between chlorophyll a and b modify the light reflectance in the range between 650-800 nm the correlation between these pigments and spectral reflectance indices could be a useful tool to evaluate vegetation changes (Ustin et al. 2004). In this report I calculated eight of the most common indices used in the literature (Table 3) to evaluate changes in pigments using the reflectance values obtained from the green and red plants at Yenyening Lakes. Due to the high variability in the spectral reflectance between 800-1200 nm (mainly because of the limitations of the equipment) these wavelengths were not used to perform spectral indices with the exception of the water index that uses reflectance at 900-970 nm. Most indices to detect changes in pigments used in this report consider wavelengths between 445-800 nm. Three of these indices estimated here have been commonly employed to estimate chlorophylls (Chlorophyll index) and also to estimate “greenness” and primary productivity mainly at plot and landscape scale (NDVI; Red edge NDVI), four of them have been developed to detect the presence of carotenoids and anthocyanins (Photochemical Reflectance Index (PRI), Plant senescence reflectance index (PSRI), Structure Insensitive Pigment Index (SIPI) and the Red/Green index) and the last has been applied to estimate water content (Water index) (equations are shown in Table 3). We also define a “550/640-index” based on the observation of opposite changes in reflectance at 550 and 640 nm when comparing green and pinkish-red *Tecticornia* plants. Each index was correlated with the pigment concentrations and the reflectance observed at different angles of measurement.

Table 3: Indices used to estimate chlorophylls, water and carotenoids at leaf and plot scale. Reproduced from Ollinger (2011) except for the 550/640 index which is defined here for diagnostic reasons.

INDEX	EQUATION	APPLICATION
- Carter stress	- R605/ R760	- Chl content
- Chlorophyll index	- R750/ R710	- Chl content
- Normalized Difference Vegetation index (NDVI)	- (R800-R680)/ (R800+ R680)	- Chl concentration and energy absorption
- Photochemical reflectance index (PRI)	- (R531-R570)/ (R531+ R570)	- Carotenoids
- Plant Senescent Reflectance Index (PSRI)	- (R680-R500)/ R750	- Carotenoids, Chl content
- Water Index (WI)	- R900-R970	- Canopy water content
- Structure Insensitive Pigment Index (SIPI)	- (R800-R445)/ (R800+ R680)	- Carotenoids/Chl ratio
- Red/Green index	- $\sum{}^{600}{}_{699} R / \sum R^{500}{}_{599}$	- Anthocyanins
- 550/640- index	- R 550/R 640	- Putative Betacyanins

Results

Chlorophyll a concentration in the *T. indica* samples obtained from Yenyening Lakes showed, as expected, a positive and significant relationship with indices such as NDVI, Red-Edge NDVI and the Chlorophyll Index (Fig 10). Linear regression coefficients varied according to the angle but in general they presented a good fit, showing correlation coefficients greater than R^2 0.4 (Table 3). Chlorophyll concentration also showed a strong and positive relationship with the Water index especially at 45°, 90°, 135° and 180° (data not shown). Betacyanin concentrations in *Tecticornia* plants did not show a good correlation with indices such a Photochemical Reflectance Index (PRI) and the Structure Insensitive Pigment Index (SIPI) which have been related to changes in the xanthophyll cycle. (Fig 11). Carotenoids did correlate positively with the chlorophyll index especially at measurements performed at 0° and 90°

(R^2 0.45 and 0.42, respectively) but not with other indices such as PRI or SIPI. A strong and positive correlation was observed between carotenoids and chlorophylls (R^2 0.8). Putative betacyanins on the contrary, were not correlated with total chlorophyll content but had a weak and positive relationship with carotenoids (R^2 0.21). Finally the 550/640 index, estimated by the ratio between 550 and 640 nm showed large differences between red and green plants at all angles and at leaf scale (Fig 12 and 13) demonstrating that this ratio could be a useful spectral indicator to detect changes in coloration (and perhaps pigment concentration) in this samphire species (i.e. *T. indica*).

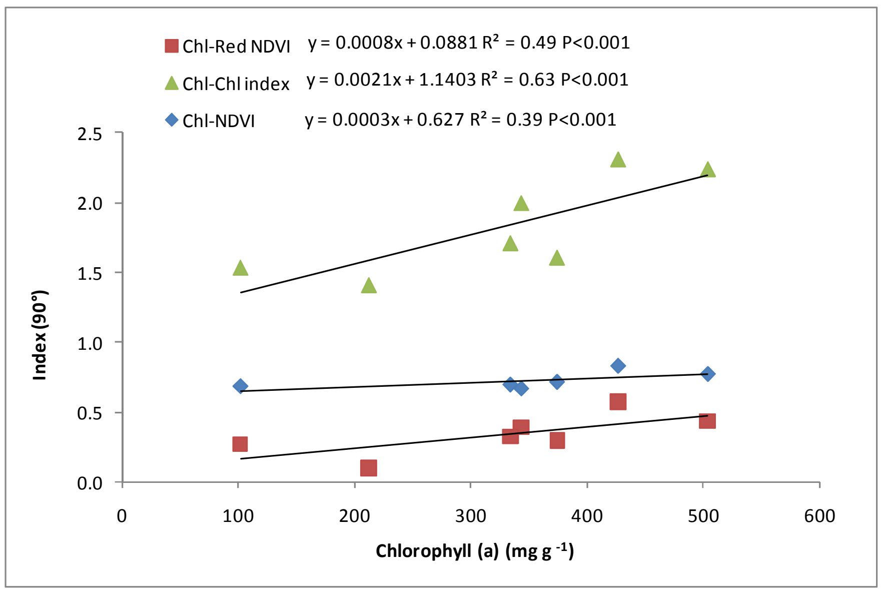

Figure 10: Linear regression between chlorophyll a concentration and different spectral indices estimated from reflectance measurement performed on red and green plants of *T. indica* at 90° at Yenyening Lakes during November 2011. Linear regression between chlorophyll and reflectance at 90° is shown as example, equations for all the angles and the indices are listed in Appendix 1.

a) b)

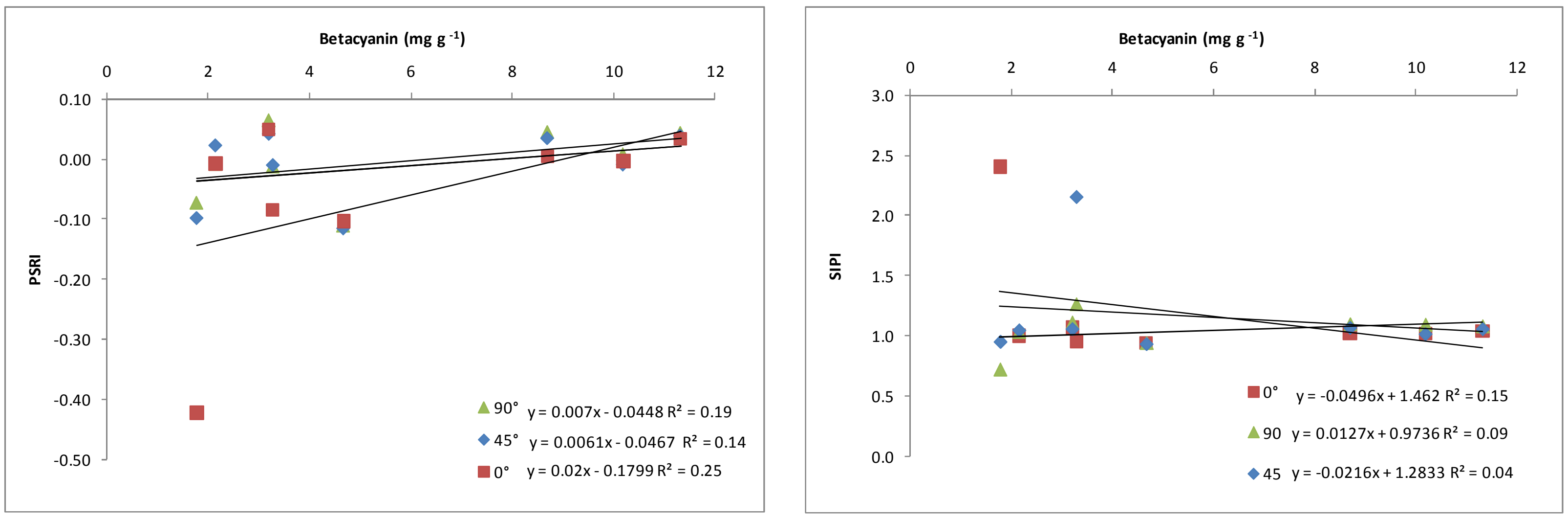

Figure 11: Linear regressions between putative betacyanins and the Plant Senescent Reflectance Index (a) and the Structure Insensitive Pigment Index (b) estimated on pinkish-red and green plants of *T. indica* at 0°, 45° and 90° at Yenyening Lakes during November 2011.

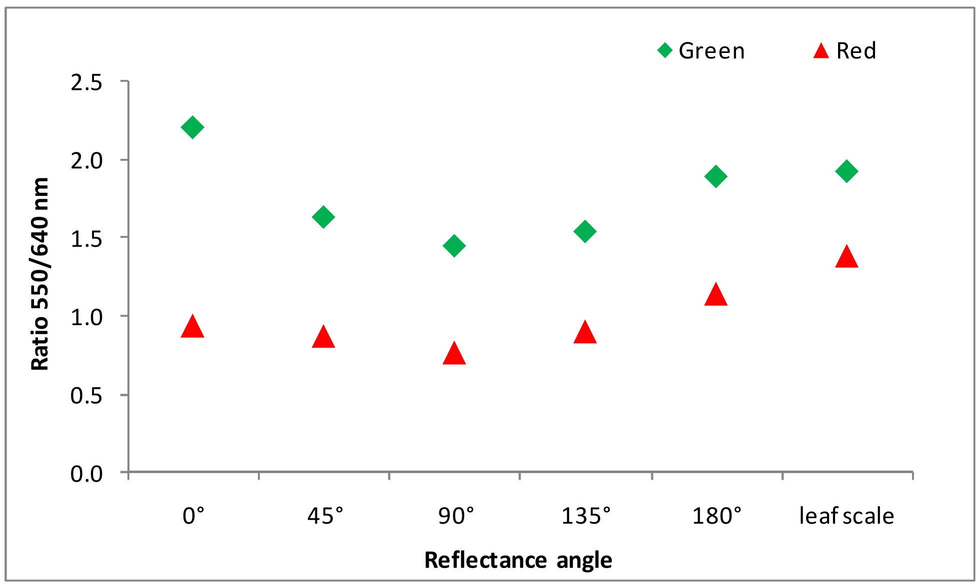

Figure 12: Ratio between reflectance at 540 and 650 nm estimated for pinkish-red and green plants of *T. indica* at different angles and at succulent stem scale.

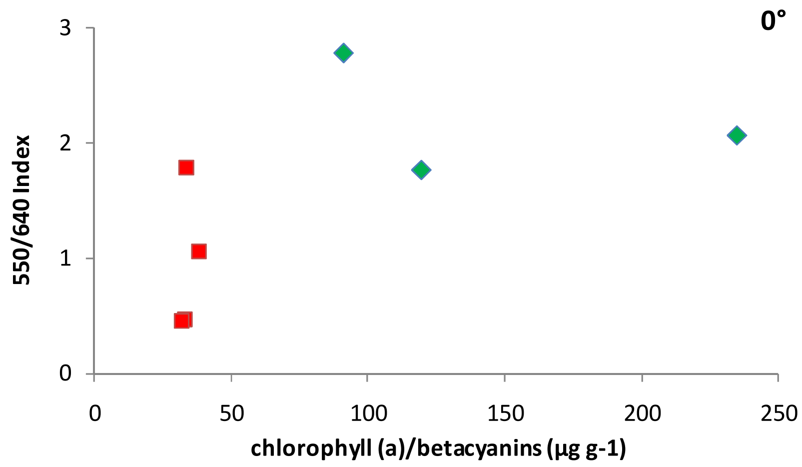

Figure 13: Relationship between the ratio chlorophyll a/betacyanin and the ratio between the reflectance at 550 and 640 nm estimated for 4 pinkish-red and 3 green plants of *T. indica* at 0° and at succulent stem scale.

Conclusions

The results support that *Tecticornia* spp. plants that differ in colouration (pinkish-red and green plants) do contain different pigment concentrations (mainly putative betacyanins and chlorophylls) and reflected differentially the visible light, in particular those wavelengths between 500 and 700 nm, so that such differences can be quantified using a hand-held spectrometer. From all spectral indices selected, NDVI, red-edge NDVI and the Water Index correlate well with chlorophyll concentration and could be potentially useful to estimate this variable through remote sensing. On the other hand, putative betacyanins were not well correlated with the spectral indices such as PRI and SIPI, indices that have been previously related to drought and leaf senescence. It is suggested the realization of this remote sensing application for the evaluation of samphire health/condition will require more spectral measurements at a larger temporal and spatial scale, and the inclusion of more replicate plants or plots per treatment (red-green).

Future research

The activities and objectives listed below have been proposed as a continuation of the current project for the next 6 months (the period of my Endeavour Fellowship):

- Monitor spectral changes and pigment composition in plants under drought stress using a hand held spectrometer under controlled conditions: a glasshouse experiment on the three *Tecticonia* species (*T. indica*, *T. medusa and T. auriculata*) from the Fortescue Marsh, for plants grown in soil exposed to a drying cycle or maintained well-watered.
- Evaluation of spectral changes (at plant and transect level) and pigment dynamics in plants (*T. indica* and *T. auriculata*) at the Fortescue Marsh. Measurements will include plant cover, soil cover and saline soil patches. Three field trips are planned: one at the beginning of April 2012, another at the beginning of June 2012 and a final one at the beginning of July 2012. The pigment data collected to date indicate that samphires at Fortescue Marsh can undergo large changes in pigment compositions during this time frame as the soils dry down. Data analyses will include correlation and repeated measures analysis for betacyanins, carotenoids, chlorophylls and climatic data, also considering spatial variation.

APPENDIX I

Table 4: Linear regression between pigment concentration and spectral indices obtained through measurements on plants at different angles and at "leaf" scale (succulent stem articles). The regression coefficient (R^2) is shown for each case.

Regresion values (R^2)						
Carotenoids	0°	45°	90°	135°	180°	LEAF SCALE
NDVI	0.3	0.0	0.3	0.3	0.4	0.1
Red NDVI	0.3		0.4	0.4	0.3	0.2
PRI	0.1	0.0	0.1	0.0	0.0	0.1
PSRI	0.1	0.2	0.0	0.0	0.0	0.1
SIPI	0.2	0.1	0.0	0.1	0.0	0.0
Red/Green	0.1		0.1	0.2	0.2	
Water Index	0.0	0.1	0.5	0.2	0.4	0.3
Chlor. Index	0.5	0.1	0.4	0.3	0.3	0.1
Putative betacyanins	0°	45°	90°	135°	180°	LEAF SCALE
NDVI	0.4	0.0	0.1	0.2	0.6	0.3
Red NDVI	0.2		0.0	0.3	0.4	0.2
PRI	0.3	0.1	0.0	0.5	0.1	0.0
PSRI	0.2	0.0	0.1	0.0	0.0	0.1
SIPI	0.2	0.2	0.2	0.1	0.0	0.0
Red/Green	0.1		0.0	0.1	0.1	
Water Index	0.7	0.0	0.0	0.1	0.0	0.3
Chlor. Index	0.4	0.0	0.0	0.3	0.3	0.2
Chlorophyll a	0°	45°	90°	135°	180°	LEAF SCALE
NDVI	0.6	0.4	0.4	0.4	0.6	0.0
Red NDVI	0.6	0.2	0.5	0.7	0.6	0.3
PRI	0.1	0.0	0.0	0.2	0.3	0.2
PSRI	0.0	0.2	0.1	0.2	0.0	0.0
SIPI	0.2	0.2	0.0	0.1	0.1	0.0
Red/Green	0.3	0.2	0.3	0.1	0.4	
Water Index	0.1	0.4	0.5	0.6	0.3	0.1
Chlor. Index	0.6	0.4	0.6	0.5	0.6	0.3

Figure 14: Pinkish-red and green plants of *T. indica* in Yenyening Marshes. Images were taken in November 2011.

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Spectral responses and ecophysiology of *Tecticornia* species subject to changes in water availability

Preliminary internal report to FMG Ltd

March-August 2012

Victoria Marchesini

School of Plant Biology, The University of Western Australia

1. INTRODUCTION

In December 2011, a new collaborative research project between Fortescue Metal Group Ltd (FMG) and the School of Plant Biology (UWA) was proposed. The project aimed to study changes in spectral signatures in the Fortescue Marsh samphires subjected to water deficit and high salinity, by analysing spectral changes at different scales: from tissue level to plot scale. The main objective was to determine which spectral signatures were best suited to detect stress in these halophytes to eventually extrapolate these results at larger scale for vegetation monitoring. Two approaches were used to achieve these objectives: i) a large drought experiment in a glasshouse at UWA and ii) field measurements at the Fortescue Marsh for different species at contrasting times (dry and wet season). The project was conducted by Dr. Victoria Marshesini in two phases (phase 1 report already completed and submitted to FMG), and this report summarises activities during phase 2 when Dr. Marchesini was an Australian Endeavour Fellow at UWA.

The glasshouse experiment involved spectral measurements at tissue and whole-plant scale and detection of plant physiological changes by analysing growth, pigment concentrations, water relations and physiological stress indicators. Field measurements included two of the three dominant species at Fortescue Marsh: *T. indica* and *T. auriculata,* and comprised plant pigments analysis as well as spectral measurements on single plants, bare soil and whole plots.

2. GLASSHOUSE EXPERIMENT

The glasshouse experiment simulated field conditions: an environment subjected to long dry periods with occasional heavy rainfall in the Pilbara region (where these species grow naturally), by exposing the plants to progressive soil water deficit, followed by a recovery phase. The experiment made use of a salt lake soil, adding new information beyond the previous work performed in controlled artificial substrates (sand-perlite mixtures).

Experiment characteristics:

- Three species: *Tecticornia indica, T. auriculata* and *T. medusa*
- Clay-rich soil from a salt lake
- Rate of soil drying similar for all species and treatments, achieved by manipulating plant number and combining 2-3 species in the same pot

Germination and seedling growth commenced in the last week of December 2011. Three months later the seedlings were transplanted and five months later the plants were of sufficient size for the proposed experimental work (Appendix A). Drought treatments commenced early June 2012. We collected 2000 kg of soil from the margins of a salt lake on a farm near Kalannie, WA (30° 13 39.4 S, -117° 22 29.4 E), an analogous system to Fortescue Marsh habitat of *T. indica*. Soil moisture retention curves (relationship between soil water potential and soil water content) were measured using a psychrometer (Appendix B). Nutrients were added to the soil and salinity was adjusted to the desired level by addition of NaCl to further increase the soil EC above the native levels. Plants were raised until ~5 months old and the responses to drought were evaluated by monitoring spectral changes and pigment compositions with time and by measuring water use, tissue water content, sap osmotic potential, growth, and chlorophyll fluorescence.

Drought stress was achieved by withholding water, after which plants depleted soil moisture through transpiration. Since *T. indica, T. auriculata* and *T. medusa* have different sizes (growth differences) and different transpiration rates (C3 or C4 photosynthesis), the experiment used two approaches to achieve similar rates of soil drying for different species:

1. Vary the number of plants per pot according to their expected sizes and transpiration rates
2. Grow different species in the same pot to ensure that they experience identical soil moisture conditions.

By combining different plant species, the experiment comprised pots with different treatments for different objectives:
1. multiple-plant single-species (to observe species at similar drying rates; number of plants adjusted to ensure similar drying rates)
2. multiple-plant two-species (to test competition in a pairwise set-up; number of plants adjusted to ensure similar mass for each species and similar drying rates)

3. multiple-plant three-species (to test competition in a complete all-species set-up, with the resulting exposure to the same drying rates)

In addition to these treatments, there were also single-plant single-species pots of smaller pot volume, to check that plant growth and physiology were not affected in unexpected ways by growing multiple plants together in one pot. Results for the small pot experiment are not presented in this preliminary report. Water use was estimated by weighing each pot every 2 days. Control plants were watered with DI water three times per week to the initial water content of 0.15 g g^{-1} (0.15 g water per g soil dry weight; just below field capacity). A number of pots without plants were monitored to measure evaporation in order to estimate transpiration as the difference between total water losses and soil evaporation. To assess growth and to do destructive plant water status and pigment measurements, a number of sequential harvests were necessary: one at the beginning of the experiment (H0, well watered/control plants), 35 days later (H1), 49 days later (H2) and 83 days later for plants that were rewatered (RW).

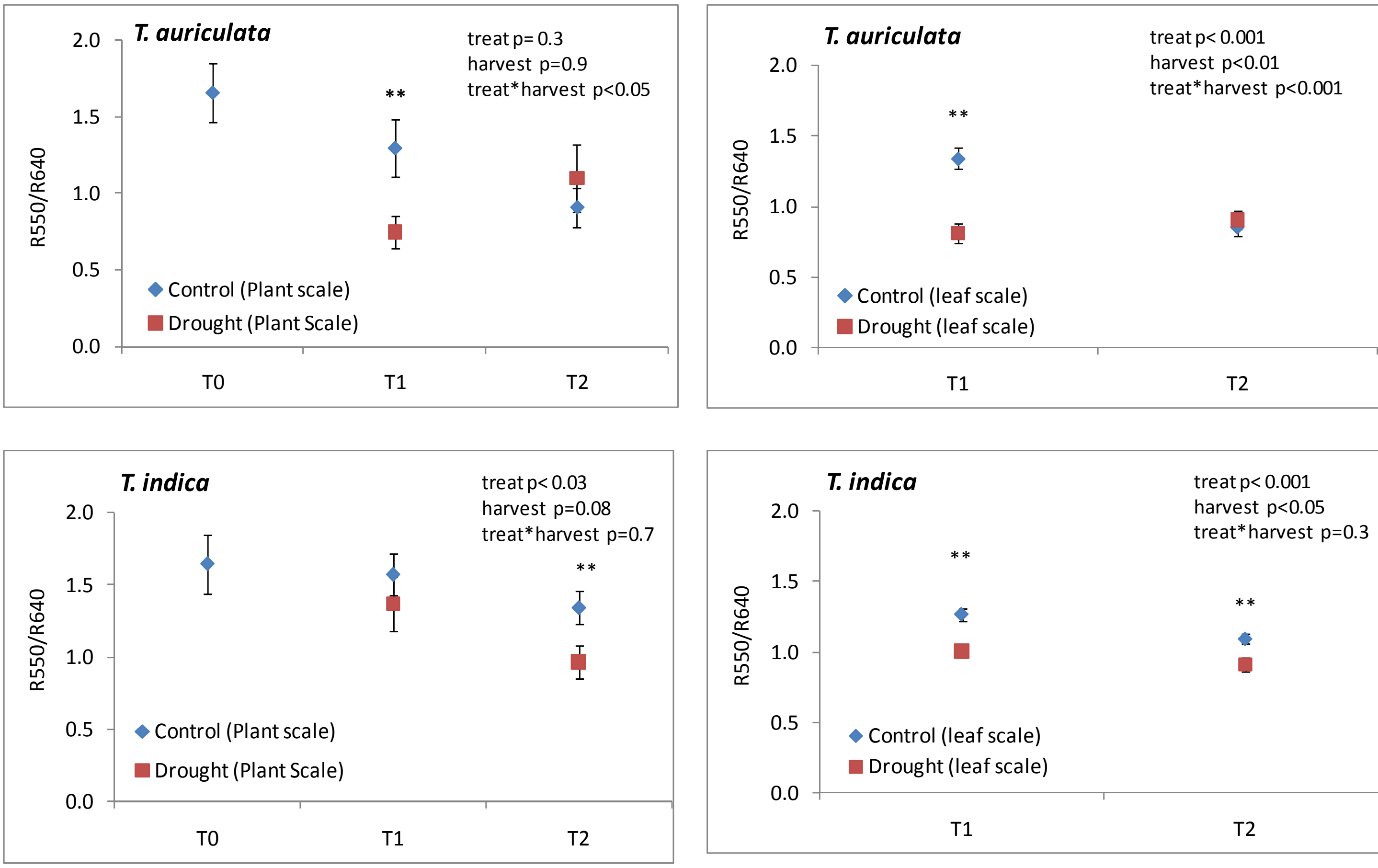
The day before each harvest, spectral measurements were taken for four replicate plants in each treatment. The number of plants measured per pot varied according to the treatment. Spectral measurements were performed using a handheld spectrometer (JAZ, Ocean Optics), which is designed to measure reflectance between 400-1200 nm (visible and near-infrared wavelengths). Reflectance is estimated as a percentage between a maximum (pure white surface) and a minimum reference value (obtained by blocking the fiber optic). Measurements were performed at noon (when the sun is close to the zenith) on four consecutive days during each harvest time, distance between the sensor and the target plant was 10 cm and the angle of measurements was 45°. Based on previous research (Marchesini 2012; phase 1 of this research initiative), the new reflectance index R_{550}/R_{640} (ratio of reflectances at 550 and 640 nm) was calculated as it was shown to correlate with pigment changes in these species and is not sensitive to large variation in total reflectance. The ratio is low for plants that are high in putative betalain concentrations (pinkish pigments) and low in chlorophyll concentrations (green pigments).

A stem segment of each plant (in each pot) was also harvested to determine spectral reflectance at tissue scale. Fresh biomass of each single plant was weighed and separated in succulent, woody and young tissues. Growth was determined by weighing fresh and dry shoot and root biomass. A small sample of fully expanded succulent stem articles was weighed, and placed in cryovials in liquid N_2 and stored at -80°C for osmotic potential analyses. Also a sample of succulent tissues was dried in a freeze drier for pigment and ion analysis. The remainder of the material was oven-dried at 60°C. Root biomass was determined for each pot after washing out the soil from roots and oven-drying at 60°C.

Results (glasshouse experiment)

Spectral reflectance

Drought treatment changed *Tecticornia* plants' reflection spectra both at tissue and plant scale. The ratio R_{550}/R_{640} decreased as soils dried between H0 and H1 in all three species (Fig. 1), but this was only statistically significant for *T. auriculata*, both at plant and tissue scale. *T. indica* and *T. medusa* showed significant treatment effects at harvest 2 (49 days after the beginning of the treatment), when differences in *T. auriculata* were not significant anymore. Interestingly, R_{550}/R_{640} also decreased with time for well-watered plants. Overall, these results indicate an effect of drought on spectral signatures of all species, as well as unexplained interactions between treatment and time.



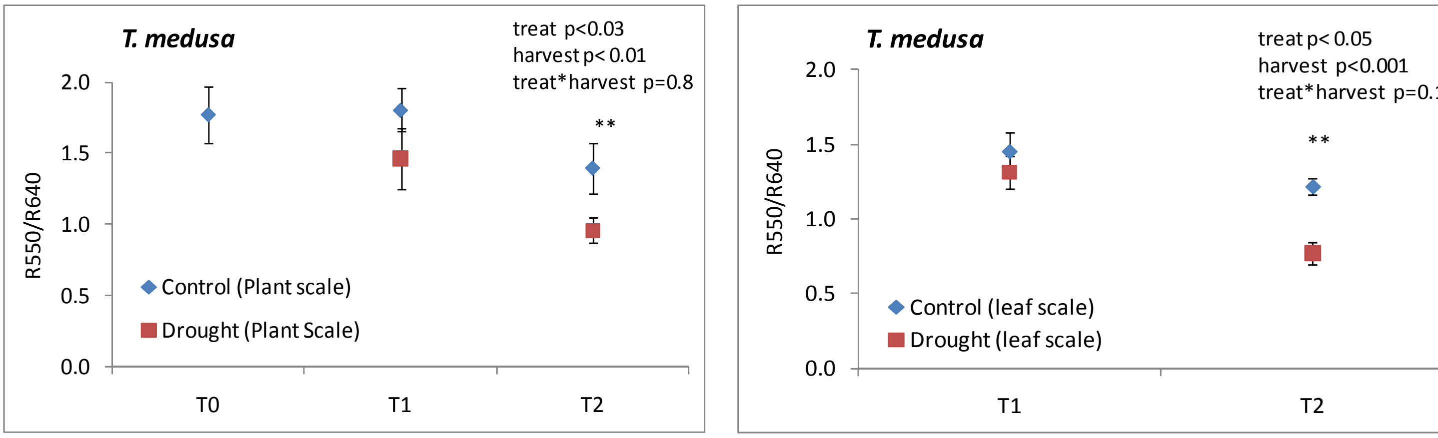


Figure 1. R_{550}/R_{640} for *Tecticonia* spp. at plant (left panels) and leaf (right panels) scales for different sampling dates: initial harvest (H0), 35 days (H1) and 49 (H2) days after the drought treatment. Asterisks indicate significant differences at P<0.05.

Transpiration

Transpiration rates were estimated from weight loss of each pot after subtracting mean weight loss from pots without plants (due to evaporation only), and taking into account changes in the biomass of the plants. For the purpose of this preliminary report, results are summarised for single-species pots only. To quantify the influence of soil water content on transpiration, transpiration rates of droughted plants were expressed relative to transpiration rates of well-watered plants. This largely removes the effect of varying evaporative conditions (e.g. including daily differences in radiation, in daylength and in vapour pressure deficits caused by differences in relative humidity and air temperature). Transpiration rates are expressed per unit fresh weight (succulent parts only, woody parts excluded).

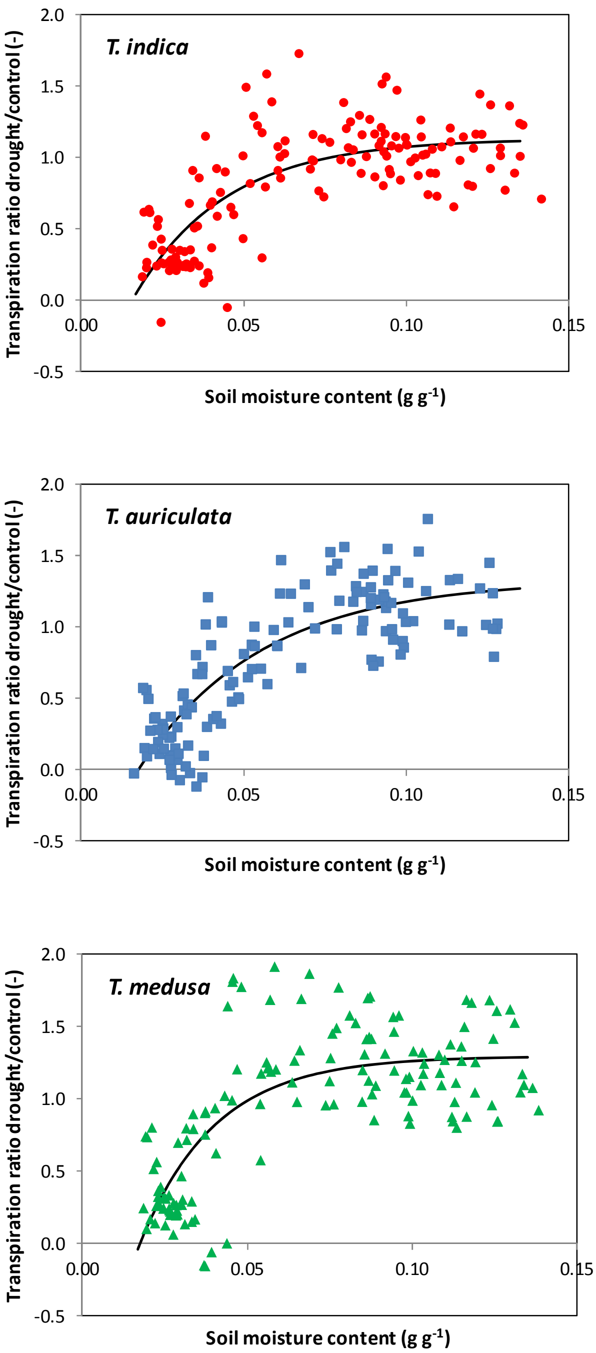


Figure 2. Relationship between transpiration rates and soil moisture content for *T. indica, T. auriculata* and *T. medusa*. See text for details about normalisation of transpiration rates. Lines were fitted using an exponential decay function with an offset: $y = C * (1-e^{-k*(x-a)})$.

Chlorophyll fluorescence

Chlorophyll fluorescence measurements indicated a strong deterioration of the photosynthetic apparatus due to drought (Fig. 3). The ratio Fv/Fm, or dark-adapted quantum yield, is an indicator of photo-damage or down-regulation of photosystem II. Values of approximately 0.8, found in all three species under well-watered conditions, are typical for non-stressed plants. At H1, Fv/Fm had declined most in *T. medusa* (41%) and least in *T. indica*, and similarly, at H2, when the droughted plants had 80% and 93% lower values for these two species. These results indicate the development of severe stress, and this happened faster in the most sensitive species, *T. medusa*, and slower in the least sensitive species, *T. indica*. Drought sensitivity of the species thus appears to correlate with the likeliness of severe drought in their habitat.

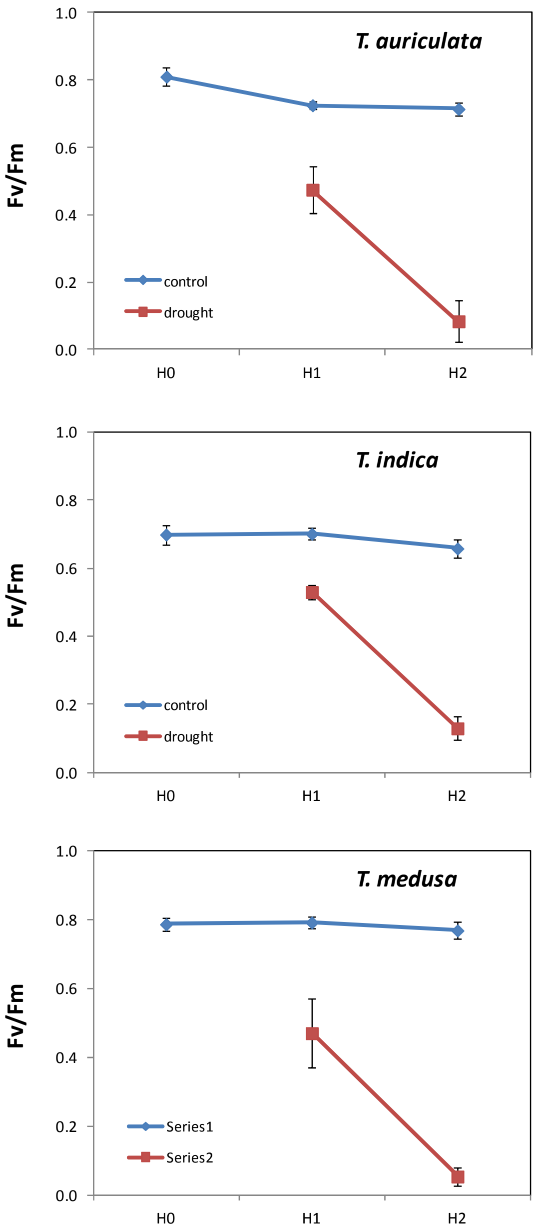


Figure 3. The chlorophyll fluorescence ratio Fv/Fm for plants of the three study species under drought and control treatments. Data collected by Dr Chuanhua Yin.

Mortality

Mortality, assessed at the time of rewatering, varied according to species treatment/combination. *T. auriculata* and *T. indica* had the highest mortality rate when grown combined with the other two species while *T. medusa* showed 100% of mortality in the single-species treatment. 100% survivorship was observed when *T. medusa* and *T. auriculata* grew together. *T. indica* showed similar mortality values when it grew alone or together with *T. auriculata* or *T. medusa.* The results in monoculture indicated *T. medusa* as the most vulnerable species to changes in water availability followed by *T. auriculata* and *T. indica.* Further analysis will consider the soil water content at the point in time when mortality assessments were made.

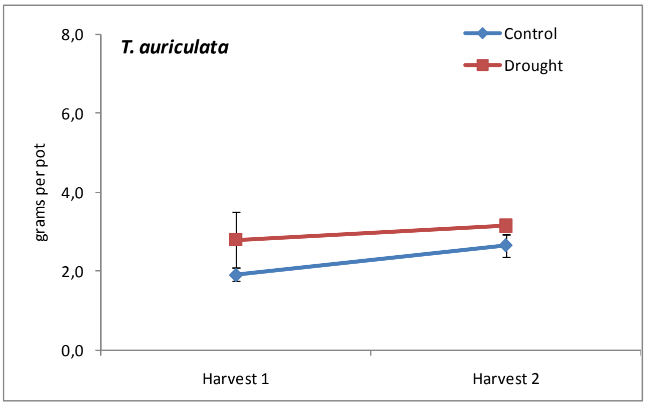
Table 1: Mortality rates for *T. medusa, T. indica* and *T. auriculata*. Mortality was estimated as the number of dead plants divided by the number of total plants of the same species in each pot.

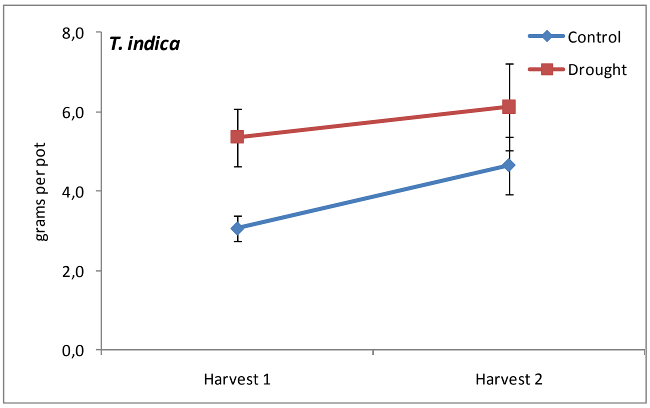
Species combination	**Number of dead plants / total plants of the same species per pot**		
	T. medusa	*T. auriculata*	*T. indica*
T. auriculata		0.5	
T. indica			0.4
T. medusa	1.0		
T. indica-auriculata		0.0	0.3
T. indica-medusa	0.4		0.4
T. medusa-auriculata	0.0	0.0	
T. medusa-auriculata-indica	0.5	0.8	1.0

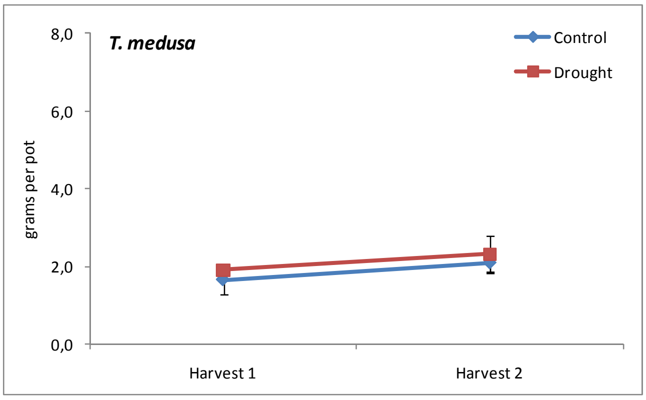
Growth

Results for aboveground plant parts are still being processed as dry weights are not yet available due to the long freeze-drying process. The presentation here is limited to root dry mass.

At H1, after an initial period of drought, root dry mass was enhanced by drought, especially for *T. indica* and only moderately for *T. auriculata*, but not for *T. medusa* (Fig. 3, Table 2). At H2, after continued drought, differences between the droughted and well-watered plants became smaller in the single-species treatments, but bigger in the mixed-species treatment (Fig. 3, Table 2).


T. auriculata
Control
Drought
grams per pot
8,0
6,0
4,0
2,0
0,0
Harvest 1
Harvest 2


T. indica
Control
Drought
grams per pot
8,0
6,0
4,0
2,0
0,0
Harvest 1
Harvest 2


T. medusa
Control
Drought
grams per pot
8,0
6,0
4,0
2,0
0,0
Harvest 1
Harvest 2

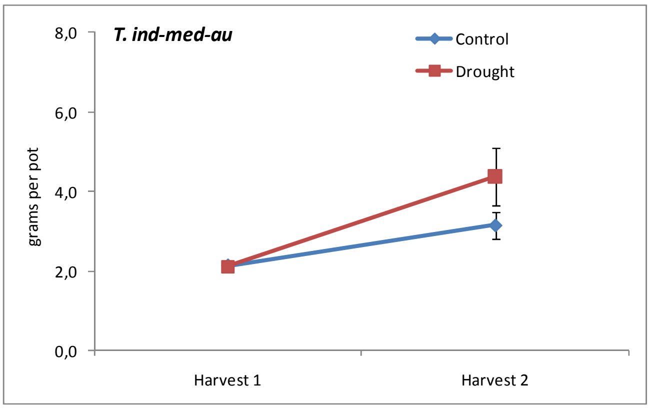


Figure 4: Root biomass per pot (multiple plants) for single species and mixed-species treatments at different sampling times.

Table 2: Drought treatment effect on root dry mass (%) defined as (Drought-Control)/Control *100% for two harvesting dates

Species	Sampling times	
	Harvest T1	Harvest T2
T. au-ind-med	-1.1	+28.0
T. auriculata	+31.7	+15.8
T. indica	+42.8	+24.3
T. medusa	+13.5	+9.9

3. FIELD MEASUREMENTS AT FORTESCUE MARSH

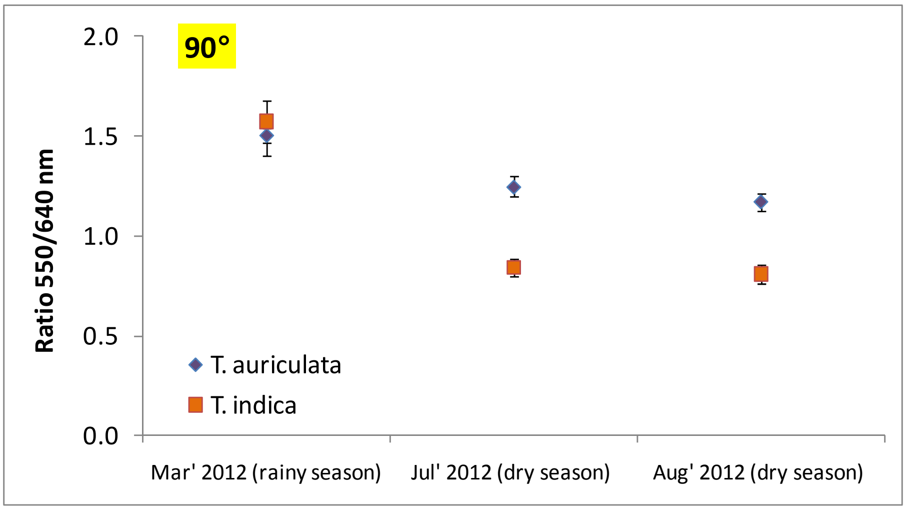
Monitoring of samphires was conducted in *T. indica* and *T. auriculata* plots (Transect A, UWA previous work, 22° 21.976 S, 119° 20.170 E) at Fortescue Marsh. Plots monitored were selected to have a dominance (i.e. cover) >80% of the target species. Field samplings were done at strategic times to test whether pigment changes can be detected with a hand-held spectrometer device. During each field trip spectral reflectance was measured and then plant material was collected for pigment analyses (chlorophylls, carotenoids and betalains). Measurements for spectral signatures included plants and soil patches with or without salt crusts. Photographs were taken, soil samples collected to 10 cm depth for water content determination, and plant tissue samples collected for pigment analyses and tissue water content measurement. Spectral data were obtained with the same device as used in the glasshouse experiment. Measurements were performed holding the device at two angles, 45° and 90°, determined by a clinometer. The distance between the sensor (optical fiber) and the target branch was 10 cm.

Three field trips were conducted: (i) at the end of March 2012 (late 'wet' season), (ii) at the beginning of July 2012 (middle of dry season), and (iii) at the end of August 2012 (late dry season). Measurements were done on three plots per species, with four plants per plot. In each plot, two spectral vegetation measurements were also taken at plot scale and four measurements on bare soil only.

After measurements, representative parts of the plants were sampled for pigment analysis. Two large branches (from lowest succulent article to tip) were kept on ice in the dark for approximately 8 hours for transport to UWA where they were then snap-frozen in liquid N_2 and subsequently freeze-dried

Results (field)

The ratio between 550/640 nm reflectance (R_{550}/R_{640}) for *T. indica and T. auriculata* plants showed strong temporal changes, declining from 1.5 after the rainy season to ~1.0 during the dry season. These changes were similar at measurement angles of 90°and at 45° (Fig. 5). Changes in plant reflectance coincided with visible changes in colouration (Fig. 6) and with a reduction in soil water content (Fig. 7) which, as expected, declined almost 50% after the wet season. As in the glasshouse experiment, the ratio R_{550}/R_{640} was always higher for plants at higher soil water content than for plants under drought stress (Fig. 1, 5)



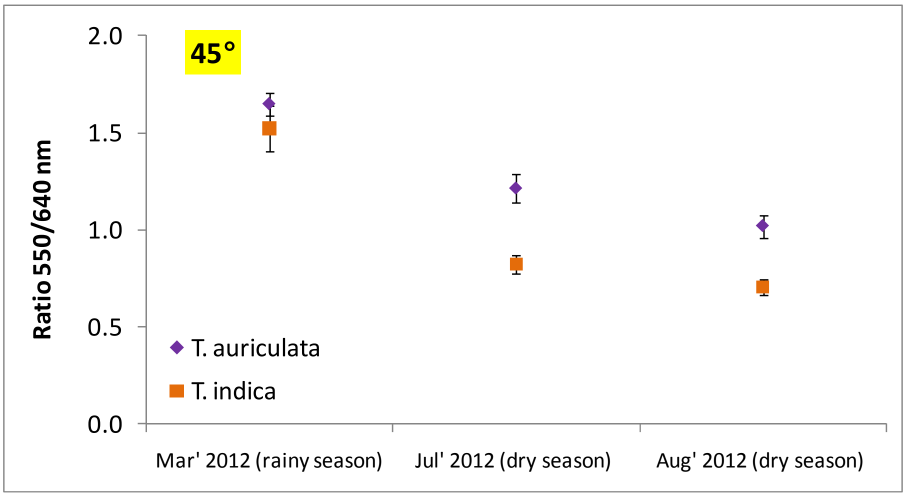


Figure 5. Changes in R_{550}/R_{640} at plant scale for *T. auriculata* and *T. indica* at 45° and 90° measurement angles in the field at Fortescue Marsh for three dates, March, July and August 2012.

Figure 6: Seasonal changes in colouration of *T. auriculata* (above panel) *and T. indica* (below panel). Pictures were taken in March (left panel) and August 2011 (right panel), respectively, at Fortescue Marsh.

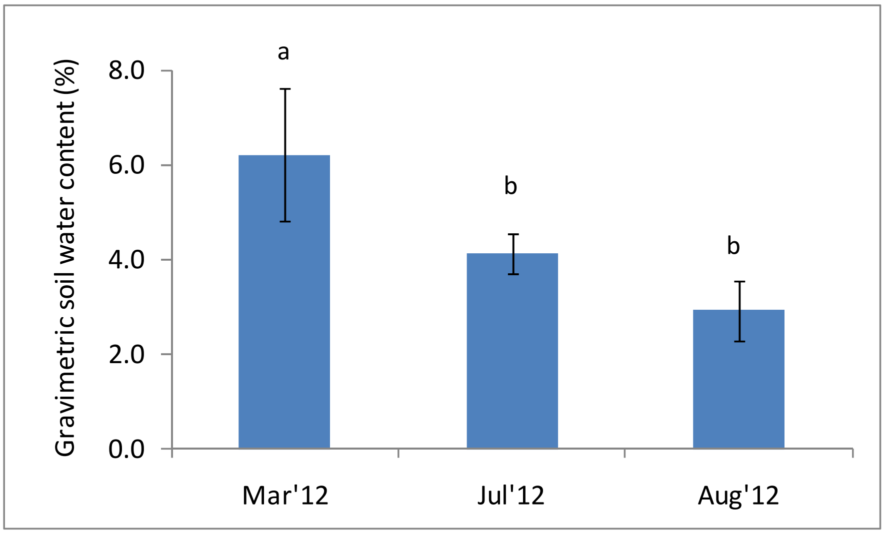


Figure 7. Gravimetric soil water content (10 cm depth) for different sampling times. Average and standard error values for six *Tecticornia* plots (n = 24 samples, n = 4 per plot). Different letters indicate statistical differences at P<0.05.

4. OTHER RESULTS (forthcoming)

Glasshouse experiment:

The experiment was successful, but the long duration needed for the plants to grow to the size needed for the experiment, and then the slow draw-down of water in the drought treatments, as well as the slow freeze-drying process of the succulent stems, all mean that the exact timing of these experiments is difficult to predict and therefore some analyses have not yet been completed.

- Plant water use. Transpiration results will be analysed further and correlated with soil volumetric water content and soil water potential. It will be attempted to infer if matric or osmotic components of the soil water potential were dominant, and if this changed as soils dried out. Soil texture remains to be measured to characterise the soil. Transpiration will also be expressed on a plant surface area basis for comparison with the wider literature.
- Growth will be summarised with special attention to drought effects on biomass allocation (root-shoot) and desiccation of succulent stems.
- Stress physiology. Two independent indicators of stress were measured: plant osmotic potential and chlorophyll fluorescence. Data analyses for both are near completion. Tissue is available also for ion analysis which would help understand changes in osmotic potential.

- Pigments. A key objective is the correlation of pigment concentrations with spectral measurements. Tissue preparation for pigment extraction is in process. Analysis will commence after tests in an expert German laboratory have been finalised – these tests aim to identify the putative betalains in these species and confirm the appropriate extraction procedure.
- Two-species combinations. This preliminary report only shows results for pots that held a single-species or all three species. The three pairwise combinations of the three species will help understand possible competitive interactions.
- Statistics. Appropriate tests and curve fitting will be performed.

Field:

- Pigments: analysis and correlation with spectral information will be carried out as for the glasshouse experiment.
- Tissue water content will be examined as a possible indicator of drought stress. Weather data will be summarised.

Other outcomes:

- Transpiration observations and soil-plant water relations have already helped parameterising the Hydrus model of the Fortescue Marsh, currently in development by Jinquan Wu and Dan Huxtable.
- The minirhizotron pilot experiment (not reported here) will strengthen future grant proposals by demonstrating the importance of root distribution and dynamics and our capacity to assess these.

5. CONCLUSIONS

Results from the spectral changes observed both under glasshouse and field conditions support the hypothesis that drought stress in *Tecticornia* plants is associated with measurable differences in spectral reflectance. The magnitude of changes in the ratio of reflectances at 550 and 640 nm is considerable and seems well-correlated with physiological stress indicators and environmental changes such as soil water content. This ratio was developed based on analyses in phase 1 of the seasonal samples collected as part of the larger ARC Linkage project, and therefore is potentially useful to estimate changes in colouration of the samphire communities due to drought through remote sensing. Upon completion of the analyses of the 2012 glasshouse and field observations, we will have greater insight in the factors influencing plant colouration. This information and further testing in the field at larger scale is essential to determine if remote sensing of samphire vegetation can reliably assess its condition. Dr. Marchesini has completed her Endeavour Fellowship, but will continue to work in collaboration with the UWA team to finalise the data analyses and manuscript preparation, albeit on a part-time voluntary basis.

REFERENCES

Marchesini V. 2012. *Pigment concentrations and spectral signals of samphires.* Internal Research Report for the period October 2011-February 2012. School of Plant Biology, The University of Western Australia.

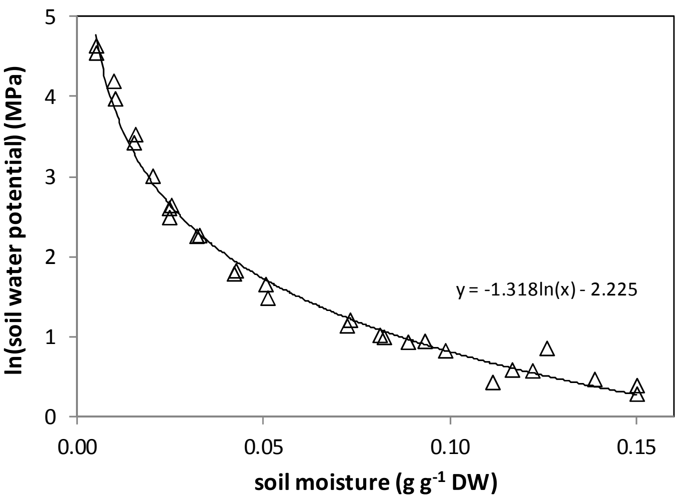
APPENDICES

Appendix A.

Recently germinated *Tecticornia* seedlings in water-saturated sand (left) and after transplanting into large pots containing a field soil (right) in glasshouse at UWA. The soil in pots on the right is covered by a layer of white plastic beads to impede evaporation from the soil surface.

Appendix B.

Soil water retention curve for the soil used in the glasshouse experiment. Water potentials were determined psychrometrically and include matric and osmotic components.



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Eco-hydrological monitoring of the Fortescue Marsh region with remote sensing and on-ground observations

Pilot Project

Olga Barron, Richard Silberstein, Geoff Hodgson, Tom van Niel, Irina Emelyanova, and Mike Donn

30 March 2012

Report to Fortescue Metals Group Ltd

[Insert partner or collaborator logos here, scale to fit, 3cm maximum height (delete if not required)]

Citation

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Copyright and disclaimer

Important disclaimer

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Acknowledgments

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Executive summary

Fortescue Metals Group (FMG), CSIRO and UWA (the Project Partners) have identified a collaborative project opportunity related to the development of remote sensing (RS) tools to monitor the eco-hydrology of the Fortescue Marsh, supported by on-ground observations of the water regime and vegetation dynamics. The Fortescue Marsh is a wetland of high conservation significance and is located in proximity to where the FMG operates the Cloudbreak and Christmas Creek iron ore mines. Mine expansion plans have the potential to affect the marsh through altered hydrology. Consequently FMG has a need to better understand the potential impacts of groundwater dewatering, surplus water injection and disrupted surface flows on the marsh vegetation. Appropriate vegetation health monitoring techniques and impact mitigation strategies need to be developed. Considering the limitation of the on-ground investigations due to the conservation value of the Marsh, remote sensing methods provide opportunities for improving understanding of the eco-hydrological function of the Marsh; and contributing to a framework for broad scale vegetation health monitoring.

To explore the opportunities for RS to monitor the eco-hydrology of the Fortescue Marsh, a pilot project was established with the main objectives to illustrate the capability of RS techniques to identity land cover classes which are characterised by various responses to changes in water regime; to illustrate whether these RS techniques can provide a useful contribution to water balance estimation; to determine if the current monitoring program provides adequate validation of RS techniques and to propose a program to monitor the eco-hydrology of the Fortescue Marsh.

Our results show that land cover classes in the Marsh and its surroundings can be characterised by RS analysis, which can also define the spatial and temporal variability in evapotranspiration. The results are also in agreement with available on-ground observations conducted by UWA and FMG.

Remote sensing for vegetation-land cover classification and evapotranspiration

Assessment of vegetation response to mostly dry conditions over the 18 month period from May 2009 to December 2010 was based on analysis of greenness (measured as the Normalised Difference Vegetation Index, NDVI) and wetness (measured as the Normalised Difference Wetness Index, NDWI) identified using Landsat data. The results are in agreement with on-ground observations at six locations (UWA observation sites) as well as vegetation mapped outside the Marsh area. The areas associated with three vegetation types, monitored by UWA, showed different responses to drying, some of which appeared to show step changes in their greenness and wetness, possibly indicating a threshold response. The use of alternative indices to NDVI, namely the Enhanced Normalised Vegetation Index (EVI) and Structure Insensitive Pigment Index (SIPI) resulted in similar classification results.

Spatial and temporal patterns in actual evapotranspiration (ET) were examined using two RS based methods: (i) surface energy balance analysis and (ii) vegetation index and wetness index analysis, known as the SLST and CMRSET methods, respectively. The results were in agreement with other observations, and indicated that the inundated areas in the Marsh were characterised by high annual ET in 2009, summer ET exceeded winter ET in 2009 and 2010, commensurate with both available water and potential evaporation rates, and higher ET rates were associated with the Marsh border, possibly indicating groundwater discharge zones. High ET values, both monthly and annual, were identified along the southern slopes of the Chichester Ranges north of the mine area, on the northern flanks of the Hamersley Ranges, and west and east of the Weeli Wolli Creek alluvial fan.

The analysis indicated that land cover condition and ET may be linked to thresholds of soil moisture, and possibly salt, storage that govern the greenness, redness and transpiration of the marsh vegetation. We found a good qualitative correspondence between the RS analysis and on-ground observations by the UWA team. Aligning the timing and extent of on-ground observations with the time of RS data acquisition, and extending the ground measurements to a longer series, would support a quantitative analysis.

More detailed and combined analysis of land cover classes and associated ET rates may assist in identification of vegetation dependency on groundwater or soil water. Isotope methods could be used to separate between the water sources in the unsaturated and saturated profile and for defining ages of groundwater and flow paths.

A major advantage of using RS for ET measurement is that regional scale water balances are possible. However, RS of ET needs validation in the Pilbara or similar regions. Integrative methods, such as eddy covariance or scintillometers, would give this validation with their intermediate scale (a few km^2) ET measurements. The sap flow measurements, by UWA, also assist in local plot scale ET estimation and these can be used, with soil evaporation measurements to support the eddy covariance. There is a real need to run these measurements in parallel so that we can close all the gaps at once.

Ecohydrological monitoring framework

This report also provides a scope of a monitoring programme that would support the development of a Diagnostic Framework for Ecohydrology of the Fortescue Marsh, which will separate the effects of mining from other influences, such as climatic variability, on vegetation communities in the Marsh and elsewhere. To meet this objective it is proposed that RS techniques be combined with on-ground observations. These activities are commonly related to different scales of assessment, however, when they are aligned, RS will allow upscaling of local on-ground observations to larger areas of the Marsh.

There is a need to clarify the groundwater–vegetation interaction and particularly the vegetation's groundwater use and dependence. The role of groundwater in the Marsh water balance is not yet quantified (Aquaterra estimated it to be 10% of inflow to the Marsh) and changes in soil moisture dynamics, salt accumulation or flushing, or inundation could all effect the vegetation.

The proposed framework aims to:

1. Monitor changes in marsh vegetation condition, for this we propose a combination of RS and ground observations.
2. Monitor changes in marsh ecohydrology, particularly vegetation dependence on surface and groundwater. This is:
   i) an explanatory factor for vegetation changes observed, and
   ii) a predictor of ecological changes that might occur if hydrological changes continue.
3. Separate changes in marsh condition between natural variability of climate, through rainfall and drying cycles, from changes possibly caused by mining related activities.
4. Add value to existing datasets for the hydrogeological modelling to improve recharge and discharge estimation and the evaporation/recharge boundary condition of groundwater models.

Complementary to the need for adequate coverage of spatial scales is the need for alignment of temporal scales. The analysis of data collected to date has shown the advantages of common timing of observations to align the plant observations with soil and hydrological sampling and RS images as much as possible. It is also of great value to collect a continuous data stream if possible.

1 Introduction

Fortescue Metals Group (FMG), CSIRO and UWA (the Project Partners) have identified a collaborative project opportunity related to the development of remote sensing (RS) tools to monitor the eco-hydrology of the Fortescue Marsh, supported by on-ground observations of the water regime and vegetation dynamics.

The Fortescue Marsh is a wetland of high conservation significance. FMG operates the Cloudbreak and Christmas Creek iron ore mines near the northern fringe of the marsh. Mine expansion plans have the potential to affect the marsh through altered hydrology. Consequently FMG has a need to better understand the potential impacts of groundwater dewatering, surplus water injection and disrupted surface flows on the marsh vegetation. Appropriate vegetation health monitoring techniques and impact mitigation strategies need to be developed. Considering the limitation of the on-ground investigations due to the conservation value of the Marsh, RS methods provide opportunities for:

- improving understanding of the eco-hydrological function of the Marsh; and
- contributing to a framework for broad scale vegetation health monitoring.

Two particular advantages of RS techniques are the availability of historical satellite datasets and the ability to cover large areas with low cost. The historical data can be used to investigate relationships between flooding cycles, vegetation dynamics and vegetation stress in the past, prior to FMG's mining operations and the hydro-ecological relationships could provide the basis for predicting how the marsh vegetation is likely to respond to future disturbances. The image analyses could also inform the design of targeted vegetation monitoring and management programs.

The RS technologies are best used where their outputs can be validated by on-ground measurements. For three years the UWA team have monitored groundwater levels, soil moisture dynamics and salinity, and vegetation response to changing meteorological conditions and groundwater levels. In addition, groundwater levels have been monitored in the vicinity of FMG mining areas. These monitoring programs were initially designed without consideration of their potential application as validation for RS technologies and, as such, there is a need to clarify if the monitoring results are sufficient for this purpose and, if not, what additional monitoring may be required.

To explore the opportunities for RS to monitor the eco-hydrology of the Fortescue Marsh, a pilot project was established. The main objectives of this project were:

- to illustrate the capability of RS techniques to identity land cover classes which are characterised by various responses to changes in water regime
- to illustrate whether these RS techniques can provide a useful contribution to water balance estimation
- to determine if the current monitoring program provides adequate validation of RS techniques
- to propose a program to monitor the eco-hydrology of the Fortescue Marsh.

This report provides the results of the 6-month plot study, which was structured as three linked activities:

Activity 1 - Using time series LANDSAT images, define the Fortescue Marshes vegetation response to flooding and drying in the period Autumn 2009 to Summer 2010 by applying a methodology developed for the National Water Commission (NWC) Groundwater Dependent Ecosystems (GDEs) Atlas. The method was tested for the Marsh conditions.

Activity 2 - Using currently available time series of evapotranspiration (ET) derived from MODIS data, test the CMRSET product (Guerschman et al., 2009), and the newly developed SLST product (Van Niel, in prep) to approximate the regional scale water losses to evaporation.

Activity 3 - Based on the results of Activities 1 and 2 identify needs for additional investigation to validate the RS ET approaches and aid future monitoring of marsh condition.

In what follows we outline the proposed research activities in development of diagnostic tools for eco-hydrological monitoring in the region of Fortescue Marsh combining RS and on-ground observations. The results of the pilot project are also presented, while the detailed assessments are provided in Appendices A and B.

1.1 Fortescue Marsh description

Fortescue Marsh is listed as a “Nationally Important Wetland” by the Department of Environment and Heritage and as an “Indicative Place” on the Register of National Estate because of its significance as habitat for waterbirds (ENVIRON, 2005). Samphire species dominate the vegetation cover of the Fortescue Marsh and therefore the conservation of the samphire community is essential to maintain the marsh ecosystem.

The cycle of flooding and evaporation over time has developed a hypersaline body of groundwater beneath the Marsh which is an important part of the present day flow system. Brackish groundwater flowing southward from the Chichester Ranges meets the hypersaline groundwater under the marsh in a broad transition zone where the less dense brackish water flows up and over the hypersaline groundwater via low permeability alluvial sediments. Conceptually the marsh is considered a regional groundwater discharge zone, but further quantitative analyses are required to confirm, or revise, this.

The Fortescue Marsh is surrounded by a number of mining activities, some long standing, others more recent, and some yet to commence operation. FMG have opened the Cloudbreak and Christmas Creek mines to the north of the marsh. Hancock Prospecting are preparing to open the Roy Hill mine at the eastern end of the marsh. To the south, Rio Tinto and BHPB operate the longest running iron ore operations in the region, with a number of mines around Hamersley and Newman. Brockman resources are commencing operations at Marillana on the southern boundary of the Marsh.

Since the groundwater component of the Marsh water balance is not clearly understood (Aquaterra assumed groundwater contributed 10% of its inflow, and a detailed water balance has not been undertaken), its importance to the Marsh’s vegetation has not been quantified. This increases uncertainty in the assessment of potential mining effects on the Marsh ecohydrological conditions. Both mine dewatering, impacting groundwater fluxes within aquifers, and occasional water discharge via stream channels have a potential to influence the Marsh habitats by modifying the natural seasonal wetting and drying leading to freshening and salinisation of Marsh sediments.

2 Results of the pilot project

The results of the analysis show that the RS techniques allowed adequate characterisation of the land cover classes in the Marsh and its surroundings as well as defining the spatial and temporal variability in ET. The results are also in agreement with available on-ground observations conducted by UWA and FMG.

Remote sensing for vegetation-land cover classification

The adopted GEM method (Barron, et al, 2012), based on Landsat imagery analysis, was shown to be adequate for identification of land cover classes and their response to drying conditions over the 18 month period from May 2009 to December 2010.

Assessment of the vegetation response to drying of the marsh was based on analysis of greenness (measured as the Normalised Difference Vegetation Index, NDVI (Kriegler et al., 1969; Rouse Jr et al., 1973) and wetness (measured as the Normalised Difference Wetness Index, NDWI, Hardisky et al., 1983) identified using Landsat data. The results are in agreement with on-ground observations at six locations (UWA observation sites) as well as with the vegetation mapped outside the Marsh area. The areas associated with three vegetation types, monitored by UWA, showed different responses to drying, some of which appear to show step changes in their greenness and wetness, possible indicating a threshold response.

The use of alternative indices to NDVI, namely the Enhanced Normalised Vegetation Index (EVI, Huete et al., 2002) and Structure Insensitive Pigment Index (SIPI, Penuelas et al., 1995), resulted in similar classification results.

Remote sensing to estimate evapotranspiration

Spatial and temporal patterns in ET were examined using two RS methods: (i) surface energy balance analysis and (ii) vegetation index and wetness index analysis, known as the SLST and CMRSET methods, respectively. The results provide an insight into aspects of water balance in the region and were in agreement with other observations, namely:

- the inundated areas in the Marsh were characterised by high annual ET in 2009,
- summer ET exceeded winter ET in 2009 and 2010, commensurate with both available water and potential evaporation rates, and
- higher ET rates were associated with the Marsh border, possibly indicating groundwater discharge zones.

High ET values, both monthly and annual, were identified along the southern slopes of the Chichester Ranges north of the mine area, on the northern flanks of the Hamersley Ranges, west and east of the Weeli Wolli Creek alluvial fan.

Combining remote sensing with on-ground observations

The analysis indicated that land cover condition and evapotranspiration may be linked to thresholds of soil moisture, and possibly salt, storage that govern the greenness and redness and transpiration of the marsh vegetation. We found a good qualitative correspondence between the RS analysis and on-ground observations by the UWA team but, due to difference in timing of on-ground observations (soil moisture and salinity measurements) and RS data acquisition, a quantitative analysis was not feasible. Aligning the timing and extending the ground measurements to a longer series are likely to improve the value and interpretation of both data sets. The sap flow measurements, established by UWA (but not available during this pilot study), are likely to be useful for localised ET estimation. Based on the communication with UWA colleagues it appears that there are significant difficulties with measuring sap flow in the samphire and up-scaling the result to more regional scales of the Marsh. RS ET might be used to assist this upscaling.

3 A framework for ecohydrological assessment of Fortescue Marsh

This pilot project was required to scope a monitoring programme that would support the development of a Diagnostic Framework for monitoring the ecohydrology of Fortescue Marsh, application of which will allow separation of the effects of mining activities on vegetation communities in the Marsh, and possibly elsewhere in the region, from the effects of the climatic variability.

The current approach to management of the Fortescue Marsh is outlined in the Fortescue Marsh Management Plan (FMMP) (FMG, 2006). The FMMP is founded on the requirement to avoid any impact on the marsh from FMG's activities and the data collected and analysis undertaken should be sufficiently robust to test whether this requirement is met. The monitoring and evaluation needs to avoid a false conclusion there is an impact when there is not, and avoid a failure to detect a significant impact. In statistical methods these are referred to as Type I and Type II errors, respectively (Fairweather, 1991). Baseline data are to be assessed to determine the Minimum Detectable Change (MDC) so that these statistical errors can be avoided.

A number of factors that may cause deterioration of the Fortescue Marsh were identified in the FMMP, including changes in surface and groundwater hydrology, invasive species and disease, and physical damage such as through dust and machine damage. The framework proposed here addresses only the hydrology and its connection to the ecology of the marsh, that is the ecohydrology.

The description of a proposed framework for ecohydrological assessment of the Fortescue Marsh is outlined below. It provides a general approach to such a framework development, the opportunities to incorporate the current monitoring in the framework and suggestions on additional monitoring activities, which may improve the ecohydrological assessments.

There are two key challenges to be addressed by the framework:

1. Identification of the criteria which can characterise vegetation "health" and of which variations could be used as a measurement of impact: *if there are changes, are they detrimental?*
2. Identification of the historical variability of the identified criteria to provide a baseline for potential impact assessment related to mining activities: *if there are changes, are they due to FMG's activities?*

It is also expected that the results of this programme will also add value to existing datasets for the hydrogeological modelling by improving recharge and discharge estimation and thus improving the evaporation/recharge boundary condition of the groundwater models.

3.1 Framework approach

It is proposed that the framework objective can be met by adopting RS techniques combined with on-ground observations. These activities are commonly related to different scales of assessment, however, when they are adequately designed and aligned, RS will facilitate upscaling of on-ground observations to larger areas of the Marsh.

As some RS (e.g. Landsat) data are available for over 30 years, historical changes in land cover classes and their characteristics can be analysed statistically and potentially linked with known climatic conditions, changes in groundwater and surface water fluxes and historical land use. This analysis will provide the baseline to any investigation of the impact of mining activities on vegetation. Any future observed changes in the Marsh will be measured against the historical variability within the identified land cover classes. This will help separate the changes in Marsh conditions due to natural climate variability from the changes possibly caused by mining related activities.

In addition, our analysis has demonstrated the RS techniques provide a valuable contribution in estimation of regional ET and as such are useful in assessing regional water balance. However, on-ground validation of the ET values is needed to confirm the RS estimates.

The RS-based diagnostic framework requires validation by on-ground observations, to link the changes in vegetation condition with changes in water or salt balance. Hence the Marsh monitoring program has to include combined physiology studies (both field and laboratory) with hydrological field observations. The on-ground monitoring and laboratory analysis should aim for definition of explanatory factors for observed vegetation changes, and development of predictors of changes that might occur if hydrological changes continue. These should define the changes in vegetation, such as pigmentation, foliage density, transpiration and other parameters, as a result of soil moisture dynamics, salt accumulation or flushing, or inundation. These plant and plot scale responses then contribute to interpretation of RS data.

There is also a need to clarify the groundwater–vegetation interaction and particularly the vegetation's groundwater use and dependence. The role of groundwater in the Marsh water balance is not yet quantified (Aquaterra estimated it to be 10% of inflow to the Marsh), hence it is not clear how mining related impacts on groundwater flow may affect the Marsh vegetation. There are a number of possible scenarios related to changes in soil moisture dynamics, salt accumulation or flushing, or inundation which could have effects on vegetation. These include:

1. ***Freshening the soil profile***: groundwater abstraction could reduce groundwater flow to the Marsh and the lower heads result in increased salt flushing from soil to deeper groundwater layers.
2. ***Freshening the soil profile***: as above but occasional surface water discharge affecting a localised area.
3. ***Reduction on soil moisture***: groundwater abstraction may reduce the groundwater flow to the Marsh, lowering the watertable and reducing water availability to the plants.
4. ***Salinisation of the soil profile***: groundwater injections may increase groundwater flow to the Marsh and increases evaporative losses from soil, resulting in greater salt accumulation at the surface.
5. ***Salinisation of the soil profile***: as above but occasional surface water discharge affecting a localised area and with limited outflow leading to increase in evaporative losses from soil
6. ***Watertable rise or inundation***: groundwater injections or occasional surface water discharge may lead to soil inundation affecting the vegetation

With any of these possibilities, it is important to understand the vegetation response to the conditions, and further to interpret the outcome of the RS based analysis.

3.2 Monitoring program

The proposed monitoring program aims to:

1. Monitor changes in marsh vegetation condition, combining RS techniques and on-ground observations.
2. Deploy RS techniques to statistically define the historical variability in the Marsh ecohydrology due to inundation and drying cycles, using agreed vegetation response criteria (such as vegetation resilience, vulnerability, recovery) and utilising the RS data for ET estimation
3. Define vegetation response to changing conditions, including water availability and salinity regime
    a. the vegetation characteristics influencing reflectance of the RS images (pigmentation, foliage density, plants density, plant mortality)
    b. ET rates
4. Ideally the program should link water availability and salinity regime to changes in hydrological and hydrogeological conditions

5. Using the identified historical ranges in vegetation response criteria to drying cycle, separate changes in marsh condition between natural variability of climate from changes possibly caused by mining related activities.
6. Add value to existing datasets for the hydrogeological modelling to improve recharge and discharge estimation to improve the evaporation/recharge boundary condition of groundwater models.

The knowledge gained as a result of the monitoring program will improve understanding of the ecohydrology and functioning of the Fortescue Marsh ecosystem, as well as help quantify the sources of water used by the marsh vegetation, that is to determine if, and to what extent, the vegetation is groundwater dependent.

The overall structure of the monitoring program is illustrated in Figure 1.

Detection of change

The concept is that two independent RS techniques provide the basis of the monitoring framework. They cover wide areas with relatively fine resolution (25 m for the vegetation classification monitoring and 250 m for the ET) and are the primary "detectors of change", in the vegetation condition and the ecohydrology. Both are supported, and validated, with ground based measurement. The vegetation classification analysis by ground spectrometry, plant physiology studies, and monitoring of soil moisture and salinity conditions.

Interpretation of change

The detection of change is founded on physiological understanding of changes in plant pigmentation, foliage density and other characteristics, and on detected changes to the hydrological and salinity conditions experienced by the plants. These factors are also part of the validation data for the vegetation change detection as the techniques are being developed. Similarly, eddy covariance, surface radiative temperature and soil moisture monitoring provide validation for the satellite estimation of ET, and the link between the ecology and the hydrology. These measurements ensure we understand what has caused the change detected by satellite.

The combination of plant condition and hydrological conditions provide the basis for *criteria of health assessment*. How these attributes are combined into a set of "health" criteria should be determined in collaboration with the Department of Environment and Conservation, Department of Water and other relevant bodies to ensure they meet regulation requirements.

Linking changes to regional water balance

Establishing the links between vegetation condition and water balance and between local and marsh scale water balance can be achieved through the complementary measurements illustrated. Water isotopes can be used as both dating techniques and markers, isotopes in plant material can be used to determine the water sources for the vegetation and hence their groundwater/surface water usage. CFC content will give more recent age measurements. The dating of water will inform the hydrogeological conceptual model through flow rates and confirmation of circulation patterns inferred from the date profile.

Groundwater piezometric heads from observation wells at various depths also inform the model of groundwater circulation, and add to the understanding of whether pressure gradients support the models of groundwater discharge and plant water uptake.

Finally, there are a number of useful data sets that could be captured to inform the understanding of the marsh, for example, airborne electromagnetic surveys performed several times over different wetting and drying conditions may detect anomalous electrical conductivity zones which may be related to recharge or discharge.

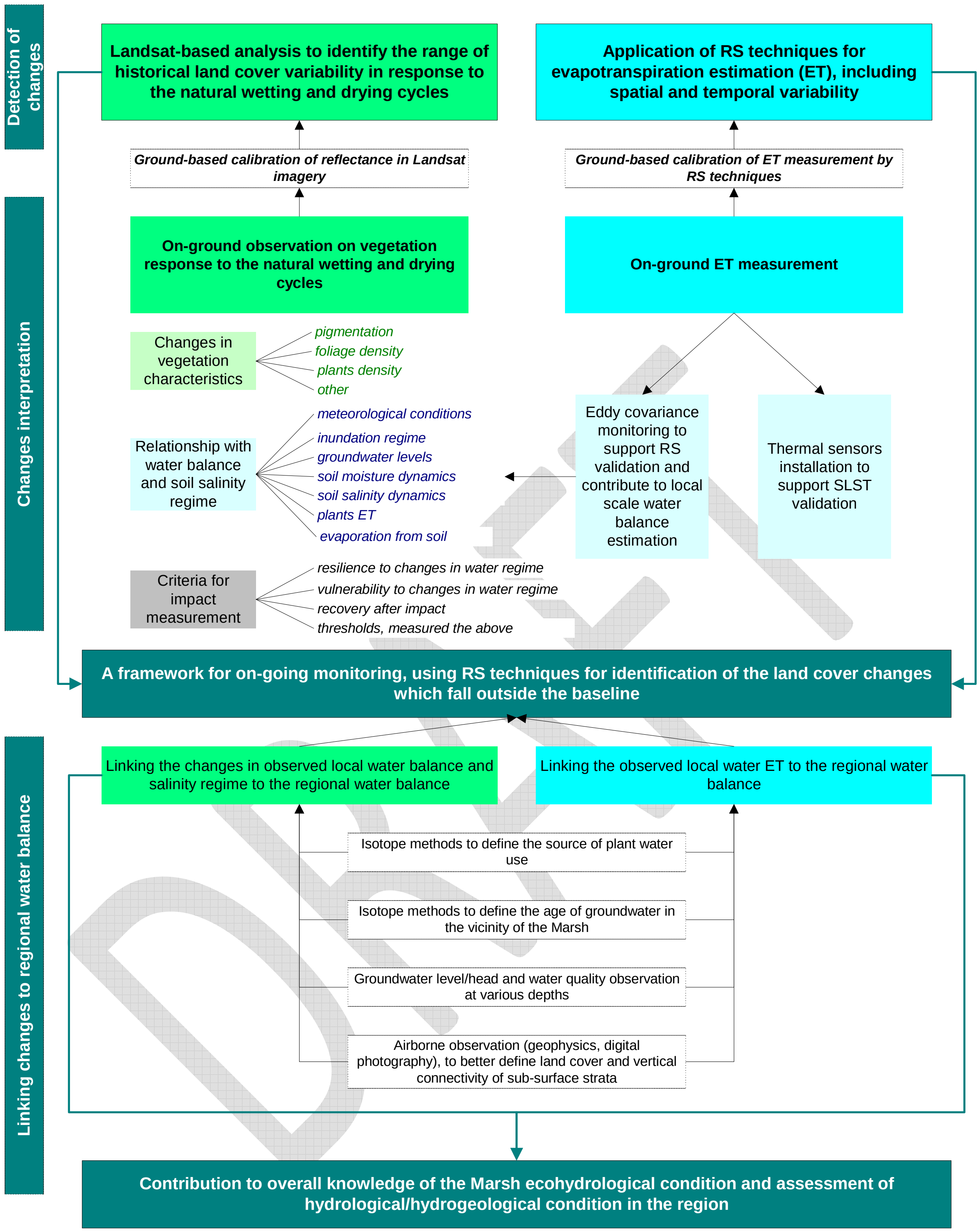


Figure 1 The conceptual structure of the proposed framework to monitor the ecohydrology of Fortescue Marsh

Table 1 gives a summary of the measurements and analyses recommended to support the suggested monitoring framework, with explanatory notes below it. We propose a joint approach with the most appropriate partners to meet the various needs.

3.3 Conclusions

This pilot project has evaluated the use of remote sensing to monitor vegetation condition and estimate evapotranspiration from the Fortescue Marsh at a large scale. Prior work by the UWA team, and other work commissioned by FMG, such as vegetation surveys (Mattiske Consulting, 2007), soil and root zone investigations (Kew Wetherby, 2011), has provided useful data at plot and plant scale. RS is a clear candidate for routine monitoring because of the areal coverage, the availability of historical data and the ability to collect large areas at reasonable cost. However, to ensure the quantitative value of the satellite data collected and explain the observed patterns in ecological terms we need adequate ground based observations. Thus measurements are required at “local” scale (1-10 m) of the order of plants and small surface plots, with a means to scale up to the “regional” scales (1-100 km) monitored by RS. The range of RS pixel sizes (1 to 25 to 1000 m) provides a vehicle to utilise an intermediate “patch” scale (100 to 1000 m) as a link between the plant based measurements.

This combination gives us a continuous link between plant scale and regional scale, and we have technologies that can provide the measurements at each of these spatial scales. Thus we have proposed what we believe is a reliable and efficient methodology for monitoring the ecohydrological status of the Fortescue Marsh and other ecosystems in remote locations.

Table 1 Monitoring measurements recommended

Focus of measurement	Scale of measurement: Regional	Intermediate	Local
Vegetation	Landsat based vegetation classification analysis through the whole Landsat TM5 record, to give historical a baseline. Time series statistical analysis required to extract changes for climatic conditions		Plant physiology, spectral response, health assessment
Water balance	Test the RS ET estimation algorithms CMRSET and SLST in this environment	Eddy covariance to measure ET over approximately 1 km^2	Continuous sap flow Soil surface evaporation, monthly Piezometer level and salinity.
	Satellite thermal imagery for areas of lower temperature that may indicate discharge.	Cosmos soil moisture continuous monitoring	Soil moisture and salinity in the unsaturated zone should preferably also be continuously logged
Complementary Geophysics	Airborne EM, to determine areas of discharge and recharge across the marsh.	A micro-seismic refraction traverse, coupled with on-ground EM, to determine the consistency of the hardpan	
Groundwater		Intermediate depth piezometers, 1, 5 and 10m continuous level monitoring in the 10 m and shallower bores,	

All piezometers should have their water analysed for full chemistry, and this should be done several times per year for first few years to establish stability and baseline conditions.

Bores should also have their C, H and O isotopic ratios determined, and CFC concentrations. These will help clarify time since the water fell as rain, flow paths, and in combination with plant isotopic ratios, depending on the differentiation of the waters, determine whether or not the vegetation is taking up deeper groundwater.

The value of data collected can be greatly enhanced if multiple types are collected synchronously. Ideally this would also be on the same day as a satellite over pass, or the centre of a satellite averaging period, so that we have greater confidence in the causal connection between the different components being measured.

It is suggested that DEC, the DoW and other relevant parties be invited to review the land-cover classification scheme to comment on its applicability as a vegetation monitoring system.

Notes:

The effort required to analyse the historical sequence of satellite imagery and determine appropriate statistics to quantify the baseline behaviour should not be underestimated. The results provided in this report are illustrative of the approach, but as pointed out elsewhere, require calibration with ground measurements and with the, yet to be developed, vegetation “health criteria”.

Eddy covariance provides continuous ET monitoring and should be run for at least two annual cycles to cover a range of conditions and fully test the RS ET, as well as provide near real time testing for the groundwater modelling.

Cosmos soil moisture monitoring also covers a range of about 1 km^2. This technique quantifies the shallow soil moisture storage on an hourly basis and hence helps the estimation of marsh shallow water balance. This also helps scale up the plot and plant scale work to an intermediate scale.

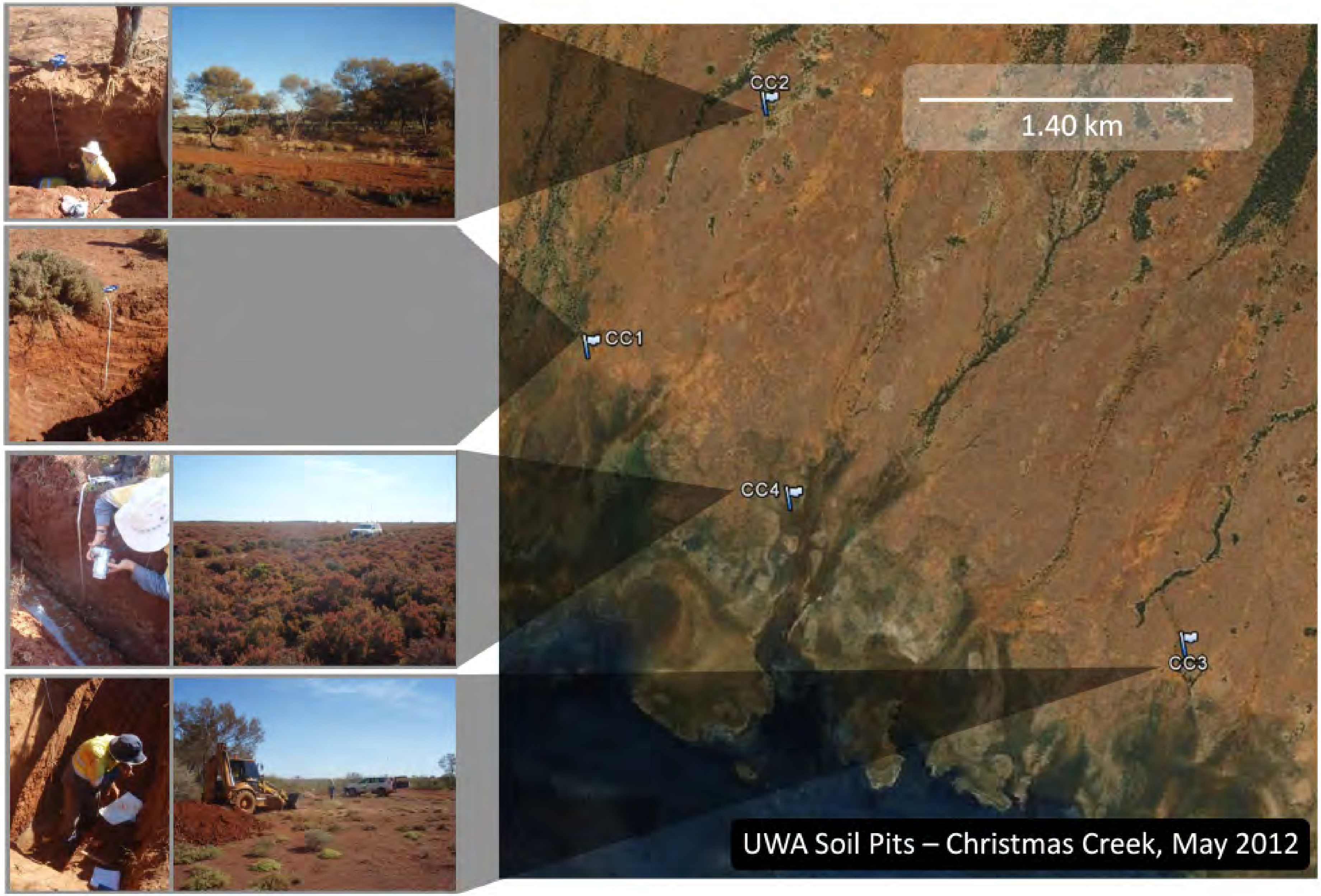
Soil moisture and salinity in the unsaturated should preferably also be continuously logged although with the experience of UWA team there should be a reassessment of the best instruments to use for this.

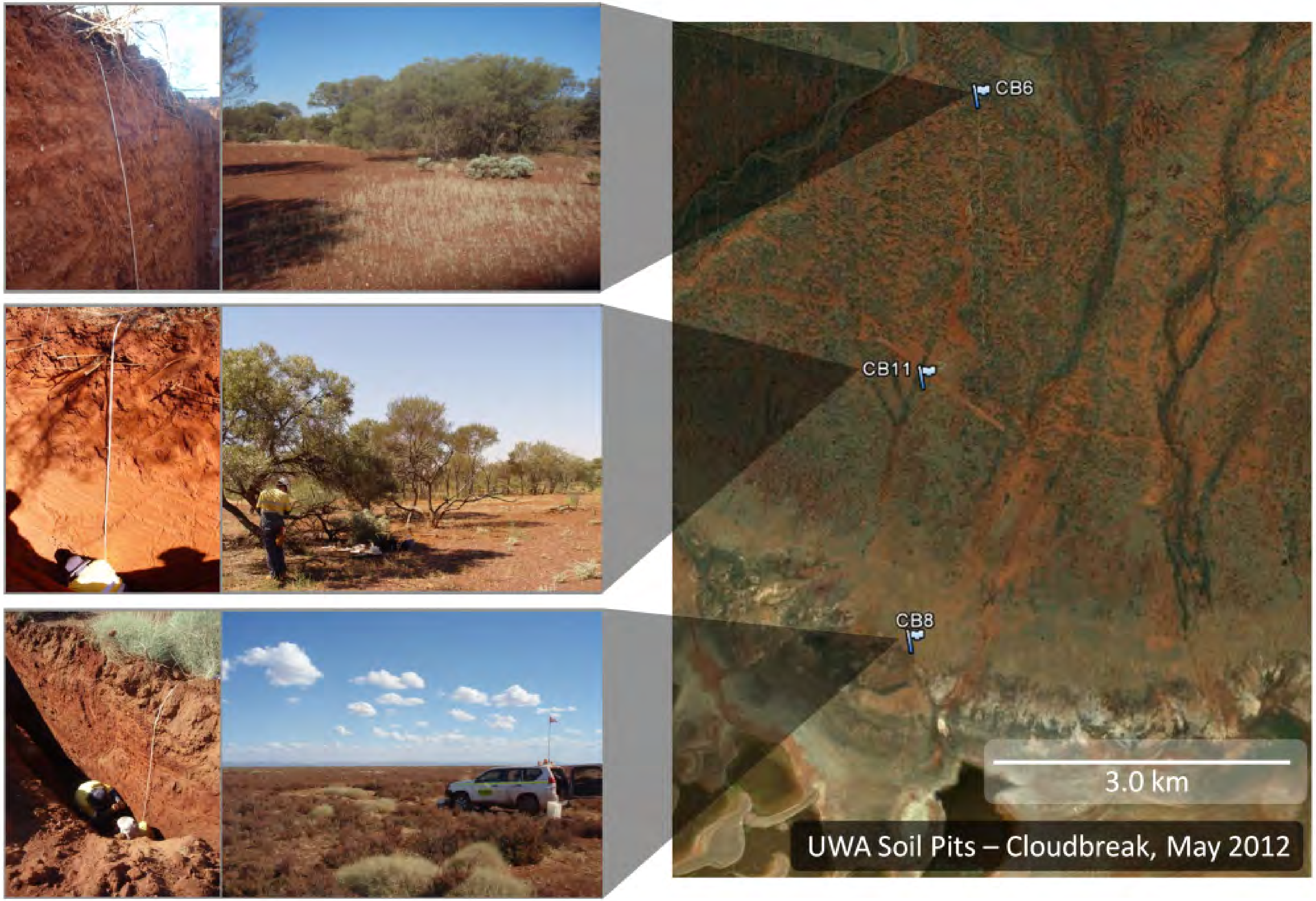
Intermediate depth piezometers, at each of the nested piezometer sites, amend the shallowest well design so that the 10m bore is screened for bottom 3m only, and sealed above this. We suggest a 5m piezometer, screened for lowest 2m and sealed above, a piezometer drilled to 3 m, screened for bottom 1.5m and sealed, and a piezometer to the hardpan or 1m whichever is deeper. We are concerned about possible leakage between the shallow and deeper systems with the 10m bore having a 9.8m screen. We are aware of drill rigs mounted on a hovercraft and tracked platforms that could be deployed with minimal disturbance to the marsh surface.

Instrument continuous level and salinity monitoring in the 10 m and shallower bores, at least monthly monitoring in the 30 m and 50 m bores, to confirm the hydrogeological model and determine the dynamics of piezometric gradients under the marsh and help determine rate of discharge at the surface and whether there are alternating periods of recharge and discharge.

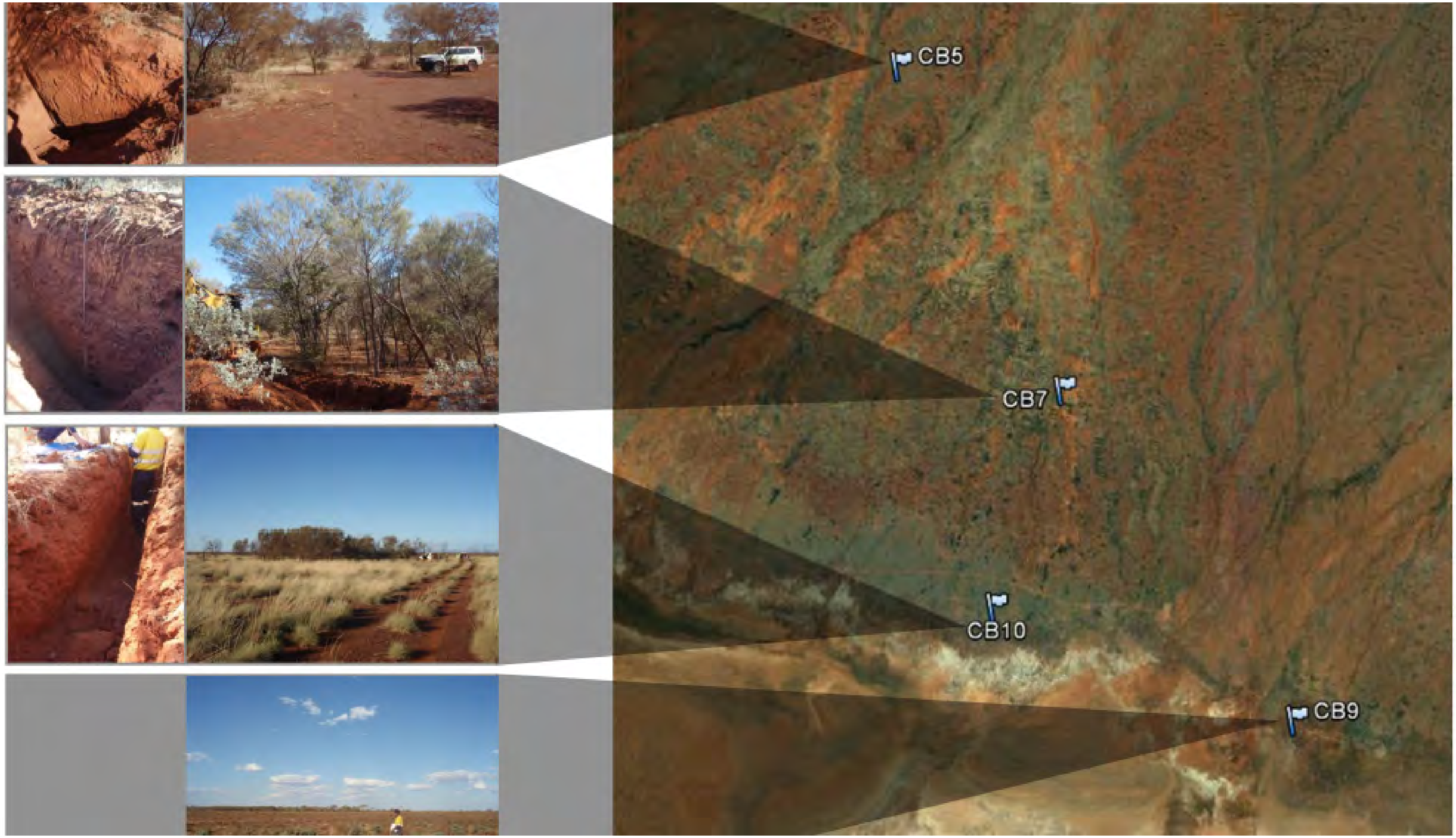
Airborne EM, to determine areas of discharge and recharge across the marsh. These should be run several times over different moisture conditions to determine changes which may reflect changes in moisture status, and hence dynamic recharge/discharge areas. Interference between soil moisture and salt concentration means that this would need to be undertaken by a team experienced in the data collection and analysis.

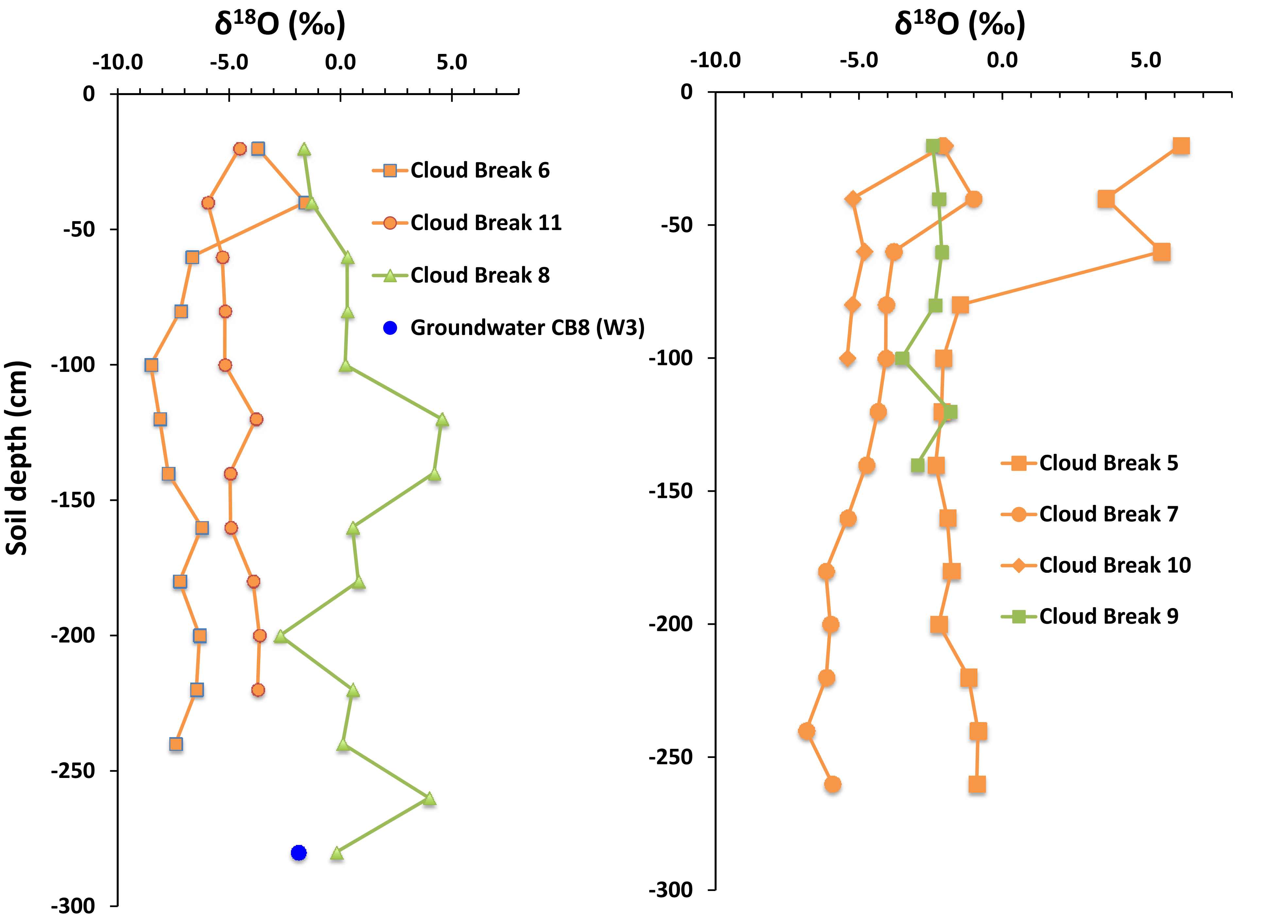
A micro-seismic refraction traverse, coupled with on-ground EM, may help determine the consistency of the hardpan, and whether there are “soft” spots that may leak. These would be undertaken on foot, along transects of several hundred metres.


CC2
1.40 km
CC1
CC4
CC3
UWA Soil Pits – Christmas Creek, May 2012

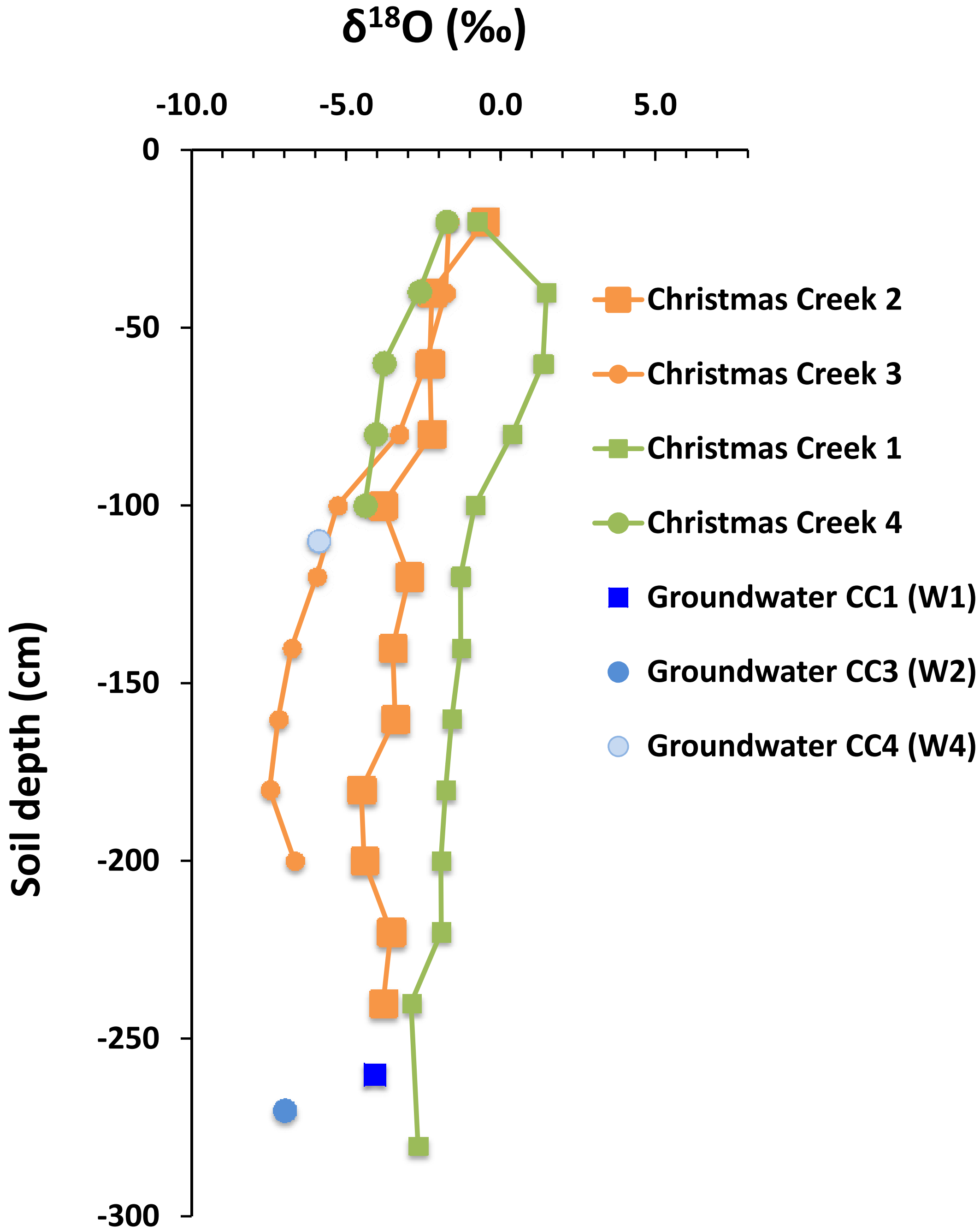


CB6
CB11
CB8
3.0 km
UWA Soil Pits – Cloudbreak, May 2012


CB5
CB7
CB10
CB9



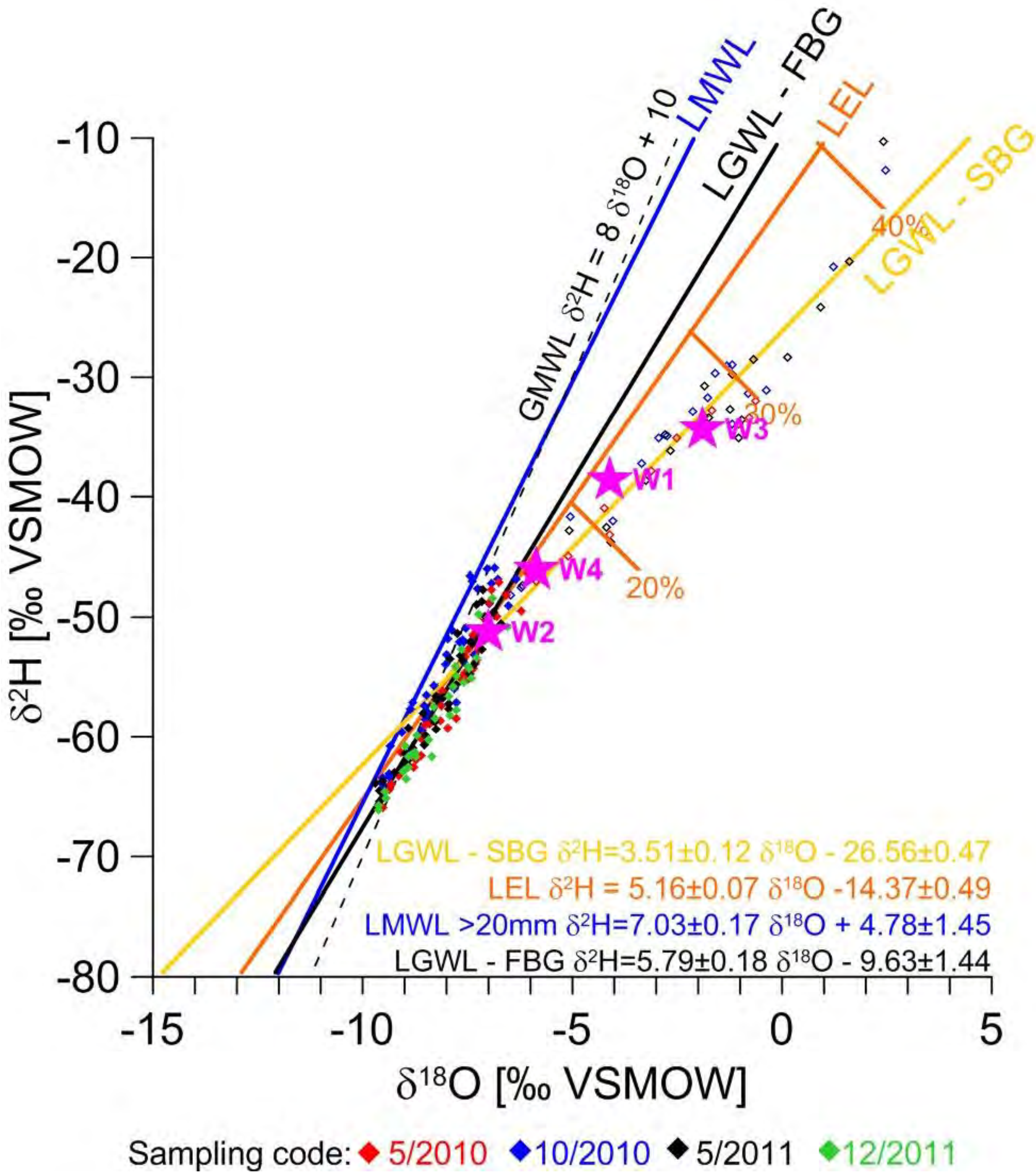
δ18O (‰)
-10.0
-5.0
0.0
5.0
0
-50
-100
-150
-200
-250
-300
Soil depth (cm)
Cloud Break 6
Cloud Break 11
Cloud Break 8
Groundwater CB8 (W3)
δ18O (‰)
-10.0
-5.0
0.0
5.0
0
-50
-100
-150
-200
-250
-300
Cloud Break 5
Cloud Break 7
Cloud Break 10
Cloud Break 9



$\delta^{18}O$ (‰) profiles with soil depth at Christmas Creek.

Soils under mulga are shown in orange while those under samphire (*Tecticornis* spp) are shown as green. Where pits hit a saturated zone (groundwater), those water samples were collected.

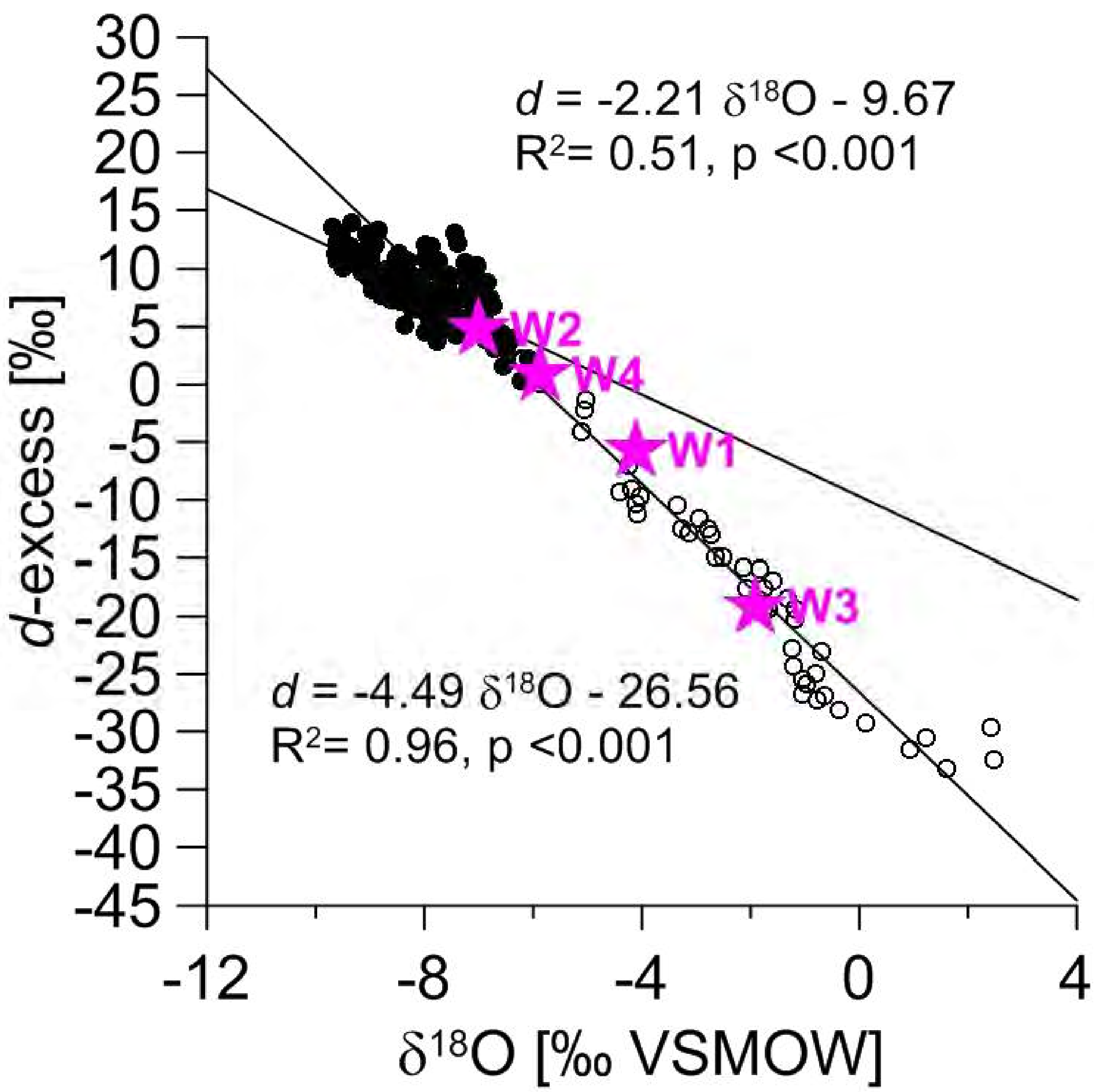
Depths for groundwater samples are as shown.



Water samples collected from the saturated zone at base of soil pits in May 2012 are shown as pink stars. All were from the Marsh boundary (see accompanying map).

These data suggest that:

- W1(CC1) and W3(CB8) – have signatures similar to highly saline groundwater
- W1 has a higher proportion of rainwater (fresh ground water compared to W3 i.e. more mixing)
- W2 (CC3) and W4 (CC4) - have signatures of fresh water but W4 is more evaporated
- W2 is typical of fresh groundwater

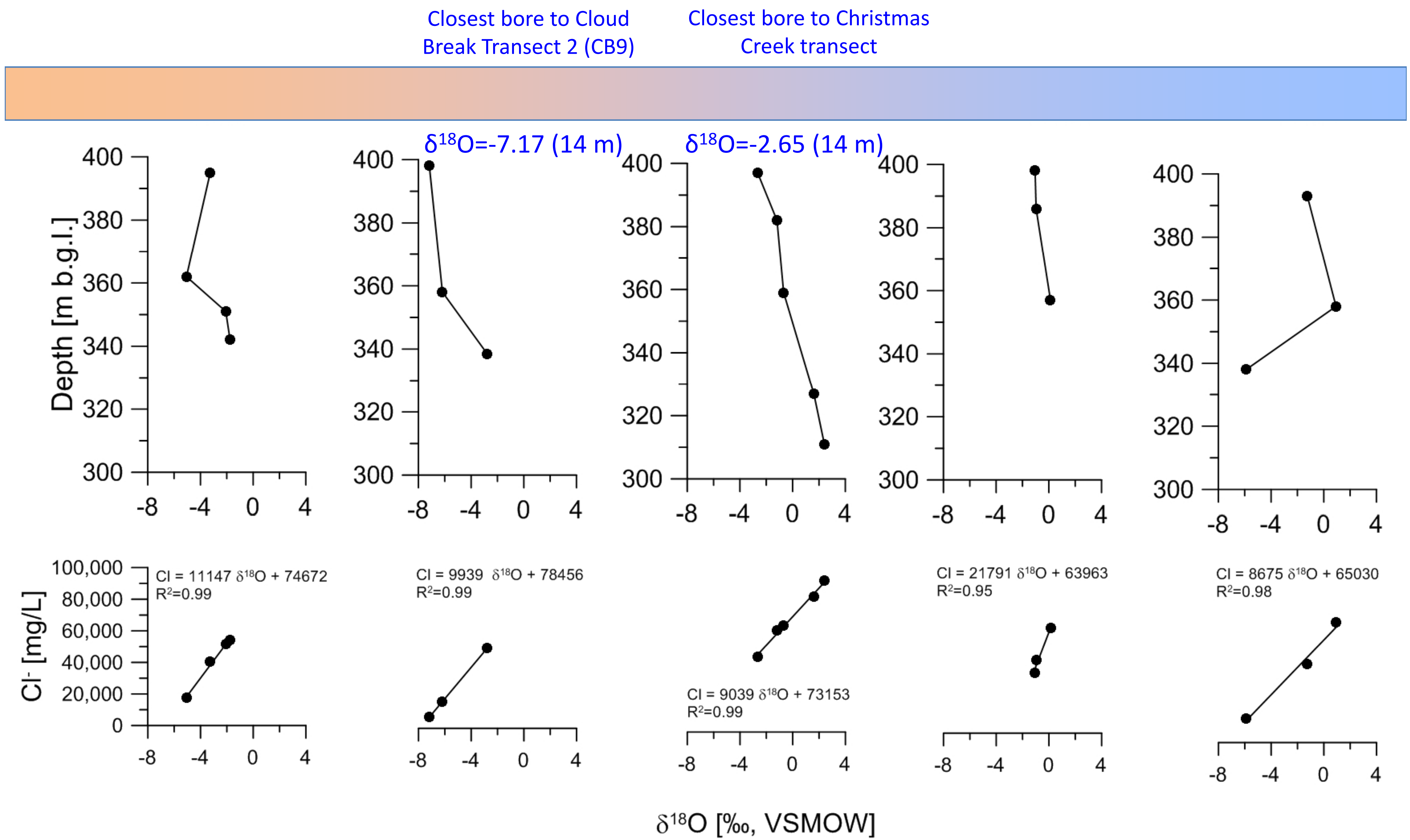


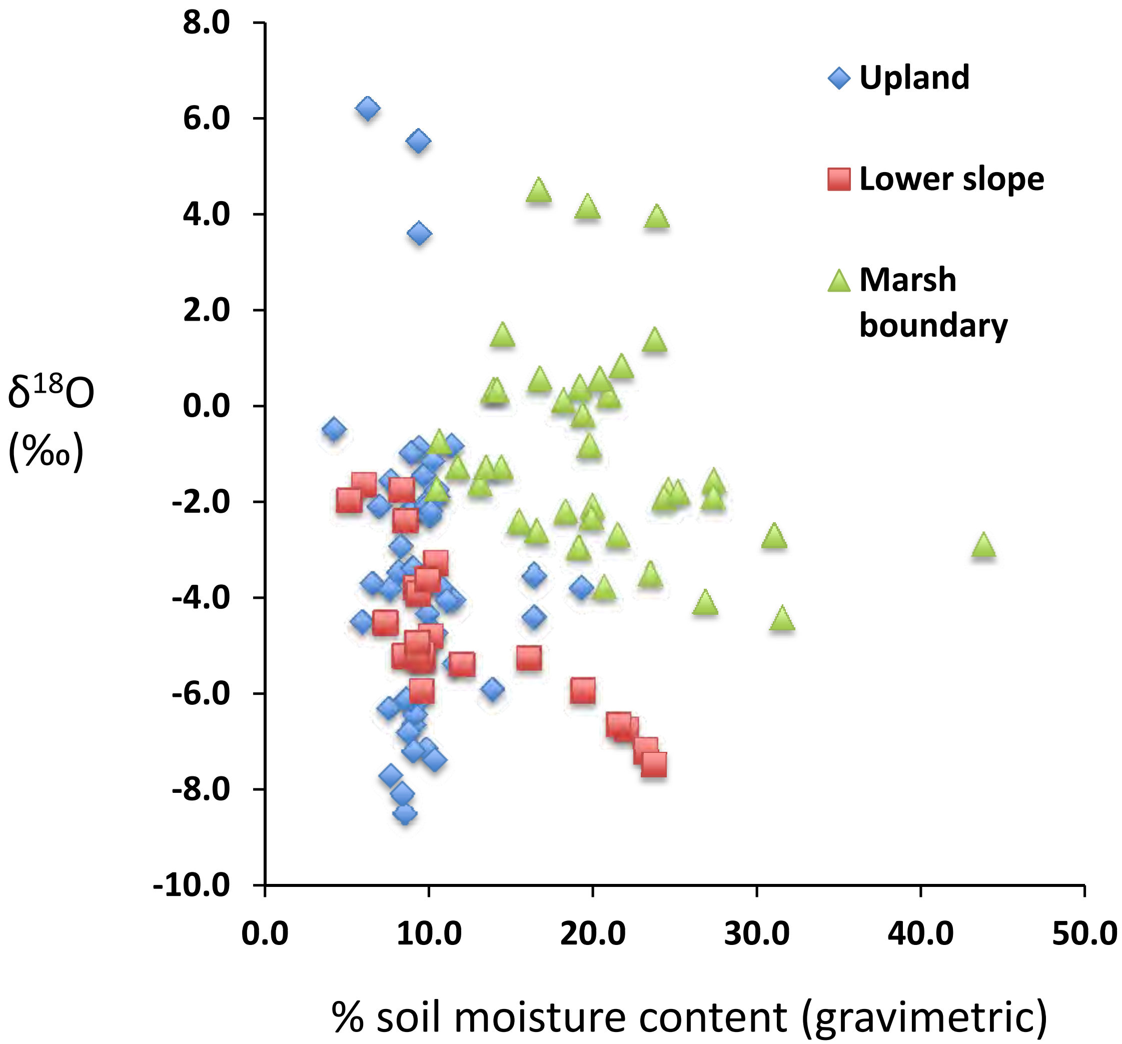
Water samples collected from the saturated zone at base of soil pits in May 2012 are shown as pink stars. All were from the Marsh boundary (see accompanying map).

These data clearly demonstrate consistency with recent assessments of the groundwater under the Marsh (Skrzypek et al.).

d-excess for the samples collected from the soil pits demonstrate the mixing of waters with different isotopic compositions.

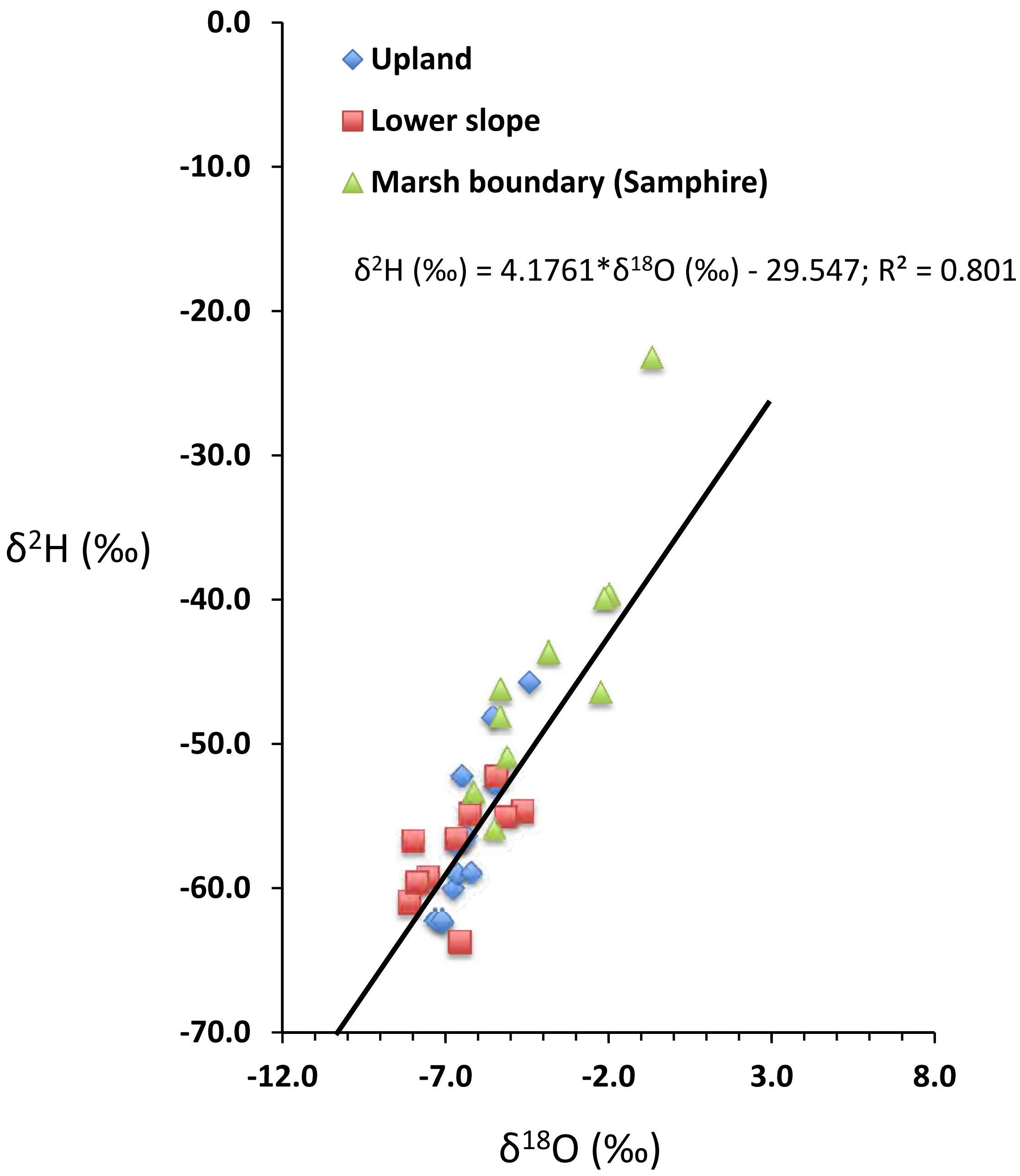
Location of the landscape gradient sites with respect to FMG bores sampled for groundwater.


Closest bore to Cloud Break Transect 2 (CB9)
Closest bore to Christmas Creek transect
δ18O=-7.17 (14 m)
δ18O=-2.65 (14 m)
Depth [m b.g.l.]
Cl- [mg/L]
Cl = 11147 δ18O + 74672
R2=0.99
Cl = 9939 δ18O + 78456
R2=0.99
Cl = 9039 δ18O + 73153
R2=0.99
Cl = 21791 δ18O + 63963
R2=0.95
Cl = 8675 δ18O + 65030
R2=0.98
δ18O [‰, VSMOW]



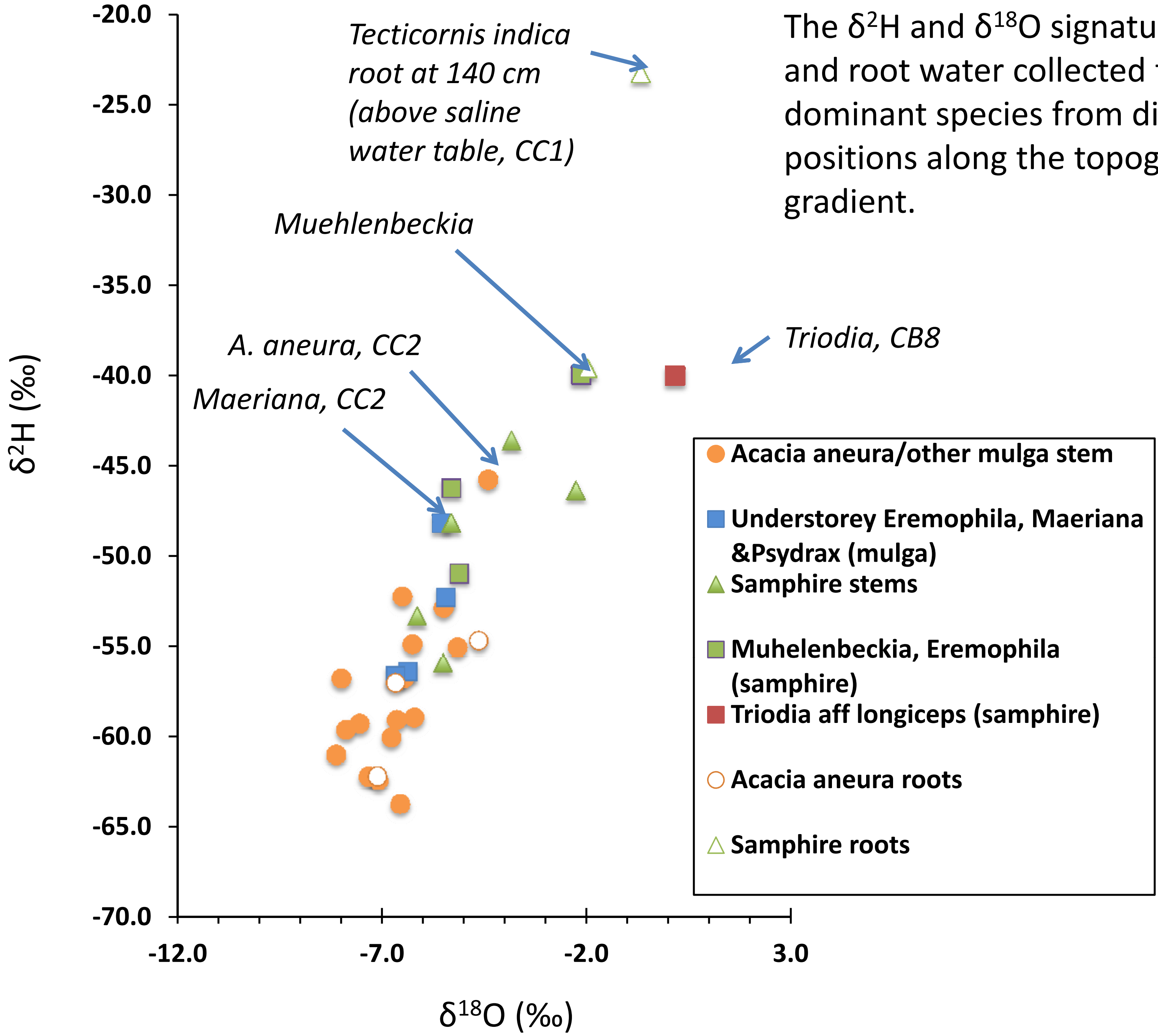
The $\delta^{18}O$ signatures of soil water (all depths) collected at different positions along the topographic gradient in relation to soil moisture content.

•Upland locations CC2, CB5, CB6, CB7, CB11;
•Lower locations CC3 and CB8 ;
•Marsh boundary locations CC1, CC4, CB9 and CB10.

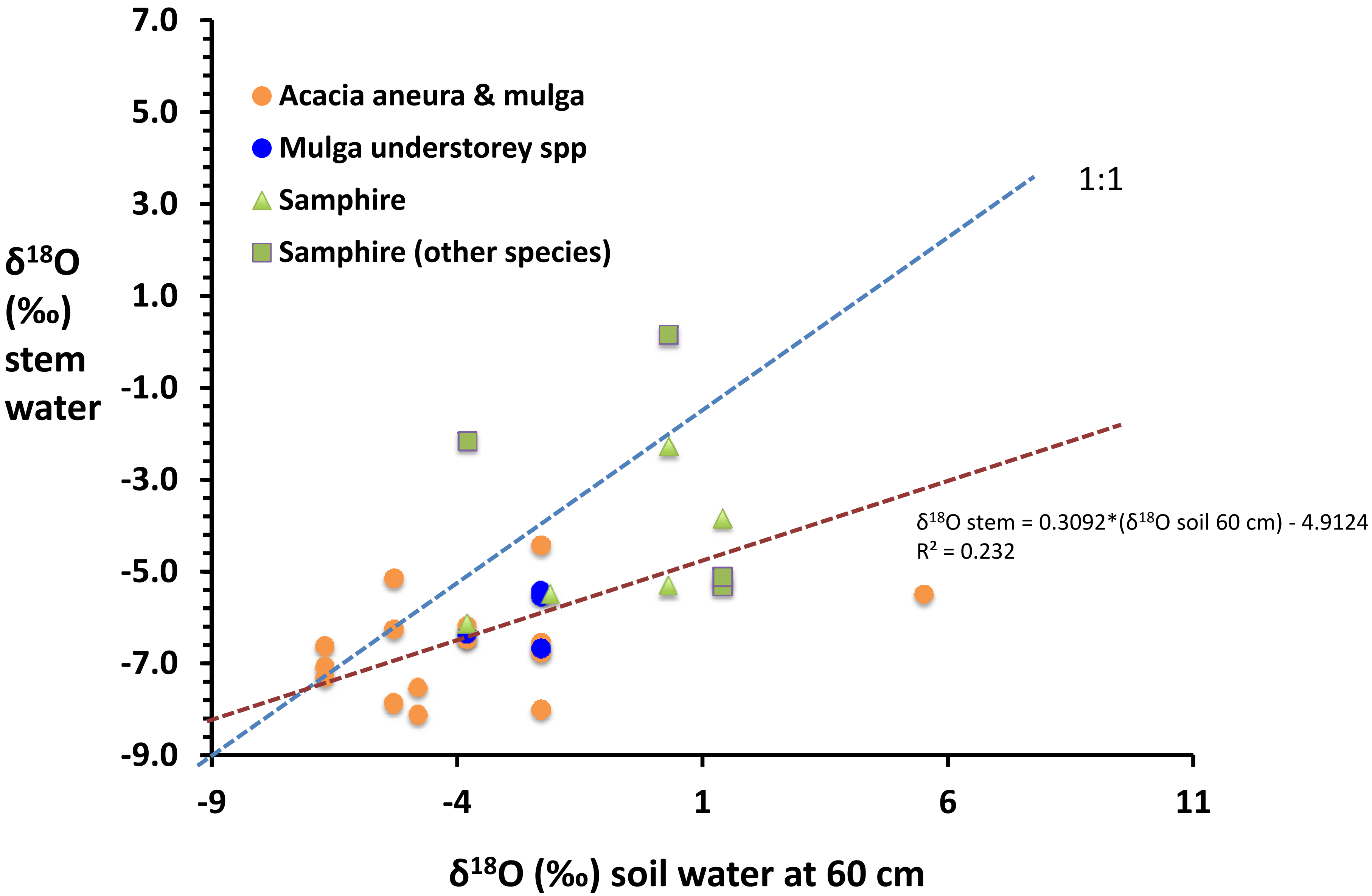


The δ^2H and $\delta^{18}O$ signatures of plant stem water collected at different positions along the topographic gradient.

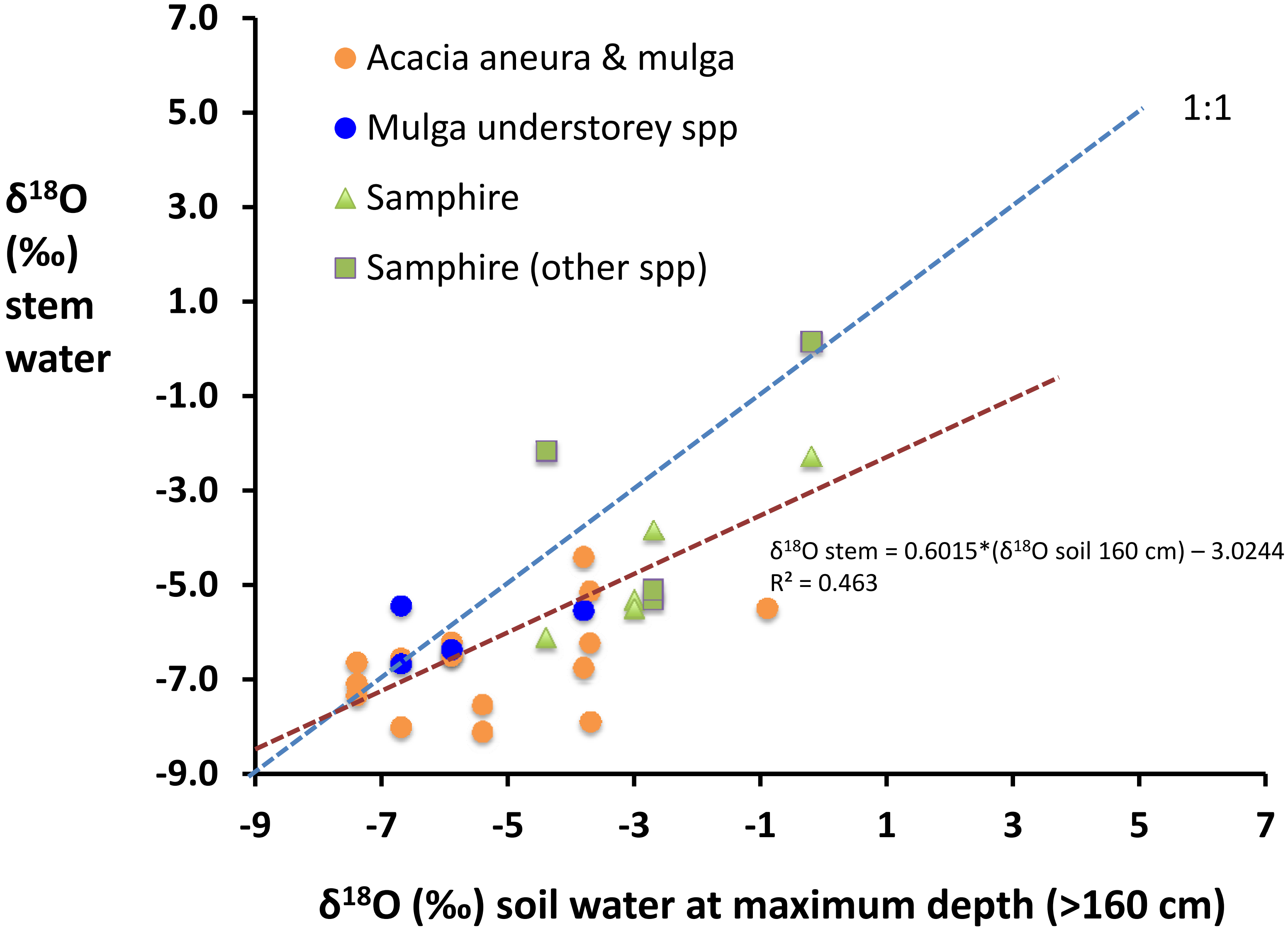
Upland plants represent the isotope signatures of plants at locations CC2, CB5, CB6, CB7, CB11; lower slope plants represent the isotope signatures of plants at locations CC3 and CB8 ; Marsh boundary plants are samphires at locations CC1, CC4, CB9 and CB10.



The δ^2H and $\delta^{18}O$ signatures of stem and root water collected from dominant species from different positions along the topographic gradient.



7.0
5.0
3.0
1.0
-1.0
-3.0
-5.0
-7.0
-9.0
δ18O
(‰)
stem
water
Acacia aneura & mulga
Mulga understorey spp
Samphire
Samphire (other species)
1:1
δ18O stem = 0.3092*(δ18O soil 60 cm) - 4.9124
R2 = 0.232
-9
-4
1
6
11
δ18O (‰) soil water at 60 cm



Acacia aneura & mulga
Mulga understorey spp
Samphire
Samphire (other spp)
1:1
δ18O stem = 0.6015*(δ18O soil 160 cm) – 3.0244
R² = 0.463
δ18O (‰) stem water
7.0
5.0
3.0
1.0
-1.0
-3.0
-5.0
-7.0
-9.0
-9
-7
-5
-3
-1
1
3
5
7
δ18O (‰) soil water at maximum depth (>160 cm)

Assessment of Mulga Root Architecture

June 2012

Prepared for
Fortescue Metals Group Limited

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Report Reference: 12312_12SRV1Rev0_120724

Assessment of Mulga Root Architecture

Prepared for
Fortescue Metals Group Limited

Job Number: 12312-12

Reference: 12312_12SRV1Rev0_120724

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B	12/07/2012	Revised Draft Issued for Client Review	T. Bleby	R. Archibald
0	24/07/2012	Final Issued for Information	T. Bleby V. Stylianou	R. Archibald

Approval

Rev	Date	Issued to	Authorised by	
			Name	Signature
A	19/06/2012	Todd Edwards	R. Archibald	
B	12/07/2012	Todd Edwards	R. Archibald	
0	24/07/2012	Todd Edwards	R. Archibald	

Abbreviations

Abbreviation	Definition
BWT	Below-water-table
CB	Cloudbreak Mine
CC	Christmas Creek Mine
EPA	Environmental Protection Authority
FMG	Fortescue Metals Group
GDP	Ground Disturbance Permit
GIS	Geographical Information System

Executive Summary

This report documents the study undertaken by Astron to describe and quantify the depth and architecture of the root systems of Mulga (*Acacia aneura*) at the Cloudbreak and Christmas Creek iron ore mines in the Pilbara, WA. Sampling was conducted at 16 sites across a range of different landscape positions extending several kilometres northwards from boundary of the Fortescue Marsh. At each site, a soil trench was excavated adjacent to 1-2 Mulga trees using a backhoe (3-6 m in length, 1.2-1.6 m in depth). Soil profiles were described and measured for the distribution and abundance of fine roots and woody roots, followed by the uprooting of a whole-tree. The exposed root system was then described and measured.

In general, Mulga displayed shallow root systems dominated by large, weakly tapered, horizontal roots in the top 0.5 m of the soil profile. Lateral roots were widely spread in the horizontal plane, with numerous roots extending well beyond the width of the canopy. Taproots and oblique roots were also present, but they tended to be short and strongly tapered, diminishing to around 10 mm diameter or less by 1 m depth. The majority of woody roots were distributed close to the soil surface, particularly in the 0.0-0.4 m depth range, and distribution decreased exponentially with depth with very few roots encountered at depths greater than 1.0 m. Fine roots were present to the depth of trenching (up to 1.6 m) in nearly all cases, with most fine roots occurring in top 0.5 m of the soil profile. The same basic root system architecture was observed across all locations. Small differences in the depth and distribution of roots were associated with local differences in the soil profile, most often related to the presence of gravels, cobbles, and compacted clay layers. No true hard pans were encountered, except at one site on the fringe of the Fortescue Marsh underlain by massive silcrete at 1.3 m depth (Area 11).

Mulga's predominantly shallow root system strongly suggests a water use strategy aimed at utilising shallow soil water derived from direct rainfall and surface inflows associated with sheetflow, natural drainage lines, and water ponding in low-lying positions of the landscape. Mulga's root system is also well suited for 'harvesting' water that funnels into the soil from stem flow. Based on the results of this preliminary study, the limited scientific literature, and other anecdotal evidence, it is reasonable to conclude that at the sampled locations, Mulga is likely to meet its ecological water requirements from the top 2-3 m of the soil profile. Mulga would not be expected to be affected by groundwater drawdown associated with the Chichester mines. Mulga could potentially be affected by groundwater mounding where elevated water tables intersect root systems. This study has shown that at Christmas Creek and Cloudbreak, rooting depth of Mulga is unlikely to extend beyond 1.5 m depth. However, fine roots may extend further, and the absolute depth and role of deep fine roots in water uptake remain unknown.

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1 Introduction

Fortescue Metals Group Limited (Fortescue) is developing the Pilbara Iron Ore and Infrastructure Project (the Project), which involves a series of iron ore mines and associated rail and port infrastructure in the Pilbara region of Western Australia. Included in the Pilbara Iron Ore and Infrastructure Project are the Chichester Operations, which have two operating iron ore mines: Cloudbreak and Christmas Creek. The mines are located approximately 120 km north of Newman, in the central Pilbara region of Western Australia.

Future mining at Christmas Creek is projected to require significant dewatering (in the order of 50 gigalitres per annum) to enable below-water-table (BWT) ore to be accessed, plus injection of surplus water into the surrounding groundwater aquifers. Fortescue is responsible for ensuring that vegetation communities are not adversely impacted by groundwater abstraction or reinjection, particularly Mulga (*Acacia aneura* F. Muell ex Benth, and closely related species), which is a dominant keystone tree species of the region.

There is a need to collect information on Mulga rooting architecture to support the selection of robust, defensible management triggers for water table rise and fall beneath Mulga vegetation. There is little hard data on the precise depth and spread of Mulga roots at Cloudbreak, Christmas Creek, or elsewhere in the Pilbara. Mulga is generally thought to be a relatively shallow rooted species, with a dependency on overland flows to meet its ecological water use requirements. Mulga may or may not be sensitive to a rise in groundwater levels or the saturation of soil layers near to the soil surface, depending on the location of the majority of the root system. A recent review by Page & Grierson (2010) recommended accurate measurements of Mulga rooting depth be obtained to determine if the roots are deep enough to access the water table, or to what depths are they able to extract stored soil water.

To address these knowledge gaps, Fortescue commissioned Astron Environmental Services Pty Ltd (Astron) to undertake a targeted assessment of the rooting depth and root architecture of Mulga in the vicinity of injection areas at Christmas Creek and Cloudbreak Mining Leases. This report presents the results from field work conducted by Tim Bleby and Toby Dight from Astron at Christmas Creek (Trip 1, 10-17th April 2012) and Cloudbreak (Trip 2, 10-14th April 2012).

The overarching objective of the work was to describe and quantify the depth and architecture of Mulga root systems in areas that may be potentially exposed to water table fluctuations, and to contribute to answering to the following key questions:

1. Where are Mulga roots located in the soil profile? What proportions of the roots are in different depth increments from the surface down to accessible depths?
2. How variable are Mulga root systems between different sampling locations? Can differences (or similarities) be explained by edaphic (soil-related) factors?
3. Based on root morphology (qualitatively assessed based on root direction and taper) and root depth, what functional water use strategies are Mulga likely to employ?
4. Based on assessment of root systems, how is Mulga likely to respond to modified water tables (drawdown or mounding)?

The current working hypotheses for Mulga root systems at Cloudbreak and Christmas Creek are: (1) that the majority of Mulga roots are contained within the upper 2 m of the soil profile, and vegetation health impacts would be unlikely if this zone is kept unsaturated; and (2) that groundwater drawdown is not likely to have any major effect on water availability for Mulga or lead to drought-induced tree deaths.

2 Methodology

2.1 Site selection

Sampling locations (Table 1, Fig. 1, Fig. 2,) were selected following a desktop survey (using GIS resources supplied by Fortescue), ground-truthing of sites (conducted by Dan Huxtable from Equinox Environmental and Tim Bleby from Astron), and receipt of Ground Disturbance Permits (GDP 5329 and GDP 5363).

Locations across Cloudbreak and Christmas Creek covered a range of different landscape positions extending from boundary of the Fortescue Marsh to approximately 4-5 km north of the Marsh, including:

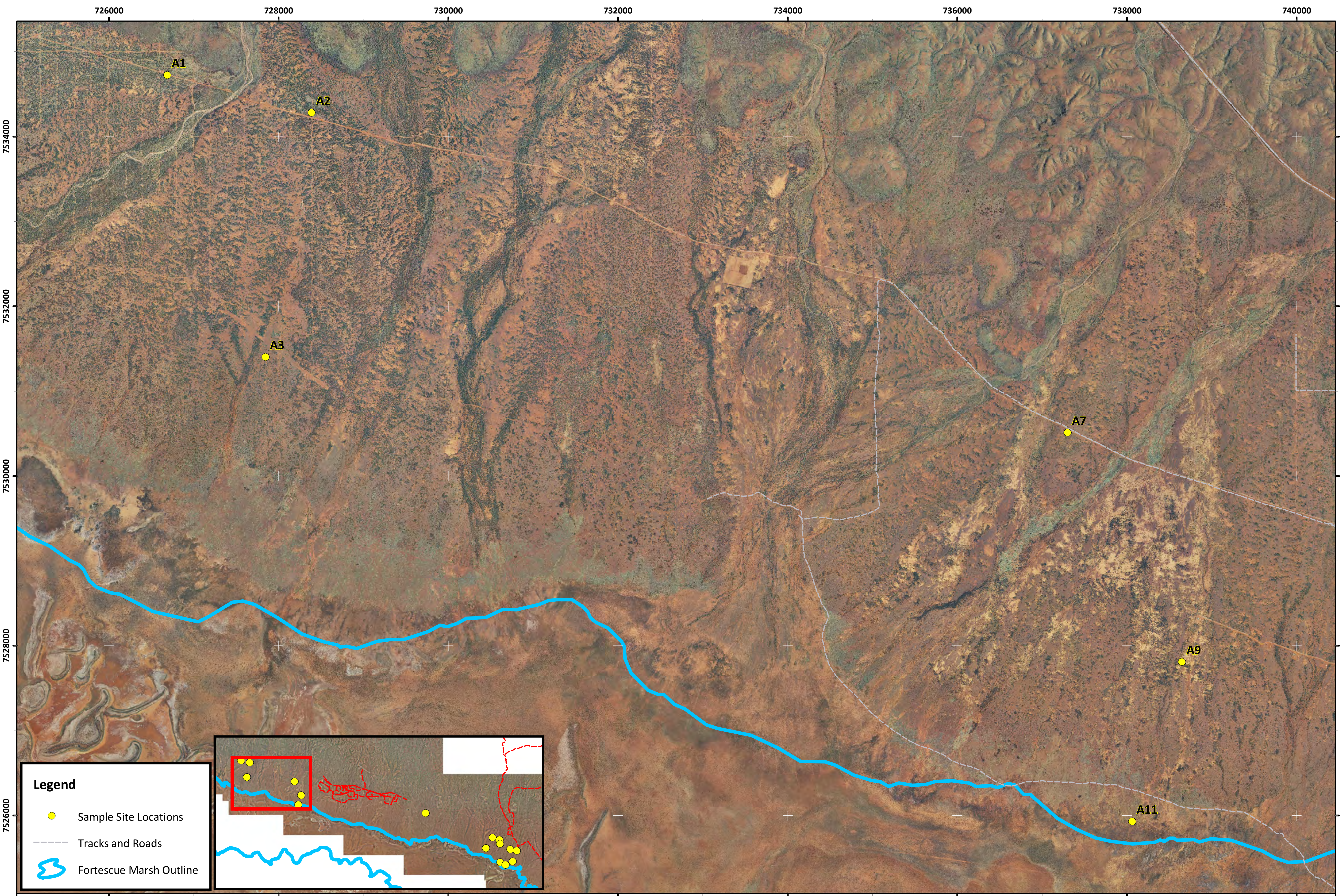
- Downstream sections of natural surface drainage lines very near the edge of the marsh, supporting relatively small, suppressed Mulga trees with lower leaf area, interspersed among stems of dead trees.
- Upstream sections of drainage lines 1-2 kilometres away from the Marsh, supporting relatively dense populations of large, healthy Mulga trees with higher leaf area.
- Isolated patches (small groves) of Mulga and individual trees of varying size situated on slightly elevated open stony plains adjacent to drainage lines.
- Moderate density woodland areas 4-5 kilometres upland from the Marsh supporting large, healthy Mulga trees with higher leaf area.

2.2 Site description

At each site, a brief written description was made of the surrounding landscape, surface soils, vegetation types, surface water hydrology and any other relevant features. Mulga trees selected for measurement were of average size for that location, in good health, and able to be accessed by heavy machinery. Selected trees were generally a mix of tall, single-stemmed or multi-stemmed trees (T4A, T4B and T4C growth forms according to Page et al. (2011) with narrow to terete phyllodes. Pairs of trees no further than 1-2 m apart were selected where possible, otherwise single trees were selected. Trees were measured for height (H), canopy width (W), basal stem diameter at 15 cm height (D15) and stem diameter at (1.3 m) breast height (DBH) (Table 1).

Table 1: Measurement locations and specifications of measurement trees at Cloudbreak (CB) and Christmas Creek (CC) CSA: cross-sectional area of the main stem(s) at breast (1.3 m) height. N/A: measurement not available.

Site	Location	ID	Easting	Northing	Tree Height (m)	CSA (cm^2)	Crown width (m)
CB	Area 1	A1	726690	7534723	8.6	272	6.2
CB	Area 2	A2	728391	7534281	7.2	246	5.7
CB	Area 3	A3	727848	7531402	5.1	37	3.4
CB	Area 7	A7	737299	7530512	6.5	175	5.2
CB	Area 9	A9	738649	7527810	5.4	129	4.8
CB	Area 11	A11	738063	7525930	5.5	95	2.9
CC	Area 12	A12	763380	7524253	N/A	76	3.9
CC	Area 16	A16	775401	7517285	5.3	148	4.3
CC	Area 18	A18	776666	7519372	8.5	174	5.6
CC	Area 19	A19	778084	7518963	5.1	208	5.4
CC	Area 20	A20	778171	7518135	8.2	314	6.7
CC	Area 21	A21	780245	7517037	7.0	129	5.1
CC	Area 24	A24	778236	7514489	8.0	135	4.2
CC	Area 26	A26	779238	7513949	N/A	149	4.7
CC	Area 32	A32	781494	7516743	6.6	255	7.3
CC	Area 33	A33	780680	7514654	N/A	92	4.5



Fortescue Metals Group Limited

Assessment of Mulga Root Architecture

Figure 1. Cloudbreak

Datum: GDA 1994

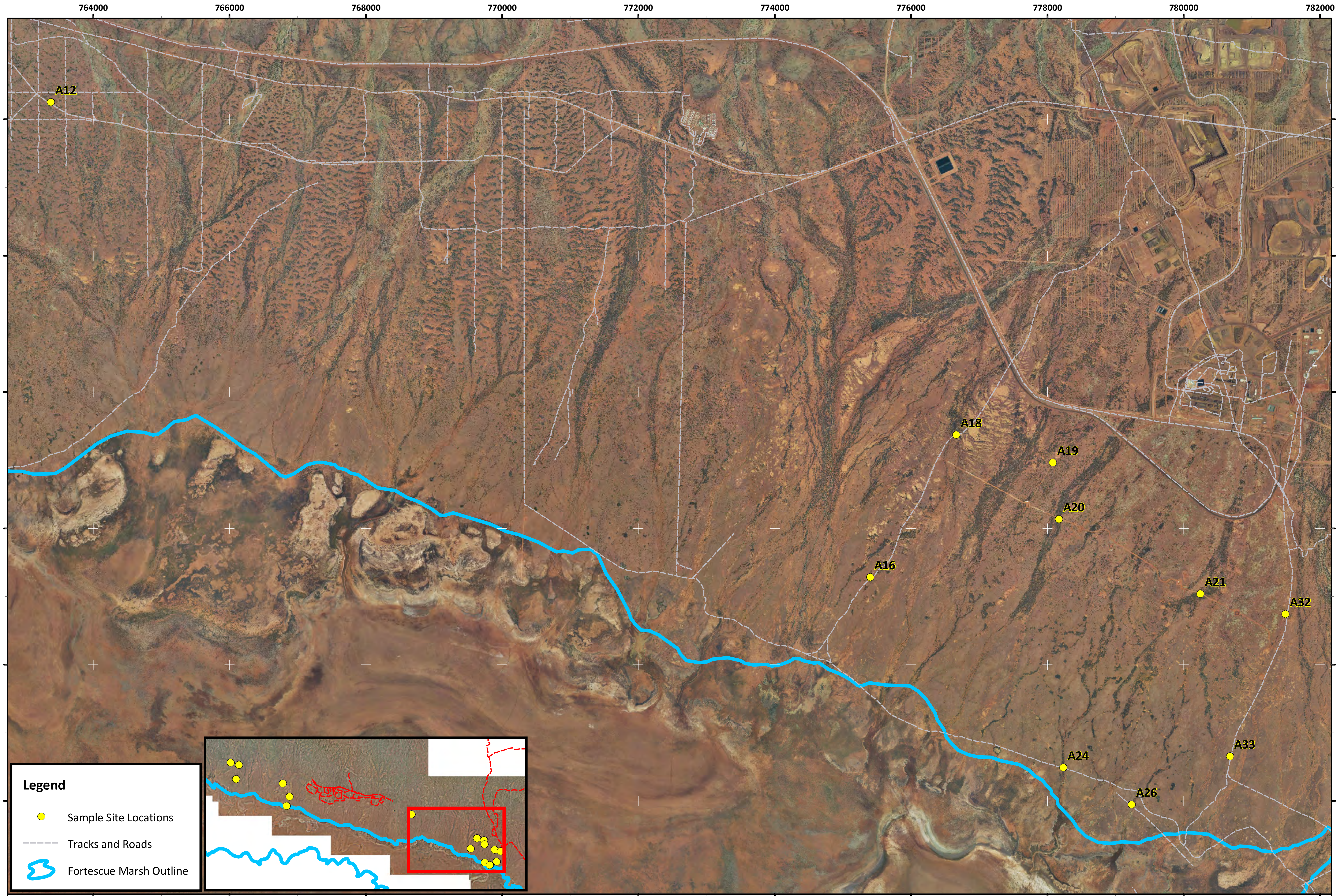
Projection: MGA Zone 50

0 500 1,000 2,000 3,000 Metres

N

astron environmental services

Author: T. Bleby | Drawn: Y.Hua | Date: 12-07-2012 | 12312-12FMV1RevB_120712_Figure_1



Fortescue Metals Group Limited
Assessment of Mulga Root Architecture

Figure 2. Christmas Creek

Datum: GDA 1994
Projection: MGA Zone 50

0 500 1,000 2,000 3,000 4,000 Metres

N

astron environmental services

Author: T. Bleby | Drawn: Y.Hua | Date: 12-07-2012 | 12312-12FMV1RevB_120712_Figure_2

2.3 Soil trenching

A single soil trench was excavated at each site using a backhoe (Onslow Contracting). Trenches were located parallel to trees at a distance of 0.5 m from the stem base. Trenches were approximately 4-7 m in length, 1.2-1.6 m depth and 0.5 m in width. Trenching depth was limited to 1.2-1.6 m to avoid the need for time-consuming benching and sloping works. Maximum trenching depth was determined following initial trenching at the first site (A18) based on the observation of no woody roots beyond 1 m depth. All trenches were back-filled and landscaped after sampling. Note: Sampling was restricted to 1.6 m depth due to logistical constraints and health, safely and environment restrictions.

2.4 Soil descriptions

Soil profiles were described in accordance with the Australian Soil and Land Survey Field Handbook (NCST 2009). Soil profile logs were completed that included a material description, classification, and additional observations (e.g. presence of hard pans or other root-impeding layers).

2.5 Root measurements

A sampling grid with 0.2 m x 0.2 m (0.4 m^2) cells was projected onto the vertical face of the soil profile on the tree side of each trench to enable root measurements. Total grid size ranged from 3.2 m length x 1.2 m depth (96 cells) for trenches that were shorter and shallower, up to 6.0 m length x 1.6 m depth (240 cells) for trenches that were longer and deeper. Half the total number of cells in the grid was allocated for root sampling, made up of columns of grid cells located at 0.4 m intervals along the length of the trench (i.e. every second column of cells). The sampling starting point was randomly selected at one end of the trench, with the tree(s) located near to the centre of the trench. Root abundance and distribution was quantified by counting the numbers of roots in different size classes that intersected each sampled grid cell.

Roots were classified based on size:

- ‘Fine’ roots (F), < 2 mm diameter
- ‘Small’ woody roots (S), 2-15 mm diameter
- ‘Medium’ woody roots (M), 15-40 mm diameter
- ‘Large’ woody roots (L), > 40 mm diameter.

Numbers of fine roots were recorded using the following category system in lieu of undertaking the time-consuming counts of all fine roots: ‘Absent’ (A) for n = 0; ‘Scarce’ (S) for n ≤ 3; ‘Few’ (F) for 3 < n ≤ 10; and ‘Many’ (M) for n > 10. Categorical fine root data were then assigned the following numeric mid-point values for analysis: A = 0, S = 1.5, F = 7 and M = 15. For each location, the abundance of each root type in each sampled cell was expressed on an area basis (i.e. # roots per m^2 sampling area), and mean abundances were calculated for each depth interval. The overall mean and standard deviation of abundance for each root type in each depth interval was then calculated from data pooled across all sites.

Following trench sampling, one tree was excavated, uprooted and extracted using the backhoe, taking care to keep the proximal root system as intact and in its original orientation as possible. The proximal root system was defined as that contained within an imaginary cylinder with a radius of approximately 1.5-2 m and a depth of approximately 0.7-1.0 m. Soil adhering to roots was carefully removed following uprooting and broken roots were repaired and placed in their original orientation. Uprooted trees were then secured horizontally for using the backhoe bucket in preparation for measurement. A total of 15 trees were excavated (all sites except for Area 9).

The lateral distribution and density of woody roots (> 2 mm diameter) of uprooted trees was quantified by measuring the diameter of all roots contained within circumferential, 30 degree sector compartments at a radial distance of 0.5 m from the main stem, with sector compartments defined by depth: 0-0.2 m, 0.2-0.4 m and 0.4-0.6 m. The area of each measurement compartment was 0.26 m x 0.2 m (based on trigonometry). Measurements were made from at least 6 sectors (180 degrees, containing least half of the root system). Measured sectors were randomly selected around the circumference of the tree, but obviously damaged sections were avoided. For each location, woody root density was expressed on an area basis (i.e. cm^2 root cross-sectional area per m^2 sampling area), and mean densities were calculated for each depth interval. The overall mean and standard deviation of density for each depth interval was then calculated from data pooled across all sites.

The taper of individual roots was quantified by measuring root diameter every 0.1-0.2 m along the length of 5-7 randomly selected 'lateral' roots (angle of descent < 20 degrees) and 5-7 randomly selected 'oblique/vertical' roots (angle of descent > 20 degrees), and any obvious taproots if present. Taper index, t was calculated from the following formula: $t = (D_p - D_d)/L$, where D_p is the diameter (in mm) of a root segment at the proximal end (towards the trunk), D_d is the diameter at the distal end (away from the trunk), and L is the segment length (in m). Increasing taper is reflected by an increasing taper index. A taper index of zero indicates no taper.

Detailed written descriptions and simple sketches of root systems were made, highlighting their general appearance, morphology, presence of different root types, general branching patterns, angles of descent, and architecture with respect to soil properties. For the purpose of this study, first order roots were defined as those roots originating from the basal root stock or taproot. Second order roots were those roots that result from branching of first order roots; third order roots were those resulting from the branching of second order roots and so on.

3 Results

3.1 Soil descriptions

A Horizons were typically 0.3-0.4 m deep, comprised of dark reddish silty loam. Soils had a weak to moderate polyhedral structure. Organic matter contents were higher in the top 0.1 m.

B Horizons extended to depth (~1.0 to 1.6 m), comprised of dark reddish brown light to medium clays. Soils were generally poorly structured and tended to be sodic at depth (Exchangeable Sodium Percentage >12). Varying amounts of gravel and cobbles were present in this profile at some locations. In most instances, smaller gravel graded to larger gravel and cobbles at depth.

Much of the trench to trench variation in soils was associated with the depth and thickness of gravel and cobble layers. Tightly packed bands of cobbles and gravel were present in many of the trenches at varying depths from near the surface to the depth of excavation. The thickness of these layers was generally between 0.2 and 0.5 m. Variability was most notable in Area 32 where two soil logs were completed (A32–M1 and A32–M2) to account for variability along the length of a single trench. This observation was consistent with the Mulga being generally associated with drainage tracts.

Complete soil profile logs for each location are presented in Appendices 1-16.

3.2 Root abundance, density and distribution

Measurements from soil trench profiles showed that large and medium size woody roots were generally restricted to the upper 0.6 m of the soil profile, while small woody roots were common to 1 m depth (Fig. 3, Fig. 4, Fig. 7). Small woody roots were at least three times more abundant than medium woody roots and ten times more abundant than large woody roots at 0-0.4 m depth, and numbers of all woody roots decreased exponentially with depth (Fig. 4).

Fine roots were most abundant in the upper 0.4 m of the profile but were always present to 1.6 m depth (Fig. 5, Fig. 7). Fine roots appeared to display a sigmoidal pattern of distribution with depth to the extent of trenching, and numbers of fine roots were an order of magnitude greater than woody roots (Fig. 5).

Measurements from exposed root systems showed that the root density was relatively high in the 0-0.2 and 0.2-0.4 m depth zones (around 100 $cm^2\ m^{-2}$), but decreased dramatically with depth in the 0.4-0.6 m zone (around 20 $cm^2\ m^{-2}$) (Fig. 6), consistent with soil profile measurements.

Figure 3: Distribution of Mulga roots along the soil trench at Area 24 (1.4m depth, 3.2m length).

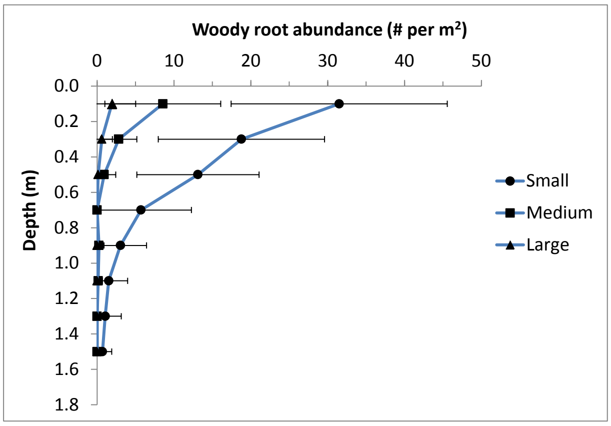


Figure 4: Mean abundance of woody roots with depth, from data pooled across all sampling locations at Cloudbreak and Christmas Creek (n = 16). Small woody roots were 2-15mm diameter; Medium woody roots were 15-40 mm diameter; Large woody roots were > 40 mm diameter. Error bars are ± one standard deviation of the mean.

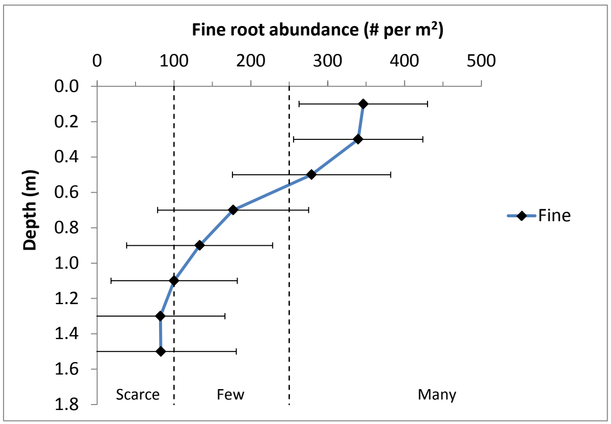


Figure 5: Mean abundance of fine roots with depth, from data pooled across all sampling locations at Cloudbreak and Christmas Creek (n = 16). Fine roots were < 2 mm diameter. Error bars are ± one standard deviation of the mean. Dashed vertical lines delineate abundances associated with non-numerical sampling categories (Scarce, Few and Many) as defined in the methods.

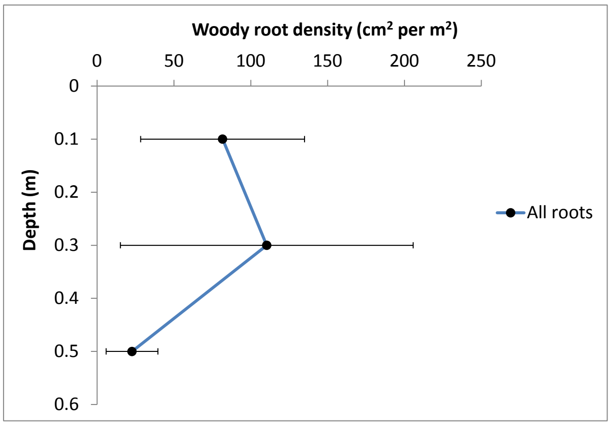


Figure 6: Mean density of woody roots (> 2 mm diameter) with depth, from data pooled across all sampling locations at Cloudbreak and Christmas Creek (n = 15). Error bars are ± one standard deviation of the mean.

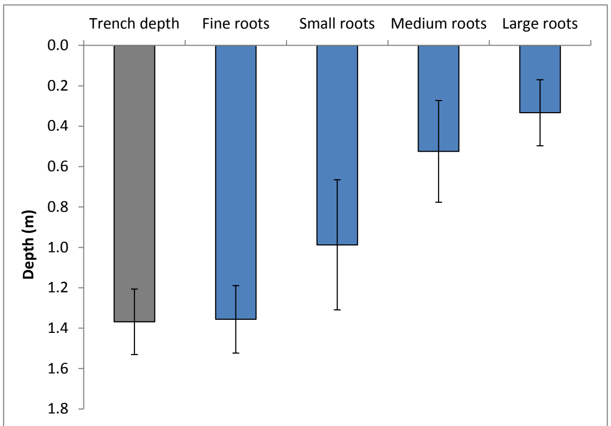


Figure 7: Mean trenching depth and mean depth to the deepest observed roots for Fine, Small, Medium and Large woody roots, from data pooled across all sampling locations at Cloudbreak and Christmas Creek (n = 16). Fine roots were < 2 mm diameter; Small woody roots were 2-15 mm diameter; Medium woody roots were 15-40 mm diameter; Large woody roots were > 40 mm diameter. Error bars are ± one standard deviation of the mean.

3.3 Root system descriptions

From visual inspections of exposed root systems of excavated trees, it was clear that Mulga root systems were comprised of eight distinct elements, described in detail below. A schematic diagram of these elements are shown in Figure 8 and examples are shown in Figures 9-11.

1. Basal root stock

Mulga trees had a basal root stock that emanated from the base of the trunk and extended below ground level to approximately 0.2-0.3 m depth. This root stock comprised an otherwise poorly-defined mass of woody tissue from which the taproot and first tier, first order lateral roots originated. The root stock of smaller trees (< 20 cm DBH) tended to be similar in diameter to the parent trunk, but the diameter of the root stock of larger trees (> 20 cm DBH) tended to be slightly larger than that of the trunk, reflecting the slightly buttressed nature of larger first tier, first order lateral roots.

2. Taproots

When present, taproots took the form of a thick vertical root emanating from the basal root stock, most often, but not always, directly in line with the tree trunk. 80% of measured trees displayed an obvious taproot, while 20% did not. Mean (± SD) taproot diameter was 80 ± 32 mm (n = 12) at 0.3 m depth, which tapered strongly to a mean diameter of 13 ± 9 mm at an average depth of 0.9 m (Fig. 11). This equated to a taper index of 109 mm m^{-1}, more than double that of most other roots (Fig. 12). Taproots descended more or less vertically but tended to flatten out to be near horizontal and branch into smaller second and third order roots at depths of 0.7-0.9 m, some of which tapered to the size of fine roots (< 2 mm diameter). The ends of taproots were often twisted, gnarly and pitted in appearance (Fig. 10), which tended to coincide with gravel and cobble layers in the soil profile.

3. Upper tier first order lateral roots

All trees displayed an even circumferential array of near-horizontal (lateral) first order roots originating from the root stock, which formed a distinct 'upper tier' of roots at a depth of approximately 0.1-0.3 m. The number of upper tier lateral roots ranged from around 6 for smaller trees (< 20 cm DBH) to more than 12 for larger trees (> 20 cm DBH), and they were typically > 30 mm in diameter. Upper tier lateral roots within a radial extension of 2-3 m tended to remain relatively horizontal and straight, rarely curving beyond an arc of around 45 degrees or descending at angles greater than around 20 degrees. It was evident from trees in drainage lines that had been subject to major soil erosion that upper tier lateral roots sometimes remained near horizontal and straight well beyond the width of the canopy (e.g. > 5 m). Upper tier lateral roots tended not to be highly branched nor strongly tapered (taper index < 50 mm m^{-1}) in the horizontal plane, but they commonly gave rise to oblique second order roots that extended from the under sides of roots.

4. Lower tier first order lateral roots

Most trees had a secondary circumferential array of near-horizontal (lateral) first order roots that originated from the taproot, which formed a 'lower tier' of roots from around 0.3 to 0.7 m depth. Lower tier lateral roots tended to be smaller and shorter than upper tier lateral roots, rarely extending beyond a radial distance of 1-2 m. Similarly to upper tier lateral roots, lower tier lateral roots commonly gave rise to oblique second order roots than extended from the under sides of roots. Unlike upper tier lateral roots, lower tier lateral roots tended to give rise to numerous small second and third order roots (< 5 mm diameter).

5. Lower tier first order oblique roots

In addition to first order lateral roots, many trees had a small number of first order roots located in the same tier that originated and descended from the tap root at angles of descent > 20 degrees. These roots were similar in appearance and size to tap roots, and they were often more abundant in cases where a tap root was absent. Similar to their lateral counterparts, lower tier oblique roots tended to give rise to numerous small second and third order roots.

6. Second order oblique roots

Oblique second order roots originating from the under sides of lateral roots tended to be relatively short (< 1 m), strongly tapered (taper index < 50 mm m^{-1}), and numerous within a radial extension of 1-2 m. These roots commonly tapered to the size of fine roots and gave rise to numerous other small second and third order roots (Fig. 6). Similar to taproots, second order oblique roots descended at steep angles, ranging from > 45 degrees to vertical, and they tended to become twisted and gnarly by around 0.7 m depth, often coinciding with gravel and cobble layers in the soil profile. Larger trees (> 20 cm DBH) with larger root systems tended to support a greater density of second order oblique roots than smaller trees.

7. Second, third and higher order small roots

Second, third and higher order roots that branched from first order roots graded downwards in size with increasing order number, with most third and higher order roots being close to the size of fine roots. Higher order roots were oriented in a wide range of lateral directions and descended at a range of angles from near horizontal to vertical. Larger trees (> 20 cm DBH) with larger root systems tended to support a greater density of higher order roots than smaller trees.

8. Fine roots

Few fine roots were retained following root system excavations, however it was clear from soil trench profiles that fine roots were abundant in the top 0.6 m and continuously present to at least 1.6 m depth, the maximum depth of trenching.

9. Root taper

There was a strong positive linear relationship between proximal root diameter and the degree of root taper; and oblique roots clearly tapered more strongly than horizontal roots (Fig. 12).

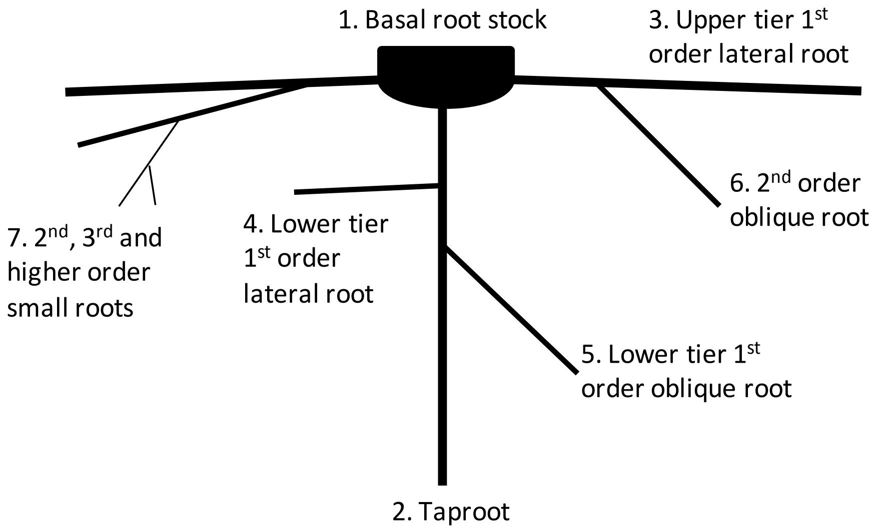


Figure 8: Schematic diagram showing the major elements of Mulga root systems as described in Results Section 3.3.

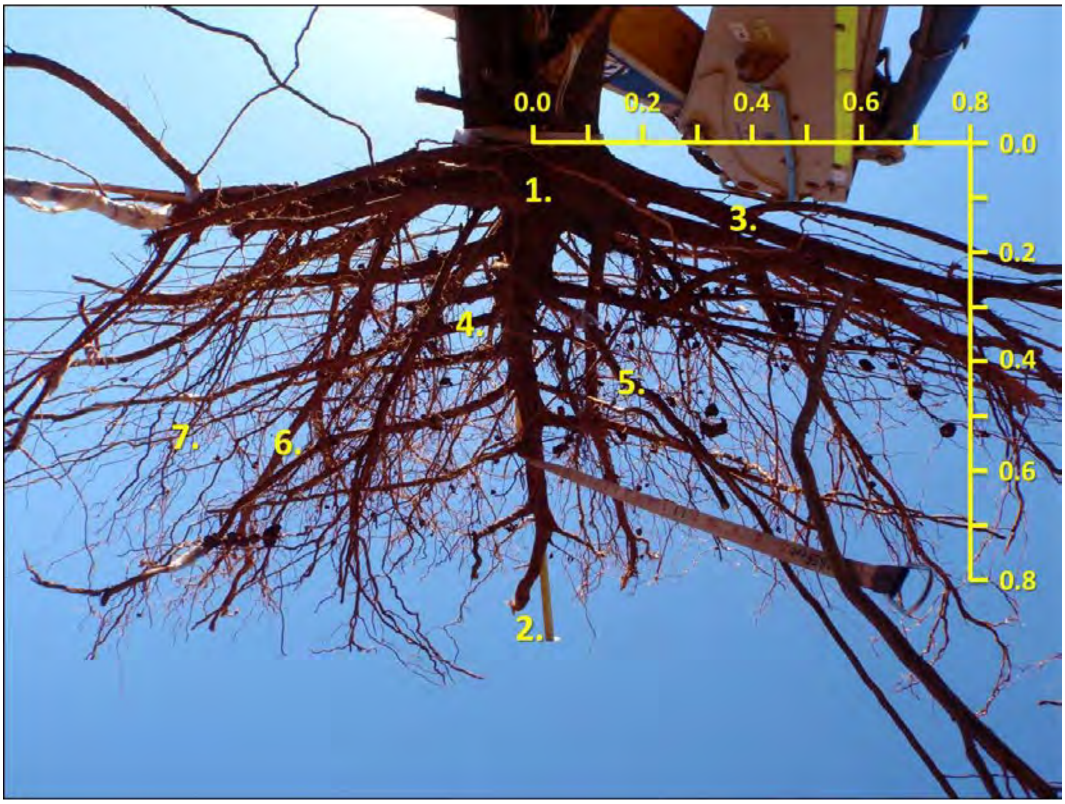


Figure 9: Root system architecture of the Mulga tree excavated at Area 12. Image shows examples of the major elements of Mulga root systems, including: (1) the basal root stock; (2) central taproot; (3) upper tier first order lateral roots; (4) lower tier first order lateral roots; (5) lower tier first order oblique roots; (6) second order oblique roots; and (7) higher order small woody roots. Scale bars (m) represent horizontal and vertical distances.

Figure 10: Example of an upper tier first order lateral root giving rise to second order oblique roots, and higher order small woody roots from the Mulga tree excavated at Area 12. Scale bars (m) represent horizontal and vertical distances.

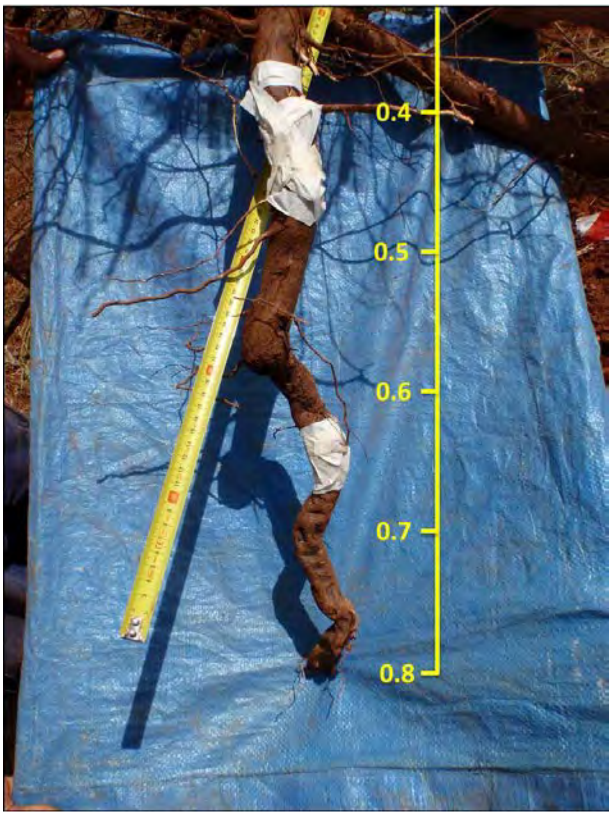
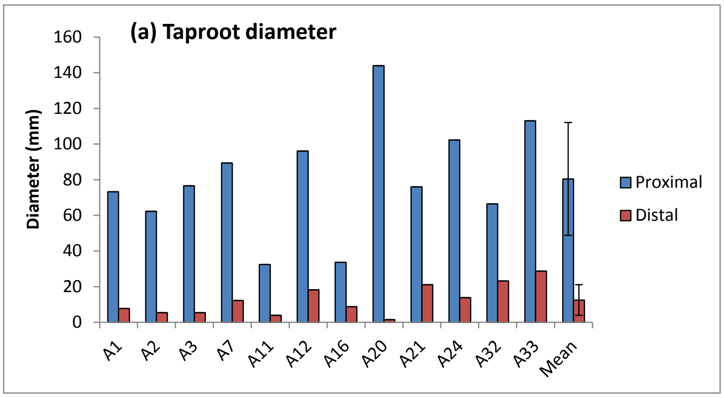


Figure 11: Example of a twisted, gnarly, pitted taproot from the Mulga tree excavated at Area 21. Scale bar (m) represents vertical depth. The same scale bar applies to the horizontal plane as the vertical plane.



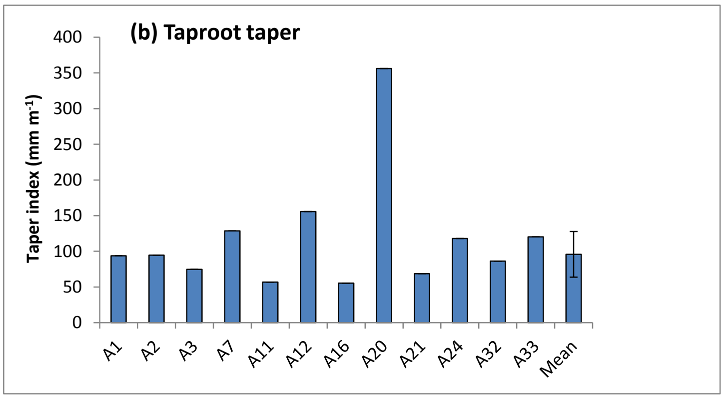


Figure 12: Proximal and distal taproot diameters (a), and corresponding taper index values (b). The mean ± one standard deviation of each parameter is also shown (excluding the A20 outlier).

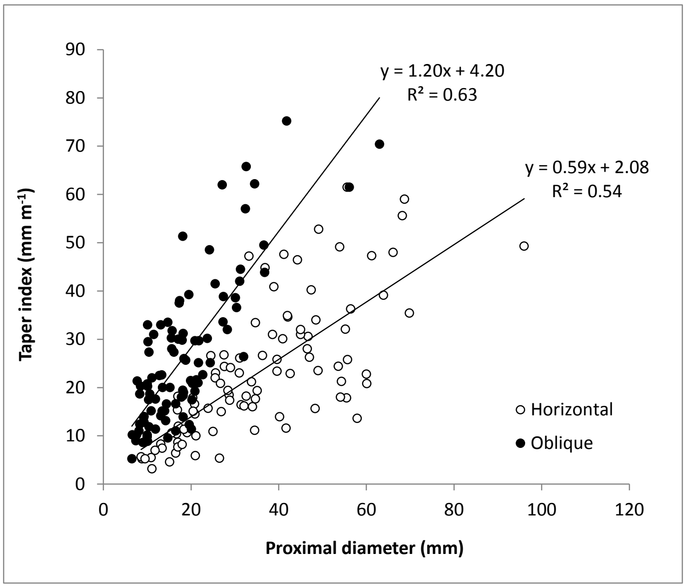


Figure 13: Relationships between proximal root diameter and root taper index for horizontal and oblique roots. Angles of descent were < 20° for horizontal roots and > 20° for oblique roots. Linear regression equations and R2 values are shown.

4 Discussion

This report outlines field work conducted to describe and quantify the depth, spread and architecture of Mulga root systems across a range of localities and landscape positions around the Christmas Creek and Cloudbreak mining leases. The main findings of the work are discussed below with direct reference to the key questions posed in the introduction.

1. *Where are Mulga root systems located in the soil profiles of selected localities at Cloudbreak and Christmas Creek? What proportions of the roots are in different depth increments from the surface down to approximately 3 m depth (where accessible)?*

Mulga trees at the Cloudbreak and Christmas Creek sampling locations had shallow root systems dominated by large, weakly tapered, first order lateral roots contained in the top 0.5 m of the soil profile. Lateral roots were widely spread in the horizontal plane, with numerous roots extending well beyond the width of the canopy. Taproots and oblique roots were also present, but they tended to be strongly tapered and relatively short. Most taproots and oblique roots were reduced to a diameter of around 10 mm diameter or less by 1 m depth. The distinct upper tier system of lateral roots was supported by a lower tier network of smaller lateral and oblique roots that were mostly contained within a cylindrical span with a radius of 1-2 m and depth of 0.7 m. The majority of woody roots were distributed close to the soil surface, particularly in the 0.0-0.4 m depth range, and distribution decreased exponentially with depth with very few roots encountered at depths > 1.0 m. Fine roots were present to at least 1.6 m depth in nearly all cases, with most fine roots occurring in top 0.5 m of the soil profile. The number and size of upper tier lateral roots, the density of the lower tier network of roots, and the size and thickness of the taproot were all proportional with tree size.

Results from this study are consistent with the general perception from previous studies that Mulga in arid and semi-arid ecosystems have predominantly shallow root systems as an adaptation to acquire surface soil water (Slatyer 1961, Slatyer 1965, Winkworth 1973, Pressland 1975, Anderson & Hodgkinson 1997, EPA 1996). Our results are most similar to that of Pressland (1975) who described a concentration of roots within the top 30 cm of the soil profile and roots growing to 1.0-1.5 m depth for Mulga communities in semi-arid south-western Queensland. Unpublished studies from other regions of the Pilbara have reported similar results (Page & Grierson 2010). Although it was not quantified, it is reasonable to suggest that Mulga roots in this study were relatively extensive in the horizontal plane, with substantial numbers of lateral roots that reached several metres beyond the crown width. This compares with work by Slatyer (1965) who found that roots of Mulga near Alice Springs were mostly concentrated near the base of the tree, with some lateral roots extending beyond the crown width. In the vertical plane, it has been suggested that although taproots of Mulga in the Pilbara generally taper to less than 1 cm diameter at < 3 m depth, they may be capable of extending deeper in the profile (> 5 m depth), but the total rooting depth and contribution of the taproot to total water uptake remains unknown (Page & Grierson 2010). In this study average taproot diameter at 0.9 m depth was 13 mm. Based on a conservative estimate of root taper for vertical roots (e.g. 20 mm/m, see Fig. 12), it is likely that most taproots would have tapered to fine root size (diameter < 2 mm) at depths exceeding 1.5 m. From a global perspective, the distribution of most roots in close to the surface, particularly in the 0.0-0.4 m depth range, below which roots decreased exponentially with depth, is consistent with global models of root biomass (Jackson et al. 1996).

2. *How variable are Mulga root systems between different sampling locations? Can differences (or similarities) be explained by edaphic (soil-related) factors?*

In general, the same basic root system architecture was observed across all sampling locations. However, small differences in the depth and distribution of roots were associated with local differences in the soil profile. No true hard pans were encountered to a depth of 1.6 m, except at one site on the fringe of the Fortescue Marsh underlain by massive silcrete at 1.3 m depth (Area 11); however root growth was clearly influenced by the presence of layers of gravels, cobbles, and compacted clays which were common to most sites. Beneath lighter textured topsoil layers to 0.4 m depth, gravel, cobble and clay layers occurred at variable depths and were stacked in variable combinations from site to site, in ways that were generally not predictable from aboveground features of the landscape. This observation was consistent with the Mulga being generally associated with drainage tracts. Most large woody roots were naturally restricted to the upper soil layers (A Horizon), but the depth of the taproot and the distributions of small woody roots and fine roots were commonly influenced by the way in which gravels, cobbles and clays were layered. For example, at some sites, growth of all types of roots was restricted by the presence of either a heavy clay layer of a very dense gravel layer at a relatively shallow depth (0.6 m). At other sites, small woody roots were restricted by dense gravel or cobble layers but fine root proliferated in the same layers, and some sites displayed alternating layers of high and low density of fine roots associated with alternating layers of cobble and clay. Sites with more homogeneous soil profiles tended to have more even distributions of small woody roots and fine roots.

More generally for this system, it was apparent that root system architecture was influenced by the site 'favourability' for tree growth in terms of availability of light, water and nutrients and presence of pests, disturbance, or chemical barriers to growth (e.g. salt). In this respect, location influenced root system size as opposed to architecture. It was evident that putatively more favourable sites were able to support larger trees with larger, more expansive root systems compared to less favourable sites. The most obvious examples of 'less favourable' sites were those directly adjacent to the marsh. Here, roots systems were generally smaller and shallower and they contained numerous dead roots linked to parts of the tree that had died (natural root pruning), possibly as a result of drought, salinity, or waterlogging.

Mulga has a wide geographic distribution across semi-arid Australia (Beard 1990) and it occurs in a variety of different stand formations structures as a consequence of where they grow in the landscape (Page & Grierson 2010). The rooting architecture and ecological water requirements of Mulga almost certainly vary according to local topography, hydrology and soil type (Puigdefabregas et al. 1998), and may be quite different for communities growing on hill slopes compared to valley floors for example. In this study, the range of landscape positions represented was relatively narrow, mostly located on relatively flat portions of the landscape, and site to site variability in rooting architecture was relatively low. Much greater variability in the rooting architectures and ecological water requirements of Mulga are likely to exist elsewhere in the Pilbara (Page & Grierson 2010) and semi-arid Australia.

3. *Based on root morphology (qualitatively assessed based on root direction and taper) and root depth, what functional water use strategies are Mulga likely to employ?*

Root distribution correlates strongly with the dynamics of water availability to plants. Wide-spreading roots close to the surface allow access to soil moisture in large volumes of soil in the horizontal plane fed by rainfall, while deep-spreading roots allow access to perennial sources of soil moisture and groundwater in deeper layers. Root distribution determines plant responses to rainfall pulses and the severity of drought.

Mulga's large investment in shallow, widely spreading lateral roots clearly indicates a water use strategy aimed at sourcing water from a large volume of surface soil rather than a large volume of deeper soil. This distribution and architecture is well suited for capturing water that infiltrates into shallow soil layers during surface runoff (sheetflow) or infiltration of ponded water in lower-lying areas following episodic heavy rainfall events (Heyting 2011). Mulga's root system is also well suited for capturing water that funnels into the soil from stem flow, achieved via the proliferation of short, strongly tapered oblique roots coupled with a network of small woody roots and fine roots in a shallow cylindrical region directly below the base of the stem. Previous estimates of interception by Mulga canopies are in the order of 13-40 % of rainfall (Slatyer 1965, Pressland 1973). Networks of oblique roots are probably also important for anchoring the plant, and may be of equal importance as water acquisition for larger trees given the lack of large, deeper woody roots.

Surface soils are a very hostile environment for plant roots due to extremely high temperatures and extreme temporal fluctuations in water availability. An implied consequence of having a shallow root system in an arid climate is that Mulga must deal with extended drought and episodic wetting and drying of surface soil layers following rainfall pulses that vary greatly in their timing and magnitude, including large pulses associated with tropical cyclones. Previous studies have clearly shown that Mulga is capable of enduring drought by physiologically 'shutting down' and by employing other physiological strategies such as stomatal closure to restrict water loss. During drought, Mulga commonly maintains transpiration at rates below the level of detection (Bleby Pers. Comm.) and has water potentials as low as -12 MPa (O'Grady et al. 2009) often without showing any negative impacts such as leaf loss or branch death (Landman 2001). Recent leaf water potential data from Mulga at Christmas creek are entirely consistent with the presence of shallow root systems accessing water from relatively dry profiles in periods between rainfall events: mean (± standard deviation) pre-dawn leaf water potentials were -5.0 ± 1.3 MPa at the end of the winter 'dry season' in August 2011 (no rainfall was received in August 2011 at the Cloudbreak Mine (Fortescue unpublished data)), and similar values of -5.1 ± 1.4 MPa were recorded at the end of the summer 'wet season' in May 2012 (n = 60 trees) (unpublished Astron data); note that no rainfall was recorded in May 2012, and only 0.2mm was recorded in April 2012, at the Cloudbreak Mine (Fortescue unpublished data). Mulga is well known to be highly drought tolerant (Winkworth 1973) compared to most agricultural plants that generally show signs of severe drought stress when pre-dawn leaf water potentials fall below -1.5 MPa.

As rainfall pulses replenish soil moisture in upper soil layers first, and infiltration often does not reach deeper layers when rainfall volume is low, the shallow root system of Mulga is well adapted to capture incident rainfall and run-on. Shallow root systems imply that Mulga is likely to display a strong 'pulse response' to rainfall whereby it makes rapid, effective use of rainfall when it occurs, as reflected by increased rates of sap flow, and higher rates of stomatal conductance and photosynthesis. Unpublished work on Mulga growing on the slopes of natural mesa landforms in the Telfer region of the Pilbara indicates that Mulga are most active in terms of water use and physiological activity following rainfall pulses, and that the magnitude of responses are proportional to the magnitude of rainfall (Bleby Pers. Comm.). The rapid pulse response to water availability from rainfall suggests that it is unlikely that pre-dawn leaf water potentials of Mulga at Christmas creek remained unchanged indefinitely, but rather fluctuated along with the wetting and drying of shallow soil layers following rainfall pulses. Physiologically, previous work has shown that Mulga responds very rapidly to rewetting of shallow soils following rainfall and irrigation, with foliage rehydrating within a matter of days, followed by slow dehydration as drought conditions return (literature reviewed by Page & Grierson 2010). Again, this is consistent with the bulk of Mulga's roots being held within the top 0.5 m of the soil profile.

Mulga's rooting strategy and likely water use strategy is consistent with where it occurs in the landscape at the Cloudbreak and Christmas Creek. Mulga has a tendency to grow along natural drainage lines, in groves fed by sheetflow from portions of the landscape at higher elevations (Heyting et al. 2011), or in other areas where water may pond or infiltrate readily into the soil. At several locations it was observed that soil beneath the canopy was typically silty with an accumulation of leaf litter, which may further promote the capture and infiltration of surface water. Previous work has demonstrated that in some ecosystems, water infiltration rates within groves are five to ten times higher than in the surrounding intergrove areas (Tongway and Ludwig 1990, Greene 1992, Dunkerley 2002), and retention rates may also be higher within groves, with vegetation and organic debris slowing and trapping water from sheetflow (Wakelin-King, 1999).

5 Conclusions

4. *Based on assessment of root systems, how is Mulga likely to respond to modified water tables (drawdown or mounding)?*

Based on the results of this preliminary study, the limited scientific literature, and other anecdotal evidence, it is reasonable to conclude that Mulga at the sampled locations is likely to meet its ecological water requirements from the top 2-3 m of the soil profile. Mulga would not be expected to be affected by groundwater drawdown associated with the Chichester mines. Mulga could potentially be affected by groundwater mounding where elevated water tables intersect the root systems.

While this study represents an important advance in the knowledge of Mulga root system architecture, knowledge gaps remain. This study has shown that at Christmas Creek and Cloudbreak, rooting depth of Mulga is unlikely to extend beyond 1.5 m depth. However, fine roots may extend further, and the absolute depth and role of deep fine roots in water uptake remain unknown.

6 References

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Appendix A: Images from Sample Locations

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Cloudbreak: Area 1

Cloudbreak: Area 2

Cloudbreak: Area 3

Cloudbreak: Area 7






Cloudbreak: Area 9

Cloudbreak: Area 11






Christmas Creek: Area 12






Christmas Creek: Area 16

Christmas Creek: Area 18

Christmas Creek: Area 19



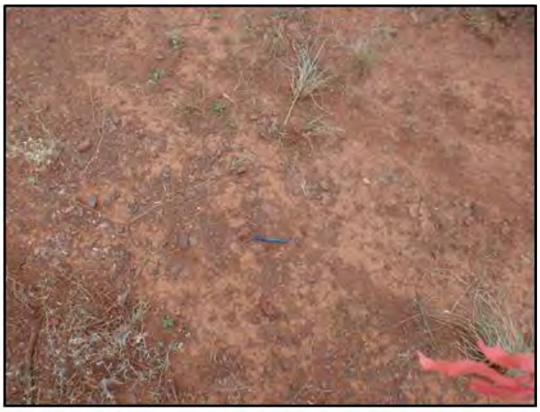



Christmas Creek: Area 20






Christmas Creek: Area 21



Christmas Creek: Area 24

Christmas Creek: Area 26






Christmas Creek: Area 32

Christmas Creek: Area 33



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Appendix B: Soil Logs from Sample Locations

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BOREHOLE NUMBER A1

Astron Soil and Water

astron soil and water pty ltd

CLIENT Fortescue Metals Group Limited
PROJECT NAME Assessment of Mulga Root Architecture
PROJECT NUMBER 12312
PROJECT LOCATION Cloudbreak

DATE STARTED 12/5/12 **COMPLETED** 12/5/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Onslow Contracting
EASTING 726690
NORTHING 7534723
EQUIPMENT Backhoe
HOLE LOCATION Area 1
HOLE SIZE 3.2 m
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH					SW-SC	Silty, gravelly clay, red/brown 2.5YR 3/4, very fine to medium grained, poorly sorted, moderately graded, abundant organics,gravel partially rounded, weak. Clayey Sand (CS).	A1 - 0.0 - 0.25	No odour at any depth. Landscape:Mulga woodland with grassy understory.
			0.5		CL-ML	Gravelly clay with minor silt, red/brown 2.5YR 2.5/4, very fine to coarse grained, well sorted, well graded, few organics, gravel partially rounded, weak. Silty Clay Loam (ZCL).	A1 - 0.25 - 0.75	
					CLS	Clayey, silty cobbles, brown/red 2.5YR 3/3, very fine to coarse grained, , poorly sorted, moderately graded, few organics, cobbles very rounded, firm. Clay Loam, Sandy (CLS).	A1 - 0.75 - 0.85	
			1.0		CL-CH	Silty clay, red/brown 2.5YR 2.5/4, very fine to coarse grained, well sorted, well graded, few organics, firm. Light Clay (LC).	A1 - 0.85 - 1.1	
			1.5		CL-CH	Clayey, silty cobbles/gravel, brown/red 2.5YR 4/6, medium to coarse grained, poorly sorted, moderately graided, no organics, cobbles rounded, firm. Clay Loam, Sandy (CLS).	A1 - 1.1 - 1.7	

Borehole A1 terminated at 1.7m

Astron Soil and Water

astron soil and water pty ltd

CLIENT Fortescue Metals Group Limited

PROJECT NAME Assessment of Mulga Root Architecture

PROJECT NUMBER 12312

PROJECT LOCATION Cloudbreak

DATE STARTED 12/5/12 **COMPLETED** 12/5/12

R.L. SURFACE

DATUM

DRILLING CONTRACTOR Onslow Contracting

EASTING 728391

NORTHING 7534281

EQUIPMENT Backhoe

HOLE LOCATION Area 2

HOLE SIZE 3.2 m

LOGGED BY T.D.

CHECKED BY T.D.

NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH					CL	Silty, loamy clay with some gravel, red/brown 2.5YR 2.5/4, very fine to coarse grained, poorly sorted, well graded, abundant organics, gravel partially rounded, weak. Clay Loam (CL).	A2 - 0.0 - 0.25	No odour at any depth. Landscape: Dense Mulga woodland, open, sparse understory, some spinifex.
			0.5		CL-ML	Silty clay with minor gravel, red/brown 2.5YR 3/6, very fine to medium grained, moderately sorted, well graded, few organics, gravel rounded, weak. Silty Clay Loam (ZCL).	A2 - 0.25 - 0.85	
			1.0		CL-ML	Gravel/cobbles with some clay/silt, red/brown 2.5YR 3/6, very fine to medoum grained, poorly sorted, poorly graded, few organics, gravel slightly rounded, firm. Silty Clay Loam (ZCL).	A2 - 0.8 - 1.3	
			1.5		CL-CH	Silty, loamy clay, red/brown 10R 4/6, very fine to fine grained, well sorted, well graded, no organics, very firm. Light CLay (LC).	A2 - 1.3 - 1.7	

Borehole A2 terminated at 1.7m

Astron Soil and Water

BOREHOLE NUMBER A3

CLIENT Fortescue Metals Group Limited
PROJECT NAME Assessment of Mulga Root Architecture
PROJECT NUMBER 12312
PROJECT LOCATION Cloudbreak

DATE STARTED 11/5/12 **COMPLETED** 11/5/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Onslow Contracting
EASTING 727848
NORTHING 7531402
EQUIPMENT Backhoe
HOLE LOCATION Area 3
HOLE SIZE 3.2 m
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH					CL-ML	Silty, gravelly clay, red/brown 10R 3/4, very fine to coarse grained, poorly sorted, well graded, some organics, gravel partially rounded, weak. Silty Clay Loam (ZCL).	A3 - 0.0 - 0.3	No odour at any depth. Landscape: Mulga grove located in surface flaked basin, sparce, grassy understorey.
			0.5 1.0 1.5 2.0		CL-ML	Silty, gravelly clay, red/brown 10R 3/4, very fine to coarse grained, poorly sorted, moderately graded, no organics, gravel partially rounded, weak. Silty Clay Loam (ZCL).	A3 - 0.3 - 2.0	
					CL-CH	Silty, gravelly clay-hardpan, red/brown 10R 3/6, medium to coarse grained, poorly sorted, moderately graded, no organics, moderately cemented, some calcium carbonate, very firm. Light Medium Clay (LMC).	A3 - 2.0 - 2.4	

Borehole A3 terminated at 2.4m

BOREHOLE NUMBER A7

Astron Soil and Water
astron soil and water pty ltd

CLIENT Fortescue Metals Group Limited
PROJECT NAME Assessment of Mulga Root Architecture
PROJECT NUMBER 12312
PROJECT LOCATION Cloudbreak

DATE STARTED 13/5/12 **COMPLETED** 13/5/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Onslow Contracting
EASTING 737299
NORTHING 7530512
EQUIPMENT Backhoe
HOLE LOCATION Area 7
HOLE SIZE 3.2 m
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH					CL-ML	Silty, gravelly clay, red/brown 2.5YR 3/6, very fine to medium grained, poorly sorted, moderately graded, some organics, gravel partially rounded, weak. Silty Clay loam (ZCL).	A7 - 0.0 - 0.2	No odour at any depth. Landscape: Sparse stoney/gravelly Mulga grove, some isolated clusters of grasses, small sink holes.Gypsum crystals present 1.3 - 1.7 mbgl.
			0.5		CL-ML	Silty, loamy clay, red/brown 2.5YR 2.5/4, very fine to medium grained, moderately sorted, well graded, few organics, no gravel, weak (transitional layer). Silty Clay Loam (ZCL).	A7 - 0.2 - 0.6	
			1.0		CL	Silty clay, red/brown 2.5YR 2.5/4, very fine to fine grained, well sorted, well graded, no organics, no gravel, firm. Light Clay (LC).	A7 - 0.6 - 1.3	
			1.5		CL-CH	Silty clay, red/brown 10R 3/4, very fine to fine grained, well sorted, well graded, no organics, no gravel, clear crystal salt inclusions (Gypsum?), very firm. Medium Clay (MC).	A7 - 1.3 - 1.7	

Borehole A7 terminated at 1.7m

BOREHOLE NUMBER A9

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Assessment of Mulga Root Architecture
PROJECT NUMBER 12312
PROJECT LOCATION Cloudbreak

DATE STARTED 14/5/12 **COMPLETED** 14/5/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Onslow Contracting
EASTING 738649
NORTHING 7527810
EQUIPMENT Backhoe
HOLE LOCATION Area 9
HOLE SIZE 3.2 m
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH					ML	Silty, gravelly clay, red/brown 2.5YR 2.5/3, very fine to medium grained, poorly sorted, moderately graded, some organics, gravel rounded, weak to firm, some surface flakes. Silty Loam (ZL).	A9 - 0.0 - 0.2	No odour at any depth. Landscape: Open stoney Mulga grove, some areas of surface flakes.
					CLS	Silty clay with minor gravel, brown/red to rust 10R 3/6, very fine to coarse grained, poorly sorted, poorly graded, no organics, gravel partially rounded, firm, moderately cemented. Clayey Sand (CS).	A9 - 0.2 - 0.5	
			0.5		CLS	Gravel and cobbles with silty clay, red/brown 10R 3/4, very fine to very coarse grained, moderately sorted, well graded, no organics, firm, moderately cemented. Clayey Sand (SC) Hardpan.	A9 - 0.5 - 1.1	
			1.0		CLS	Silty clay with some gravel, red/brown 10R 3/6, very fine to medium grained, poorly sorted, moderately graded, some organics, gravel rounded, weak, moderately cemented, grading to cobbles at depth. Clayey Sand (CS) Hardpan.	A9 - 1.1 - 1.7	
			1.5					

Borehole A9 terminated at 1.7m

BOREHOLE NUMBER A11

Astron Soil and Water

CLIENT Fortescue Metals Group Limited	**PROJECT NAME** Assessment of Mulga Root Architecture
PROJECT NUMBER 12312	**PROJECT LOCATION** Cloudbreak

DATE STARTED 11/5/12 **COMPLETED** 11/5/12	**R.L. SURFACE**	**DATUM**	
DRILLING CONTRACTOR Onslow Contracting	**EASTING** 738063	**NORTHING** 7525930	
EQUIPMENT Backhoe	**HOLE LOCATION** Area 11		
HOLE SIZE 3.2 m	**LOGGED BY** T.D.	**CHECKED BY** T.D.	
NOTES			

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH					ML	Silty clay with some gravel, brown/red 2.5YR 3/3, very fine to coarse grained, moderately sorted, well graded, abundant organics, gravel slightly rounded, weak. Silty Loam (ZL).	A11 - 0.0 - 0.25	No odour at any depth. Landscape: Dense marsh mulga grove, grassy understorey.
			0.5		CL	Silty, gravelly clay, brown/red 2.5YR 3/6, very fine to very coarse grained, moderately sorted, well graded, few organics, gravel slightly rounded, weak. Clay Loam (CL).	A11 - 0.25 - 0.8	
			1.0		GW-GC	Cemented clay with cobbles, brown/red 2.5YR3/6, very fine to very coarse grained, poorly sorted, well graded, cobbles partially rounded, moderately cemented, very firm. Hardpan.	A11 - 0.8 - 1.1	
					GW-GC	Cemented calcrete/clay with cobbles, brown/red 2.5YR 3/6, poorly sorted, well graded, no organics, cobbles partially rounded, very strong, strongly cemented. Hardpan.	A11 - 1.1 - 1.4	

Borehole A11 terminated at 1.4m

BOREHOLE NUMBER A12

Astron Soil and Water

CLIENT Fortescue Metals Group Limited		**PROJECT NAME** Assessment of Mulga Root Architecture	
PROJECT NUMBER 90941		**PROJECT LOCATION** Christmas Creek	
DATE STARTED 17/4/12	**COMPLETED** 17/4/12	**R.L. SURFACE**	**DATUM**
DRILLING CONTRACTOR Onslow Contracting		**EASTING** 763380	**NORTHING** 7524253
EQUIPMENT Backhoe		**HOLE LOCATION** Area 12	
HOLE SIZE 3.2 m		**LOGGED BY** T.D.	**CHECKED BY** T.D.
NOTES			

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH					CL	Silty, gravelly clay, brown/red 2.5 YR 2.5/4, very fine to medoum grained, well sorted, well graded, some organics, gravel rounded. Silty Clay (SC).		No odour at any depth. Landscape:Mulga grove consisting of small trees, open stoney flat, some ground cover (including; grasses and shrubs).
			0.5		CLG	Silty clay, with some gravel, brown/red 2.5YR 3/6, very fine to mesium grained, well sorted, well graded, few organics, gravel partially rounded. Light Clay (LC).		
			1.0		CL-CH	Silty, gravelly clay, graiding to silty clay with cobbles 50 - 90mm,brown/red 10R 3/6, very fine to coarse grained, well sorted, well graded, no organics. Light Medium Clay (LMC).		
			1.5					

Borehole A12 terminated at 1.5m

BOREHOLE NUMBER A16

Astron Soil and Water

CLIENT	Fortescue Metals Group Limited	**PROJECT NAME**	Assessment of Mulga Root Architecture
PROJECT NUMBER	90941	**PROJECT LOCATION**	Christmas Creek

DATE STARTED	13/4/12	**COMPLETED**	13/4/12	**R.L. SURFACE**		**DATUM**	
DRILLING CONTRACTOR	Onslow Contracting			**EASTING**	775401	**NORTHING**	7517285
EQUIPMENT	Backhoe			**HOLE LOCATION**	Area 16		
HOLE SIZE	3.2 m			**LOGGED BY**	T.D.	**CHECKED BY**	T.D.
NOTES							

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH					GC	Silty clay with minor gravel, brown/red 2.5YR 3/6, fine to coarse grained, well sorted, well graded, some organics, gravel has rounded edges, low plasticity. Sandy Loam (SL)	A16 - SS1 - 0.0 - 0.4	No odour at any depth. Landscape: flat Mulga grove, no obvious drainage channels.
			0.5		GC	Silty, gravelly clay, brown/red 2.5YR2.5/4, fine to coarse grained, well sorted, well graded, no organics, low plasticity. Sandy Loam (SL)	A16 - SS2 - 0.4 - 1.0	
			1.0		GC	Gravelly, silty clay, brown-red/rusty 2.5YR 3/6, fine to coarse grained, poorly sorted, moderately graded, no organics, low plastisity. Sandy Loam (SL).	A16 - SS3 - 1.0 - 1.3	
			1.5		GC	Sandy, silty, gravelly clay, brown-red/rusty 10R 4/6, fine to coarse grained, moderately sorted, moderately graded, no organics, moderately concreted, moderate plastisity. Sandy Clay Loam (SCL)	A16 - SS4 - 1.3 - 1.5	

Borehole A16 terminated at 1.5m

Astron Soil and Water

BOREHOLE NUMBER A18

CLIENT Fortescue Metals Group Limited
PROJECT NAME Assessment of Mulga Root Architecture
PROJECT NUMBER 90941
PROJECT LOCATION Christmas Creek

DATE STARTED 11/4/12 **COMPLETED** 11/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Onslow Contracting
EASTING 776666
NORTHING 7519372
EQUIPMENT Backhoe
HOLE LOCATION Area 18
HOLE SIZE 3.2 m
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH					CL	Silty clay surface flakes, brown/red 2.5YR 4/6, very fine to fine grained, well sorted, well graded, some organics, low plasticity, not compacted.	A18 - SS1 - 0.0 - 0.005	No odour at any depth. Landscape: Flat mulga grove located in between two creeks.
					CL	Silty clay with some gravel, brown/red 2.5YR 4/8, very fine to fine grained, well sorted, poorly graded, gravel moderately rounded, no organics, low plasticity, slightly compacted, firm to hard setting.	A18 - SS2 - 0.005 - 0.2	
					CL	Silty, sandy clay, brown/red 2.5YR 4/8, very fine to medium grained, well sorted, moderately graded, no organics, high plasticity, moderately compacted.	A18 - SS3 - 0.2 - 0.4	
			0.5		CL	Silty, sandy clay, brown/red 2.5YR 4/8, very fine to medium grained, well sorted, moderately graded, no organics, high plasticity, very compacted.	A18 - SS4 - 0.4 - 0.75	
			1.0		GC	Silty clay with rounded alluvial transported rock fragments, brown/red 10R 3/4, very fine to coarse grained, well sorted, moderately graded, no organics, low plasticity, slightly compacted.	A18 - SS5 - 0.75 - 1.0	

Borehole A18 terminated at 1m

BOREHOLE NUMBER A19

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Assessment of Mulga Root Architecture
PROJECT NUMBER 90941
PROJECT LOCATION Christmas Creek

DATE STARTED 12/4/12 **COMPLETED** 12/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Onslow Contracting
EASTING
NORTHING
EQUIPMENT Backhoe
HOLE LOCATION Area 19
HOLE SIZE 3.2 m
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH					GC	Silty clayey gravel, brown/red 2.5YR 3/4, very fine to coarse grained, poorly sorted, poorly graded, some organics, moderate to low plasticity, not compacted, gravel moderately rounded. Silty clay loam (ZCL).	A19 - SS1 - 0.0 - 0.025	No odour at any depth. Landscape: Flat mulga grove in open stoney plane, low shrubs present.
					GM	Gravelly, silty clay, brown/red 10R 3/4, very fine to coarse grained, moderately sorted, well graded, some (little) organics, moderately compacted, moderate plasticity, gravel rounded. Light clay (LC).	A19 - SS2 - 0.025 - 0.45	
			0.5		CL	Silty, clay, brown/red 10R 3/4, very fine to fine grained, well sorted, well graded, no organics, high plasticity, highly compacted and hard to break apart. Light-medium clay (LMC).	A18 - SS3 - 0.45 - 1.2	
			1.0		CL	Silty clay, dark red/brown 2.5YR 3/4, very fine to fine grained, well sorted, well graded, gravel slightly rounded, moderately compacted but can be broken apart easily, some calcrete nodules. Light-medium Clay (LMC).	A18 - SS4 - 1.2 - 1.5	
			1.5					

Borehole A19 terminated at 1.5m

BOREHOLE NUMBER A20

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Astron Soil and Water

CLIENT Fortescue Metals Group Limited

PROJECT NAME Assessment of Mulga Root Architecture

PROJECT NUMBER 90941

PROJECT LOCATION Christmas Creek

DATE STARTED 14/4/12 **COMPLETED** 14/4/12

R.L. SURFACE

DATUM

DRILLING CONTRACTOR Onslow Contracting

EASTING 778171

NORTHING 7518135

EQUIPMENT Backhoe

HOLE LOCATION Area 20

HOLE SIZE 3.2 m

LOGGED BY T.D.

CHECKED BY T.D.

NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH			0.5		GM	Silty, gravelly clay, brown/red 2.5YR 2.5/4, well sorted, well graded, some organics, rounded gravel, low plastisity. Sandy Loam (SL).	A20 - SS1 - 0.0 - 0.55	No odour at any depth. Landscape: Flat mulga grove with drainage channels either side, soil surface flakey to stoney with organics.
					CL	Silty clay, brown-red/rusty 2.5YR 3/6, very fine grained to fine grained, well sorted, well graded, no organics. Light Medium Clay (LMC).	A20 - SS2 - 0.55 - 0.9	
			1.0 1.5		GC	Silty, gravelly caly, graiding to silty, clayey rock fragments 70-100 mm, Brown/red 2.5YR 3/6, fine to coarse grained, well sorted, well graded, no organics, moderate plastisity. Light Medium Clay (LMC).	A20 - SS3 - 0.9 - 1.6	

Borehole A20 terminated at 1.6m

BOREHOLE NUMBER A21

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Assessment of Mulga Root Architecture
PROJECT NUMBER 90941
PROJECT LOCATION Christmas Creek

DATE STARTED 15/4/12 **COMPLETED** 15/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Onslow Contracting
EASTING 780245
NORTHING 7517037
EQUIPMENT Backhoe
HOLE LOCATION Area 21
HOLE SIZE 3.2 m
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH					CL	Silty clay, brown/red 2.5YR 3/4, fine to medium grained, moderately sorted, well graded, some organics, grave moderately rounded. Sandy Loam (SL).	A21 - SS1 - 0.0 - 0.3	No odour at any depth. Landscape: Large, irregular mulga grove, evidence of some ponding but no creeks/drainage.
			0.5		CL	Silty clay, brown/red 2.5YR 3/6, very fine to medium grained, moderately sorted, well graded, no organics. Light - Medium Clay (LMC).	A21 - SS2 - 0.3 - 0.8	
			1.0 1.5		GC	Silty, Clayey gravel/cobbles, brown/red 2.5YR 2.5/4, fine to coarse grained, moderately sorted, well graded, no organics. Sandy Loam (SL).	A21 - SS3 - 0.8 - 1.6	

Borehole A21 terminated at 1.6m

BOREHOLE NUMBER A24

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Astron Soil and Water

CLIENT Fortescue Metals Group Limited

PROJECT NAME Assessment of Mulga Root Architecture

PROJECT NUMBER 90941

PROJECT LOCATION Christmas Creek

DATE STARTED 12/4/12 **COMPLETED** 12/4/12

R.L. SURFACE

DATUM

DRILLING CONTRACTOR Onslow Contracting

EASTING 778236

NORTHING 7514489

EQUIPMENT Backhoe

HOLE LOCATION Area 24

HOLE SIZE 3.2 m

LOGGED BY T.D.

CHECKED BY T.D.

NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH					GC	Silty clayey gravel, brown/red 5YR 3/4, very fine to coarse grained, moderately sorted, moderately graded, some organics. Sandy Loam (SL).	A24 - SS1 - 0.0 - 0.1	No odour at any depth. Landscape: Flat mulga grove in open stoney plane, low shrubs present.
			0.5		GC	Silty clay with minor gravel, brown/red 2.5YR 3/4, very fine to coarse grained, moderately sorted, poorly graded. Sandy Loam (SL).	A24 - SS2 - 0.1 - 0.6	
			1.0		GC	Silty, clayey rock fragments, brown/red 2.5YR 3/6, very fine to coarse grained, moderately sorted, poorly graded. Light - Sandy Clay Loam (SCL).	A24 - SS3 - 0.6 - 1.35	

Borehole A24 terminated at 1.35m

BOREHOLE NUMBER A26

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Assessment of Mulga Root Architecture
PROJECT NUMBER 90941
PROJECT LOCATION Christmas Creek

DATE STARTED 13/4/12 **COMPLETED** 13/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Onslow Contracting
EASTING 779238
NORTHING 7513949
EQUIPMENT Backhoe
HOLE LOCATION Area 26
HOLE SIZE 3.2 m
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH					CL	Grass covered silty, gravelly clay, brown/red 2.5YR 3/4, very fine to coarse grained, moderately sorted, moderately graded, abundant organics, moderately rounded gravel. Sandy Clay Load (SCL).	A26 - SS1 - 0.0 - 0.1	No odour at any depth. Landscape: Drainage line adjacent to stoney plains, slightly depressed below adjacent land surface.
					CL	Silty clay with minor gravel, brown/red 2.5YR 3/6, Very fine to coarse grained, moderatels sorted, poorly graded, moderately rounded gravel. Light CLay (LC)	A26 - SS2 - 0.1 - 0.3	
			0.5		GC	Silty clay with gravel/rock fragments, brown/red 2.5YR 4/4, very fine to very coarse grained, moderately sorted, well graded, no organics, gravel/rock fragements rounded. Light to Light Medium Clay (LC to LMC).	A26 - SS3 - 0.3 - 0.9	
			1.0		GC	Silty clay with gravel/rock fragments, brown/red 2.5YR4/6, very fine to coarse grained, no organics, gravel/rock rounded, weakly to moderately cemented (1-2). Light Medium Clay (LMC).	A26 - SS4 - 0.9 - 1.25	

Borehole A26 terminated at 1.25m

BOREHOLE NUMBER A31

Astron Soil and Water

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CLIENT Fortescue Metals Group Limited

PROJECT NAME Assessment of Mulga Root Architecture

PROJECT NUMBER 90941

PROJECT LOCATION Christmas Creek

DATE STARTED 13/4/12 **COMPLETED** 13/4/12

R.L. SURFACE

DATUM

DRILLING CONTRACTOR Onslow Contracting

EASTING 774607

NORTHING 7516190

EQUIPMENT Backhoe

HOLE LOCATION Area 31

HOLE SIZE 3.2 m

LOGGED BY T.D.

CHECKED BY T.D.

NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH					GC	Silty clay with some gravel, brown/red 2.5YR 3/4, very fine to coarse grained, moderately sorted, moderately graded, some organics, gravel moderately rounded, surface flaking. Silty Loam (SL).	A31 - SS1 - 0.0 - 0.1	No odour at any depth. Landscape: broad samphire flat.
					GC	Silty clay, brown-red/rusty 2.5YR 3/4, very fine to coarse grained, well sorted, well graded, no organics. Silty Loam (SL).	A31 - SS2 - 0.1 - 0.3	
			0.5		CL	Silty clay with some gravel, brown/red 2.5YR 4/6, very fine to coarse grained, rounded gravel, no organics. Clay Loam (CL).	A31 - SS3 - 0.3 - 0.9	
			1.0		GC	Sandy, silty gravel with minor clay, brown/red 2.5YR 4/6, poorly sorted, moderately graded, no organics, partially concreted hard pan.	A31 - SS4 - 0.9 - 1.25	

Borehole A31 terminated at 1.25m

BOREHOLE NUMBER A32 - M1

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Astron Soil and Water

CLIENT Fortescue Metals Group Limited

PROJECT NAME Assessment of Mulga Root Architecture

PROJECT NUMBER 90941

PROJECT LOCATION Christmas Creek

DATE STARTED 15/4/12 **COMPLETED** 15/4/12

R.L. SURFACE

DATUM

DRILLING CONTRACTOR Onslow Contracting

EASTING 781498

NORTHING 7516745

EQUIPMENT Backhoe

HOLE LOCATION Area 32

HOLE SIZE 3.2 m

LOGGED BY T.D.

CHECKED BY T.D.

NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH					CL	Silty clay, brown/red 2.5YR 3/6, very fine to medium grained, well sorted, well graded, no organics. Clay Loam (CL).		No odour at any depth. Landscape: Sparse stoney flat, no evidence of drainage, few trees, some grasses and shrubs.
			0.5					
					CL-CH	Silty clay with very minor gravel, brown/red 10R 3/4, very fine to medium grained, well sorted, well graded, no organics. Light Medium Clay (LMC).		
			1.0					
					SC	Sand, silty, gravelly clay, brown/red 2.5YR 3/6, very fine to medium grained, moderately sorted, well graded, no organics, rounded gravel. Clayey Sand (CS).		
					CL-CH	Silty clay, brown/red 2.5YR 3/6, very fine to medium grained. well sorted, well graded, no organics. Light Medium Clay (LMC)		
			1.5					

Borehole A32 - M1 terminated at 1.6m

BOREHOLE NUMBER A32 - M2

Astron Soil and Water

CLIENT	Fortescue Metals Group Limited	**PROJECT NAME**	Assessment of Mulga Root Architecture
PROJECT NUMBER	90941	**PROJECT LOCATION**	Christmas Creek

DATE STARTED	15/4/12	**COMPLETED**	15/4/12	**R.L. SURFACE**	
DATUM					
DRILLING CONTRACTOR	Onslow Contracting	**EASTING**	781494	**NORTHING**	7516743
EQUIPMENT	Backhoe	**HOLE LOCATION**	Area 32		
HOLE SIZE	3.2 m	**LOGGED BY**	T.D.	**CHECKED BY**	T.D.
NOTES					

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH					MLS	Silty clay with minor gravel, brown/red 2.5YR 3/4, very vine to medium grained, well sorted, poorly graded, some organics. Silty Loam (SL).		No odour at any depth. Landscape: Sparse stoney flat, no evidence of drainage, few trees, some grasses and shrubs.
			0.5		CL	Silty clay, brown/red 2.5YR 3/6, very fine to medium grained, well sorted, well graded, no organics. Clay Loam (CL).		
			1.0		CL-CH	stoney/gravelly, silty clay, brown/red 10R 3/4, fine to coarse grained, well sorted, poorly graded, no organics, gravel very rounded. Light Clay (LC).		
			1.5					

Borehole A32 - M2 terminated at 1.5m

BOREHOLE NUMBER A33

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Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Assessment of Mulga Root Architecture
PROJECT NUMBER 90941
PROJECT LOCATION Christmas Creek

DATE STARTED 16/4/12 **COMPLETED** 16/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Onslow Contracting
EASTING 780680
NORTHING 7514654
EQUIPMENT Backhoe
HOLE LOCATION Area 33
HOLE SIZE 3.2 m
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
BH					CL	silty, gravelly clay, brown/red 2.5YR 3/6, fine to coarse grained, well sorted, well graded, some organics. Silty Clay Loam (ZCL).		No odour at any depth. Landscape: Flat open stoney plain, isolated mulga with a sparce understorey.
			0.5		CL	Silty clay, brown/red 10R 4/6, fine to medium grained, well sorted, well graded. Silty Clay Loam (ZCL).		
			1.0		CL-ML	Silty, gravelly clay, brown/red 2.5YR 3/6, fine to medium grained, well sorted, well graded, with clear, granulater crystal inslusions, dissolvable in water (most likely salt), partially cemented. Silty Loam (ZL).	A33 SS1 - 1.1 - 1.5	
			1.5					

Borehole A33 terminated at 1.5m

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Assessment of Salt Movement from Saline Water Dust Suppression Areas - Cloudbreak

June 2012

Prepared for
Fortescue Metals Group Limited

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Report Reference: 12313-12RevA_120606

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Assessment of Salt Movement from Saline Water Dust Suppression Areas - Cloudbreak

Prepared for
Fortescue Metals Group Limited

Job Number: 12313-12

Reference: 12313-12RevA_120606

Revision Status

Rev	Date	Description	Author(s)	Reviewer
A	06/06/2012	Draft Issued for Client Review	S. Pearse, S. Tsang	R. Archibald

Approval

Rev	Date	Issued to	Authorised by	
			Name	Signature
A	06/06/2012	Draft Issued for Client Review	R. Archibald	[signature]

Abbreviations

Abbreviation	Definition
Cal	Calibration Pit
EC	Electrical Conductivity
EM38	Electromagnetic Induction Meter Model 38
EPA	Environmental Protection Authority
EPBC Act	*Environment Protection and Biodiversity Conservation Act 1999*
GIS	Geographical Information System

Executive Summary

Dust suppression using saline water is a major operational activity with the potential to have an impact on vegetation health. Large salt loads may exist in areas where saline water dust suppression has been occurring over recent months to years, but salt movement away from targeted application sites, primarily haul roads, remains poorly understood. Also, very little is known about the natural salt levels in the areas that surround Fortescue operations, so it is essential that a rigorous baseline study of salt in the landscape is conducted to enable determination of whether salt is accumulating in areas of the landscape adjacent to operational activities where it would not naturally be found. The use of an EM38 (Geonics Ltd, Canada) electromagnetic induction meter can allow for rapid measurement of soil salinity levels over large areas and is a far more cost effective approach than manual techniques; however, when using the EM38 on a new soil type or environment the EM38 needs to be assessed for suitability and calibrated. This investigation determined that the EM38 is suitable for use and provides calibration equations for use to monitor salt at Cloudbreak and Christmas Creek mine sites. The natural level of salt present in the landscape is low in mulga areas close to operational areas, suggesting that any accumulation of salt in the soil as a result of saline water dust suppression activities can be detected if they occur. The Fortescue Marsh is known to be a saline ecosystem and this has been confirmed, although salt levels within were found to be highly variable.

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1 Introduction

Fortescue Metals Group (FMG) is developing the Pilbara Iron Ore and Infrastructure Project, which involves a series of iron ore mines and associated rail and port infrastructure in the Pilbara region of Western Australia. Included in the Pilbara Iron Ore and Infrastructure Project are the Chichester Operations, which have two operating iron ore mines: Cloudbreak and Christmas Creek. Cloudbreak and Christmas Creek mines are located approximately 120 and 110 km north of Newman, respectively, with both located adjacent to the Fortescue Marsh in the central Pilbara region.

Dust suppression using saline water is a major operational activity with the potential to affect vegetation health. Large salt loads are likely to exist in areas where saline water dust suppression has been occurring over recent months to years, but salt movement away from targeted application sites, primarily haul roads, remains poorly understood. Specifically, there is a need to quantify the degree to which salt is transported horizontally and vertically from application areas to adjacent soils that support native vegetation. A finding of low concentrations of salt in surrounding soil (compared to background levels) would indicate that salt is not very mobile under normal conditions and on-going dust suppression using saline water would be unlikely to affect plant health. On the other hand, a finding of high levels of salt would indicate the potential for an impact on plant health and require management interventions to restrict salt movement. There is also interest in understanding salt transport from a mass balance perspective to account for salt losses from the system, i.e. given the amount of salt applied, determining the quantity of salt that remains on roads and in surrounding soil. The current working hypothesis is that applied salt is not very mobile under normal circumstances and is thus, likely to be retained on roads until it is mobilised and distributed to adjacent areas following major rainfall events. Presently very little is known about the natural salt levels in the areas that surround Fortescue operations, so it is essential that a rigorous baseline study of salt in the landscape is conducted to able to determine if salt is accumulating in areas of the landscape adjacent to operational activities where it would not naturally be found.

Salinity levels in soil are typically not uniform and vary with depth. Soil salinity levels can be directly measured by excavating samples from different depths followed by shaking samples with deionised water, then measuring the extracted solution using an electrical conductivity (EC) meter. Excavation of soil pits in the Pilbara, whether by hand or by mechanical means, is time consuming and depending on location can require special permits, and hence it can be a costly process. The use of an EM38 (Geonics Ltd, Canada) electromagnetic induction meter can allow for rapid measurement of soil salinity levels over large areas and is a far more cost effective approach than manual techniques; however, when using this device on a new soil type or in a new environment they need to be calibrated against soil samples analysed for electrical conductivity (EC), and potentially soil moisture levels and other properties. The EM38 has been extensively used in the past for assessing soil salinity levels in agriculture and forestry (Archibald et al 2006; Bennet et al 2009). These devices work by generating an electromagnetic field which is estimated to penetrate to 0.75 m when held horizontally and 1.5 m when held vertically. Presently it is not known whether the high levels of iron and iron stone found in the Pilbara landscape will interfere with the signal generated by an EM38.

The purpose of this project is to:

1. Assess whether the EM38 is a suitable tool for use in the Pilbara to measure soil salinity levels, and to calibrate the EM38 to the soil types surrounding Fortescue operations.

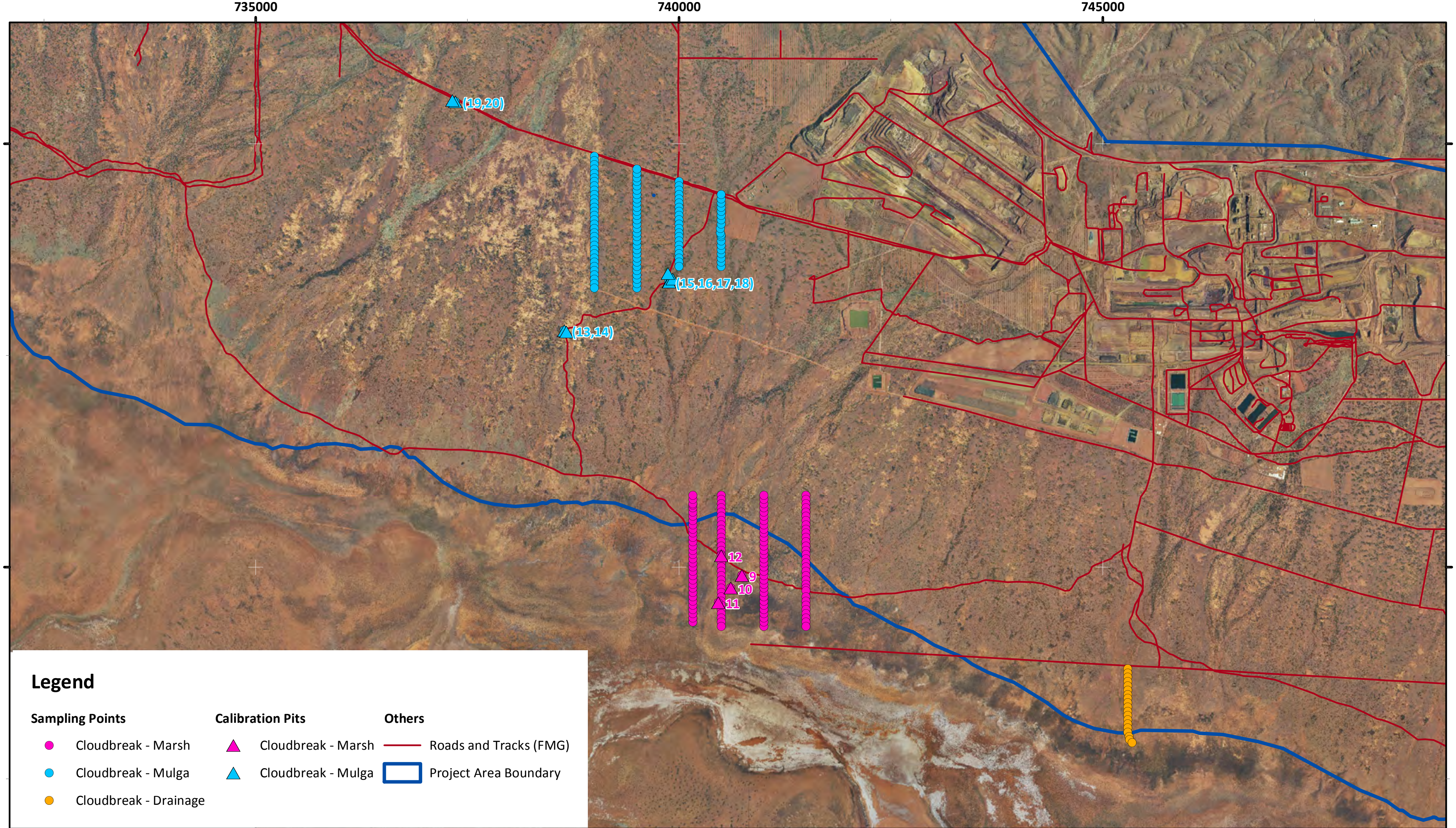
2. Provide a baseline for monitoring salt levels in the environment surrounding Fortescue's operations focusing on mulga and inter-mulga patches, in and around drainage systems and transitional increasing salt levels in proximity to the Fortescue Marsh

2 Methodology

The purpose of the methodology used in this project is to provide rigorous baseline evidence of salt in mulga and inter-mulga patches, in and around drainage systems and transitional areas in proximity to the Fortescue Marsh, which is known to be a saline ecosystem. Field work was completed from the 24th to the 30th of April 2012.

2.1 Site Selection

Sites were selected to provide sufficient representation of the areas of the landscape that surround, or are downstream of, operational areas. Broadly, the sites represent areas of banded mulga and inter-mulga, drainage lined by mulga, the Fortescue Marsh perimeter and samphire dominated areas inside the Marsh. An overview of the sites assessed at Cloudbreak and Christmas Creek mine site can be seen in Fig. 1 and 2 respectively. The sites are broadly grouped as Cloudbreak Mulga (Fig. 3), Cloudbreak Marsh (Fig. 4), Cloudbreak Drainage (Fig. 5) and Cloudbreak Marsh (Fig. 6.). EM38 transects and the location of soil sample pits can be seen in these figures. Soil sample pit locations were chosen to provide a range of salinity levels to allow for assessment of performance of the EM38, as well as provide an understanding of baseline salinity levels and other soil characteristics.



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Assessment of Salt Movement from Saline Water Dust Suppression Areas - Trip 1 - May 2012

Figure 1: Location of EM38 sample points and soil calibration pits – Cloudbreak

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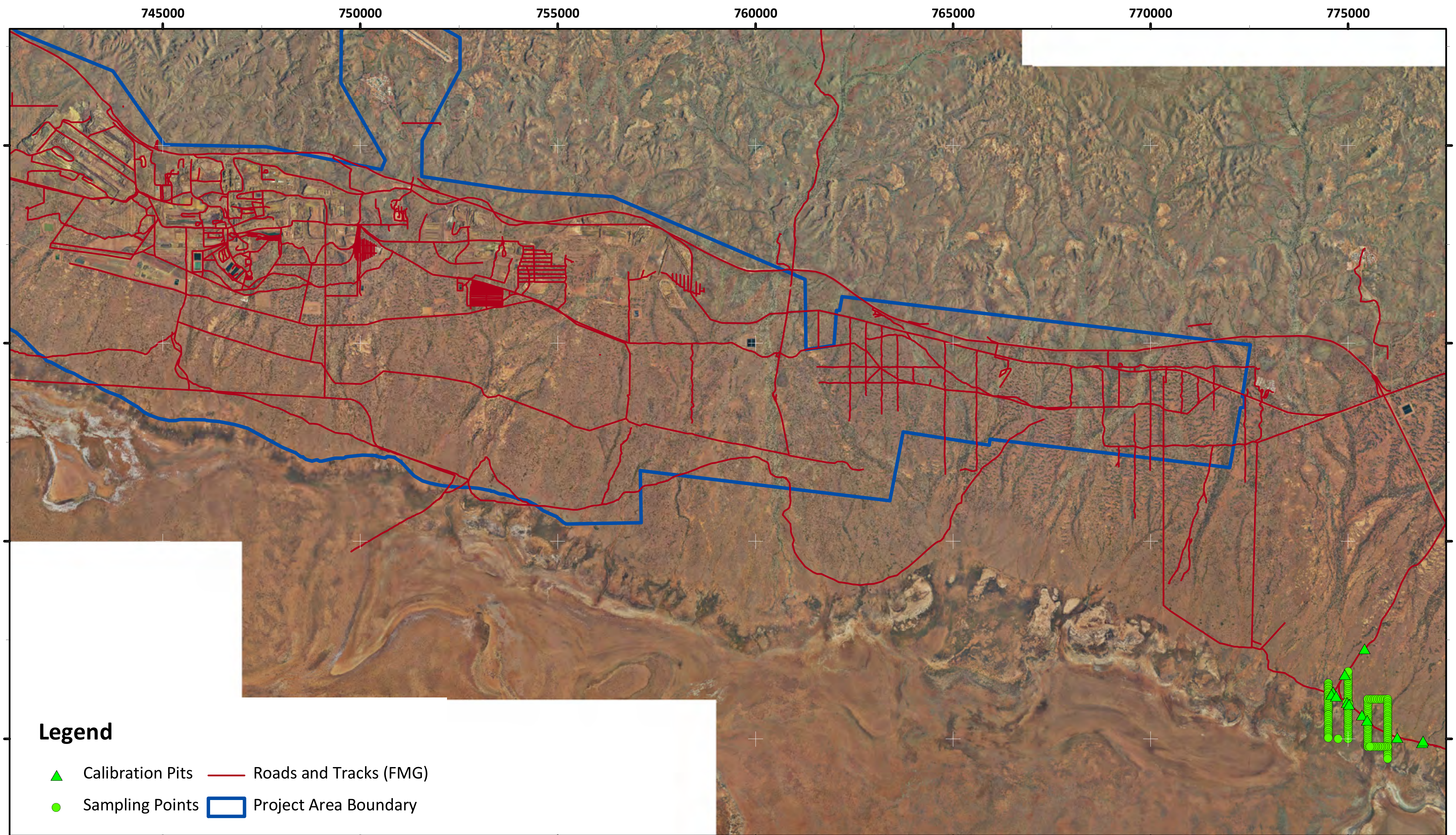
Author: S. Pearse | Drawn: E. Ongee | Date: 30-05-2012 | 12313-12FMV1RevA_120530_Figure_1



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Assessment of Salt Movement from Saline Water Dust Suppression Areas - Trip 1 - May 2012

Figure 2: Location of EM38 sample points and soil calibration pits – Christmas Creek

Datum: GDA 1994

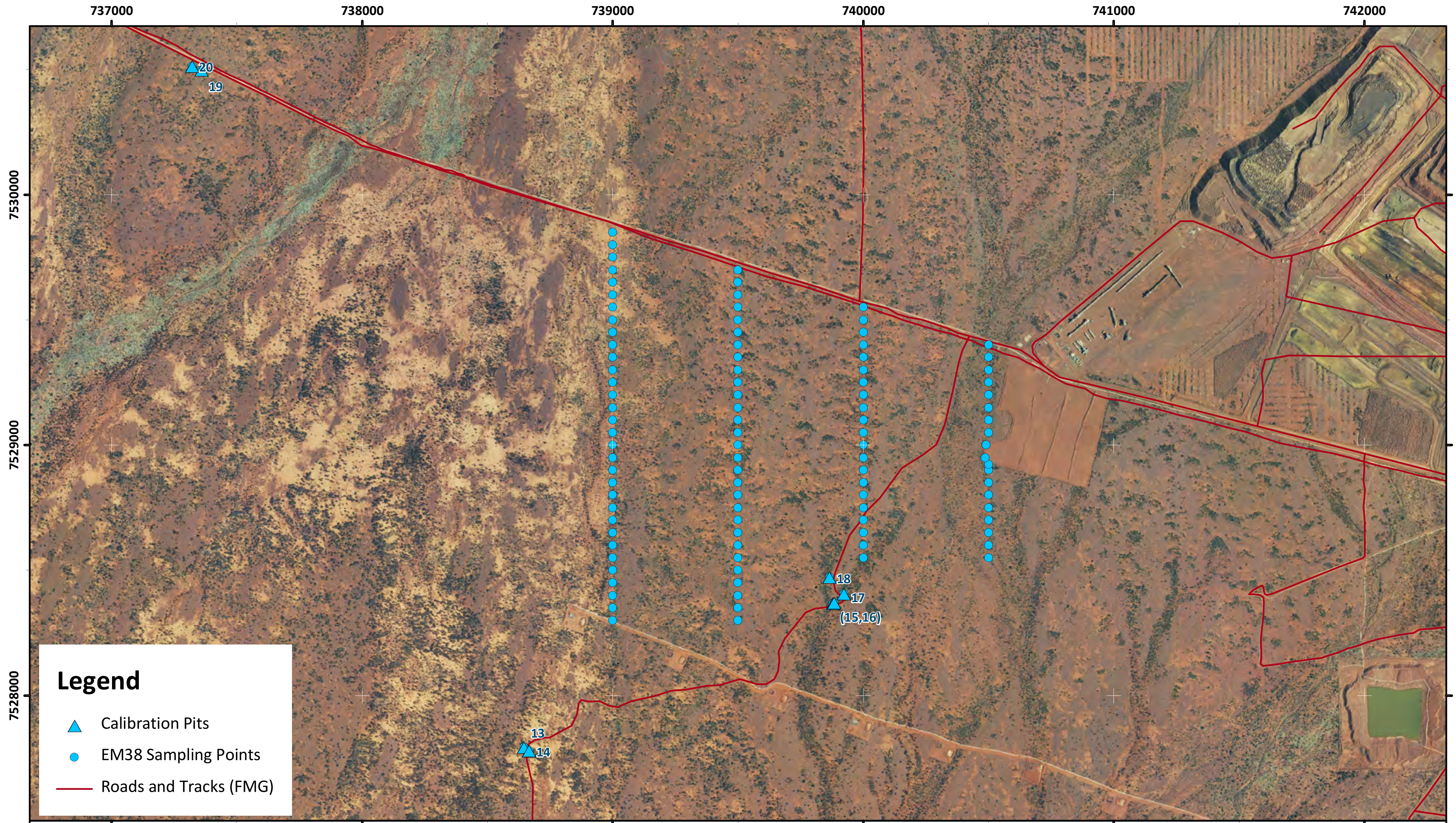
Projection: MGA Zone 50

0 2,500 5,000 Metres

N

astron environmental services

Author: S. Pearse | Drawn: E. Ongee | Date: 30-05-2012 | 12313-12FMV1RevA_120530_Figure_2



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Assessment of Salt Movement from Saline Water Dust Suppression Areas - Trip 1 - May 2012

Figure 3: Location of EM38 sample points and soil calibration pits – Cloudbreak Mulga

Datum: GDA 1994

Projection: MGA Zone 50

0 500 1,000 Metres

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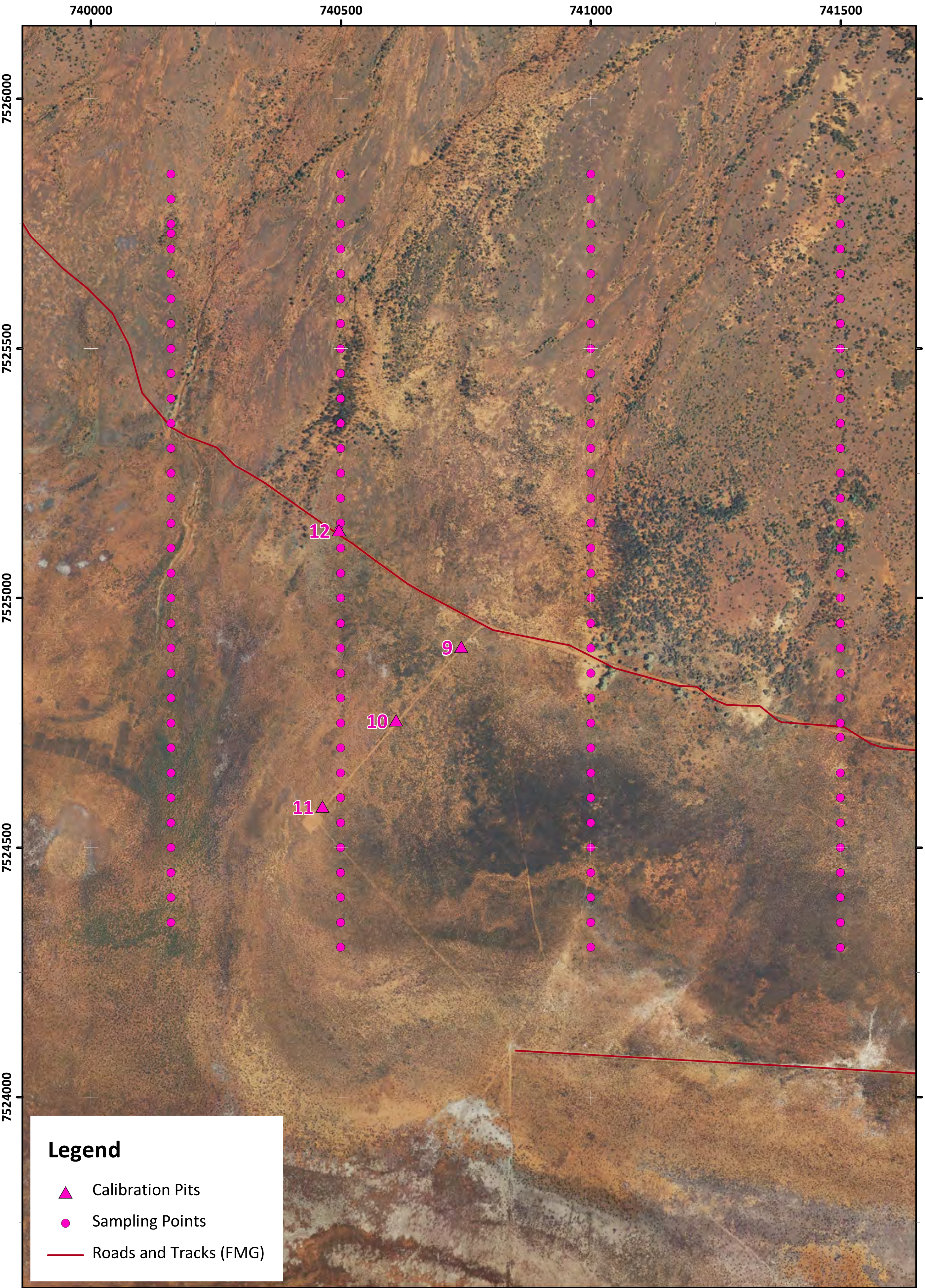
Author: S. Pearse	Drawn: E. Ongee	Date: 30-05-2012	12313-12FMV1RevA_120530_Figure_3



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Assessment of Salt Movement from Saline Water Dust Suppression Areas - Trip 1 - May 2012

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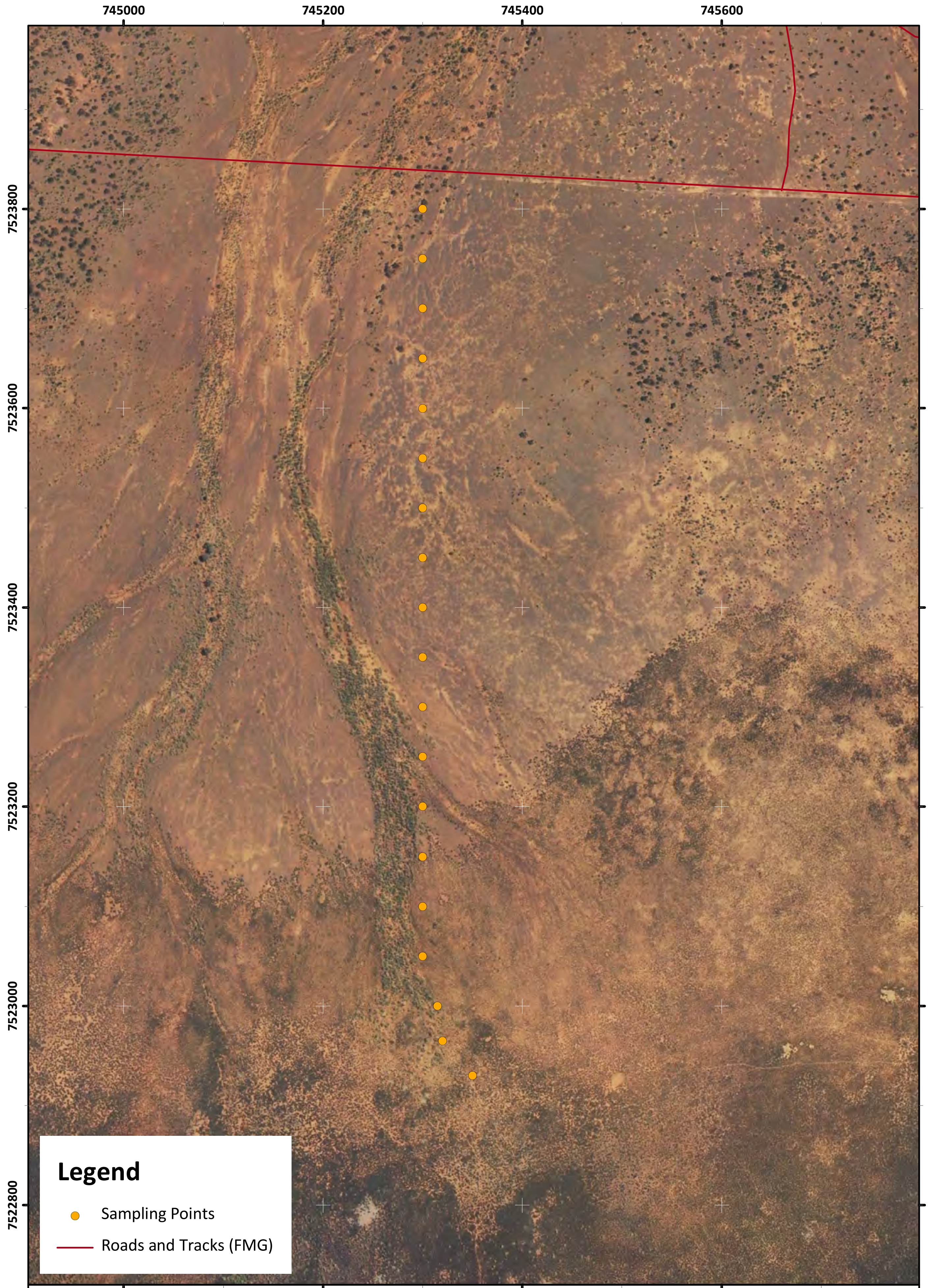
Figure 4: Location of EM38 sample points and soil calibration pits – Cloudbreak Marsh

Author: S. Pearse	Date: 30-05-2012	Datum: GDA 1994 Projection: MGA Zone 50
Drawn: E. Ongee	12313-12FMV1RevA_120530_Figure_4	0 250 500 Metres N



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Assessment of Salt Movement from Saline Water Dust Suppression Areas - Trip 1 - May 2012

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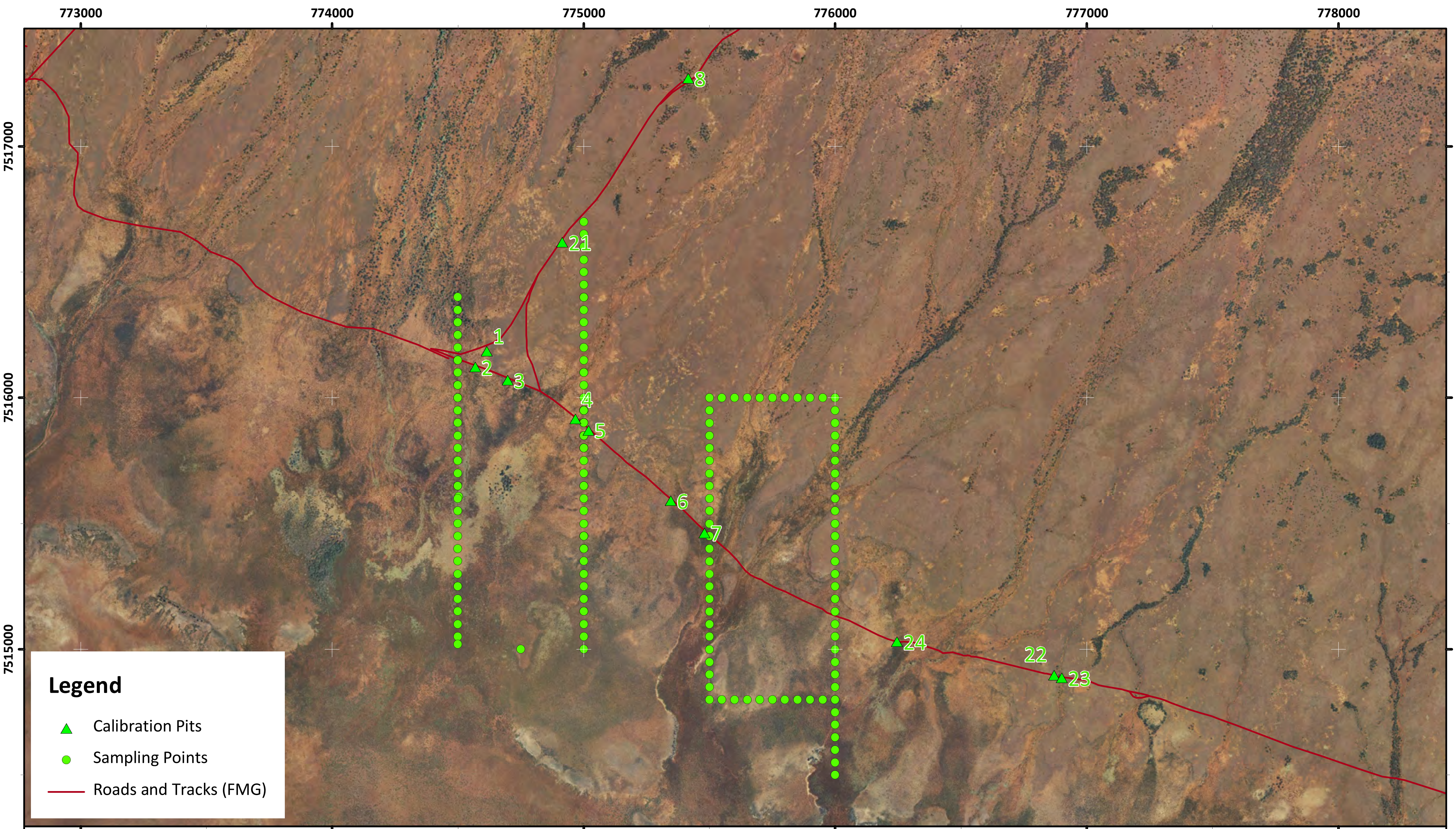
Figure 5: Location of EM38 sample points and soil calibration pits – Cloudbreak Drainage

Author: S. Pearse	Date: DD-MM-YYYY	Datum: GDA 1994 Projection: MGA Zone 50
Drawn: E. Ongee	12313-12FMV1RevA_120530_Figure_5	Metres 0 50 100 200 N



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Assessment of Salt Movement from Saline Water Dust Suppression Areas - Trip 1 - May 2012

Figure 6: Location of EM38 sample points and soil calibration pits – Christmas Creek Marsh

Datum: GDA 1994
Projection: MGA Zone 50

0 250 500 1,000 Metres

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astron environmental services

Author: S. Pearse | Drawn: E. Ongee | Date: 30-05-2012 | 12313-12FMV1RevA_120530_Figure_6

2.2 EM38, Calibration and Transect Measurements

The EM38 (Geonics Ltd, Canada) electromagnetic induction meter was used for all measurements. The EM38 has a maximum sensitivity of 0.4 m if orientated in the vertical mode (effective depth range 1.5 m) and a when used in the horizontal mode maximum sensitivity occurs close to the soil surface (effective depth range 0.75 m). The instrument was calibrated for phasing and zero at the start of each day and after every 15-20 readings according to recommendations by the manufacturer. Sample points were taken every 50 m along an easting or a northing for all EM38 transects. For all points EM38 readings were taken in both the horizontal and vertical mode. Key observations with respect to landscape changes were recorded, as well as GPS coordinates, and a photograph was taken facing south, located 15 m north from the sample point.

2.3 Soil Sampling Pits

A total of 24 soil sample pits (n = 24) were excavated by hand using a shovel, crow bar and trowel to a depth of 0.5 m. Prior to digging each pit, the EM38 (Geonics Ltd, Canada) was recalibrated and an EM38 reading was taken in both horizontal and vertical mode, as well as 4 replicate readings from within a 10 m radius of the pit to ensure the pits were representative of their surroundings. The soil profiles were sampled between the depths of 0-0.1, 0.1-0.2, 0.2-0.35 and 0.35-0.5 m. A sample of approximately 0.5 kg taken from a fresh wall of each profile depth was double bagged inside zip-lock bags and placed in an insulated container.

To compare the robustness of the relationship between hand extraction of samples with laboratory analysis, immediately following completion of the trip a selection of 6 calibration holes were chosen to represent a range in EM38 readings. Samples from 0-0.1 and 0.35-0.5 m were extracted using a hand-shaken 1:5 water extract approach, then measured using a field EC/pH meter.

All samples were sent to a commercial laboratory and analysed for gravimetric moisture content, salinity (1:5 water extract), and pH (1:5 $CaCl_2$ extract). Surface samples (0-0.1 m) were also assessed for salinity (EC paste extract), cation exchange capacity (CEC), exchangeable cations (Na, K, Mg, Ca) and particle size distribution (PSD). Soil sample pit locations were chosen to provide a range of salinity levels to assess the performance of the EM38. Photographs, GPS coordinates and a brief description of the landscape were taken for every pit. The soils were briefly described (colour (Munsell 2009), texture class and coarse fragments) in accordance with the Australian Soil and Land Survey Handbook (NCST 2009) and the Unified Soil Classification System (USCS).

2.4 Data Transformation and Statistics

The statistical analyses considered the response of EM38 readings to the measured EC readings in four different ways. These were:

1. A single vertical reading near the excavation pit.
2. The mean value of vertical readings surrounding the pit (n = 4).
3. A single horizontal reading near the excavation pit.
4. The mean value of horizontal readings surrounding the pit (n = 4).

For each of these response variables, the best predictive model was found by a stepwise linear regression approach: firstly used correlation analysis was used to select the depth which best represented EC(1:5) for all depths. Next, linear regression was used to select the depth at which EC(1:5) best correlated with the EM38 reading. Once the EC(1:5) at this particular depth was included in the statistical model, we then tested whether any readings at other depths contributed to the model. We then tested whether the inclusion of soil moisture significantly improved the model. Finally, further significant contribution of soil chemical variables (Na, Mg, Ca and K) and % clay was tested. The contribution of variables was tested by comparing the Aikake's Information Criteria (AIC) value of the ANOVA models (better models are indicated by lower AIC values) with each variable addition. P values and changes in the R^2 values of models were then examined with the addition of each variable in the models.

We considered one point to be an outlier (EC(1:5) = 1923 mS m^{-1} at soil depth 1, due to surface salt crust), so the above analyses were run with and without this outlier. Because the study of salt in this environment is concerned with addition of salt from recent watering, we also ran a model which specifically looked at the relationship between EC(1:5) at depth 0-0.1 m and the EM38 readings.

Christmas Creek and Cloudbreak, as well as defined areas (Christmas Creek Marsh, Cloudbreak Marsh and Cloudbreak Mulga), and within Cloudbreak Mulga (gravel/cobble and mulga patches) were compared using Permutation Based Multivariate Analysis of Variance (PERMANOVA) based upon all soil characteristics as described in the methods above (Primer-E, Plymouth Marine Laboratory).

3 Results

3.1 EM38 Calibration and Error

EC(1:5) from each of the four soil depths were highly correlated, but with the correlation declining with increasing depth of separation between samples (Table 1).

Table 1: Pearson correlation coefficient of EC(1:5) (mS m-1) sampled from 0-0.1, 0.1-0.2, 0.2-0.35 and 0.35-0.5 m.

Profile depth in m	0-0.1	0.1-0.2	0.2-0.35	0.35-0.5
0-0.1	1.00			
0.1-0.2	0.84	1.00		
0.2-0.35	0.82	0.97	1.00	
0.35-0.5	0.73	0.88	0.94	1.00

EC for both the horizontal and vertical mode of the EM38 were strongly correlated with EC(1:5) (Table 2).

Table 2: Summaries of statistical models testing for relationships between EM38 readings, electrical conductivity (EC1:5) and other soil parameters.

Mode	Number recordings	Model Vars[1]	AIC[2]	Adj. R^2 Var 1[3]	Adj. R^2, Var1 + Var 2[4]	P
Horizontal	At pit (n=1)	EC(0.2-0.35)	299.3	0.848	~	<0.001
Horizontal	Surrounding (n = 4)	EC(0.2-0.35) + EC(0-0.1)	281.4	0.748	0.923	<0.001
Vertical	At pit (n=1)	EC(0.35-0.5) + moisture	291.0	0.879	0.906	<0.001
Vertical	Surrounding (n = 4)	EC(0.35-0.5) + moisture	279.6	0.912	0.937	<0.001

[1] "Model Vars" are the variables which were included in the best statistical model.

[2] "AIC", Aikake's Information Criteria is a measure of model quality, with better models receiving lower scores

[3] "Adj. R^2, Var 1" is the adjusted R^2 value when only the single most important variable is included in the model. R2 is a measure of variation in the response variable explained by the model.

[4] "Adj. R^2, Var 1 +Var 2" is the adjusted R^2 value when the complete two-variable model is considered. This allows the reader to examine the increase in R^2 value once the second variable is included in the model. R^2 is a measure of variation in the response variable explained by the model.

Soil samples EC(1:5) from a single depth range explained between 85 and 91 % of variation in EM38 readings. EC(1:5) at depth 0.35-0.5 m was most strongly associated with measurements in the vertical mode (R^2 = 0.88) and EC(1:5) at shallower depth (0.2-0.35 m) was most strongly associated with measurements in the horizontal mode (R^2=0.85) (Fig. 7).

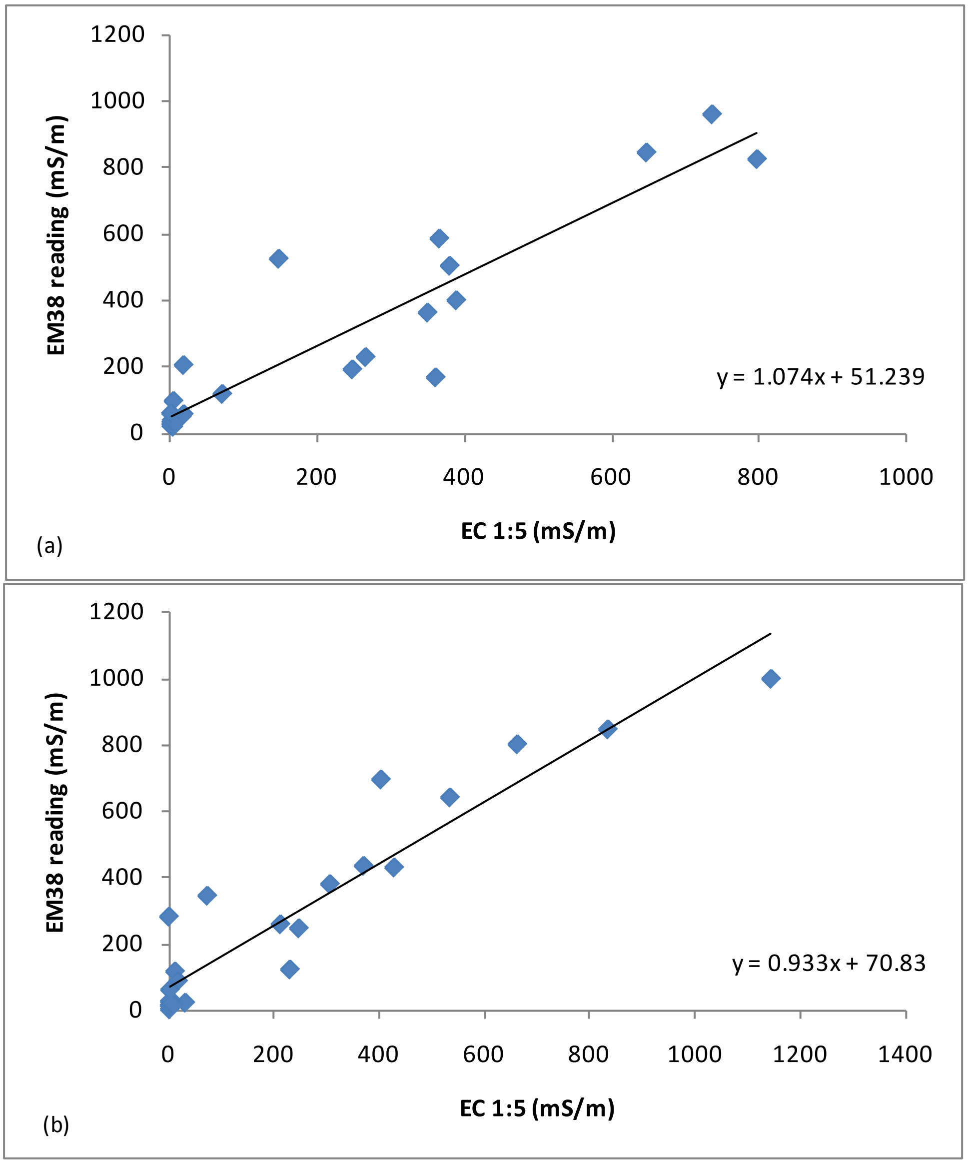

Figure 7: The relationship between EM38 readings and 1:5 water extracted EC (mS m^{-1}) values of the soil sample collected at corresponding calibration points (n=24). The black line represents the linear regression model. (a): EM38 in the horizontal position plotted with EC from depth 0.2-0.35 m (R^2 = 0.85); and (b): EM38 in vertical position EC from soil depth 0.35-0.5 m (R^2 = 0.88).

Taking multiple EM38 readings near a soil pit or including EC(1:5) from multiple depth ranges did not greatly improve the strengths of the relationships (Tables 2; 3).Soil moisture had some influence on EM38 readings in the vertical mode, but it only accounted for a 2.5 – 2.7% increase in variation explained by the models (Table 2). Soil chemistry (Na, Mg, Ca and K) and % clay did not contribute significantly to the model (Table 2) with or without the outlier removed (Table 3).

Table 3: Results with outlier (Cal 6, EC(1:5) = 1923 mS m^{-1} at 0-0.1 m) removed (models for the Vertical mode did not differ from data with outlier included (Table 2))

Mode	Number recordings	Model Vars[1]	AIC[2]	Adj. R^2 Var 1[3]	Adj. R^2, Var[1] + Var 2[4]	P
Horizontal	At pit (n=1)	EC(0-0.1) + EC(0.35-0.5)	280.7	0.739	0.857	<0.001
Horizontal	Surrounding (n = 4)	EC(0-0.1) + EC(0.35-0.5)	270	0.845	0.899	<0.001

[1] "Model Vars" are the variables which were included in the best statistical model.

[2] "AIC", Aikake's Information Criteria is a measure of model quality, with better models receiving lower scores.

[3] "Adj. R^2, Var 1" is the adjusted R^2 value when only the single most important variable is included in the model. R2 is a measure of variation in the response variable explained by the model.

[4] "Adj. R^2, Var 1 +Var 2" is the adjusted R^2 value when the complete two-variable model is considered. This allows the reader to examine the increase in R^2 value when the second variable is included in the model. R2 is a measure of variation in the response variable explained by the model.

If EC at 0-0.1 m is of particular interest, the EM38 readings provide an accurate estimate of soil EC, with 74 and 75% of variation explained by the model (Fig. 8; Table 4).

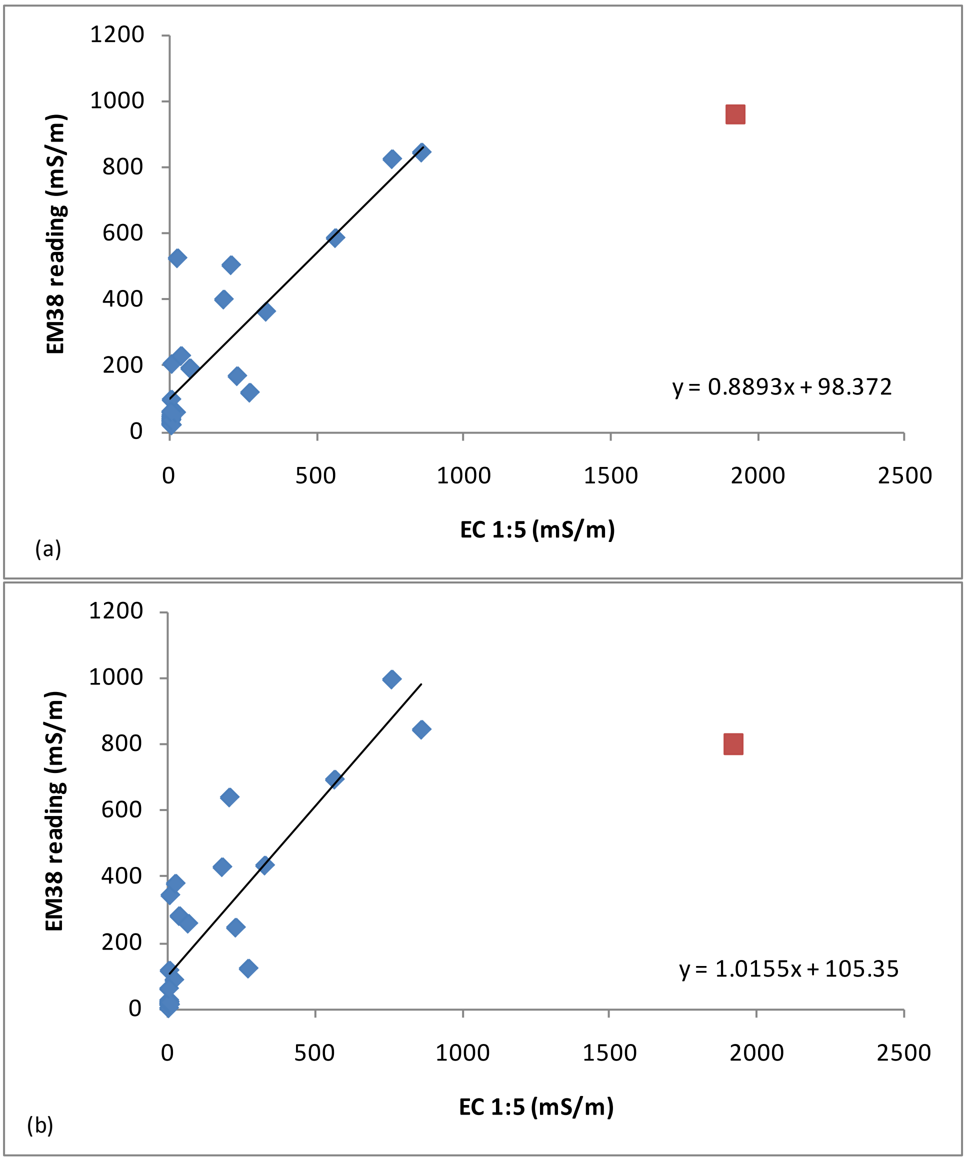

Figure 8. The relationship between EM38 readings and 1:5 water extracted EC (mS m^{-1}) values of soil samples collected from a depth of 0.0-0.1 m at corresponding calibration points (n=24). The black line represents the linear regression model. The red square represents an outlier excluded from the regression where a visible salt crust was present on soil surface. (a): EM38 in the horizontal position (R^2 = 0.74); and (b): EM38 in the vertical position (R^2 = 0.75).

Table 4: Statistical relationship between EC at 0-0.1 m and the EM38 readings.

Mode	Number recordings	AIC[1]	Adj. R^2	P
Horizontal	At pit (n=1)	293.7	0.739	<0.001
Horizontal	Surrounding (n = 4)	279.0	0.845	<0.001
Vertical	At pit (n=1)	298.3	0.752	<0.001
Vertical	Surrounding (n = 4)	294.5	0.770	<0.001

[1] "AIC", Aikake's Information Criteria is a measure of model quality, with better models receiving lower scores.

The results for an assessment of the accuracy of hand shaking 1:5 water extracts and using a hand EC meter to provide a quick assessment of soil salinity, or by using an analytical and more time consuming laboratory approach is provided in Table 5. At very low EC(1:5) concentrations, such as for sample pits Cal 8 and Cal 17, the absolute difference in measurements whether using a field or laboratory approach is inconsequential; however, at moderate to high salinity levels large discrepancies can occur (e.g. Cal 6, 13 and 23). Field-type EC analysis generally resulted in an overestimation of EC for samples from more saline areas of the landscape.

Table 5: Assessment of the accuracy of measuring EC(1:5) by quick field type assessment or by laboratory analysis for samples representing a range of salinity levels taken from a profile depth of 0-0.1 or 0.35-0.5 m. % difference was calculated as follows: ((Laboratory EC – Field EC)/Laboratory EC))*100

	EC (mS m^{-1})							
	Field		Laboratory		Absolute Difference		% Difference	
Pit #	0.0-0.1 m	0.35-0.5 m	0.0-0.1 m	0.35-0.5 m	0.0-0.1 m	0.35-0.5 m	0.0-0.1 m	0.35-0.5 m
Cal 17	3	0	1.9	1.6	1.1	1.6	-57.9	100.0
Cal 8	3	1	2	2.2	1	1.2	-50.0	54.5
Cal 13	4	44	2.2	31.2	1.8	12.8	-81.8	-41.0
Cal 23	70	367	24.4	306	45.6	61	-186.9	-19.9
Cal 10	678	1396	759	1144	81	252	10.7	-22.0
Cal 6	1870	1272	1923	662	53	610	2.8	-92.1

3.2 Landscape, Soil Types and Characteristics

For assessment of soil types and landscape characteristics, three broad landscape types were defined:

1) Two transect and soils sample areas which border the Fortescue Marsh, 'Christmas Creek Marsh', 'Cloudbreak Marsh' which encapsulate an area that extends north from well within within the moist, saline, samphire dominated ecosystem to beyond the samphire border.

The edge of the marsh is occasionally broken by fingers of mulga, as well as slightly elevated cobble/gravel covered open areas covered by sparse shrubs.

2) 'Cloudbreak Mulga' which is a region of banded mulga interspersed with areas of surface cobble/gravel and occasionally mulga which lines shallow drainage depressions.

3) 'Cloudbreak Drainage' which is an area of wide, open cobble/grave with very sparse vegetation occasionally broken by large drainage and washout areas which feed into the Fortescue Marsh.

Statistical analysis determined that there are significant differences in soil characteristics between the areas of Christmas Creek Marsh, Cloudbreak Mulga and Cloudbreak Marsh, and highly significant differences between the Mulga and Marsh areas within the Cloudbreak regional area. Comparing the soil characteristics of gravel/cobble open areas with soil from within mulga stands within the Cloudbreak Mulga area, revealed no significant difference between them (Table 6) .

Table 6: Statistical comparison of regional and local landscape characteristics based on parameters of soil collected from 24 calibration pits.

Comparison	Test	Test Value	P
Christmas Creek and Cloudbreak	PERMANOVA	0.33	0.583
Christmas Creek Marsh, Cloudbreak Mulga and Cloudbreak Marsh	PERMANOVA	3.21	0.046
Mulga and Marsh within Cloudbreak	PERMANOVA	9.25	0.004
Gravel/cobble and Mulga within Cloudbreak Mulga area	PERMANOVA	2.00	0.110

3.3 Salt in the Landscape

The EM38 transects completed in the marsh area at Christmas Creek and Cloudbreak confirmed that the Marsh is far more saline than the Cloudbreak Mulga area (Table 7). Fingers of mulga found extending into the Cloudbreak Marsh area were growing on far more saline soil (EC range 27-527 mS m^{-1}) than those well away from the marsh in the Cloudbreak Mulga area (EC range 1-67 mS m^{-1}) (Table7).

Table 7: Summary of EM38 EC (mS m^{-1}) for transects at Cloudbreak and Christmas Creek including mean, standard deviation, maximum and minimum for measurements taken in the vertical and horizontal mode.

			Vertical (mS m^{-1})				Horizontal (mS m^{-1})			
Site	**Area**	**Cover**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
Cloudbreak	Mulga	Mulga	9	7	1	41	32	9	15	67
Cloudbreak	Marsh	Mulga	243	134	27	489	244	133	38	527
Cloudbreak	Marsh	Samphire	509	352	46	1290	484	387	45	1357
Cloudbreak	Drainage	Drainage	377	113	242	600	341	116	169	539
Christmas Creek	Marsh	Samphire	358	203	40	856	308	232	29	1123

Soil moisture increased with depth at all sites, with the marsh wetter at both Christmas Creek and Cloudbreak. Soil pH was generally slightly acidic in the Cloudbreak Mulga area and slightly alkaline within the marsh (Table 8)

Table 8: Summary of mean soil moisture content (%), pH (1:5 CaCl2) and EC (1:5) for the each profile depth for 24 soil calibration pits grouped by area of origin.

	Soil Depth (m)	Christmas Creek Marsh	Cloudbreak Marsh	Cloudbreak Mulga
% Moisture (g g^{-1})	0.0-0.1	5.1 (4.6)	9.8 (7.9)	3.2 (1.0)
	0.1-0.2	11.1 (5.2)	12.8 (3.4)	7.1 (1.2)
	0.2-0.35	14.3 (4.8)	17.9 (1.7)	8.8 (1.4)
	0.35-0.5	15.7 (5.5)	23.9 (5.6)	8.8 (1.0)
$pH_{1:5}$ ($CaCl_2$)	0.0-0.1	7.0 (1.1)	7.6 (0.5)	5.6 (0.4)
	0.1-0.2	7.5 (0.9)	7.6 (0.2)	5.7 (0.5)
	0.2-0.35	7.7 (0.9)	7.8 (0.3)	6.2 (0.7)
	0.35-0.5	8.0 (0.7)	7.8 (0.4)	6.4 (1.0)
$EC_{1:5}$ (mS m^{-1})	0.0-0.1	448.9 (726.1)	524.8 (332.4)	2.9 (1.2)
	0.1-0.2	198.1 (206.1)	358.1 (282.4)	3.1 (2.5)
	0.2-0.35	241.5 (219.4)	472.9 (318.9)	4.7 (4.7)
	0.35-0.5	227.7 (214.0)	685.5 (392.7)	7.7 (10.0)

The saturation paste method for determining EC confirmed that the Cloudbreak Mulga region is of very low salinity compared to the marsh at Cloudbreak and Christmas Creek. Cation exchange capacity and Exchangeable cations were also generally lower, particularly K. More clay was present in the Cloudbreak Mulga area than in the marsh (Table 9).

Table 9: Summary of EC (paste extract), cation exchange capacity (CEC), exchangeable cations (Ca, Mg, Na and K) and particle size distribution (sand, silt and clay) from 0-0.1 m for 24 soil calibration pits grouped by area of origin.

		Christmas Creek Marsh	Cloudbreak Marsh	Cloudbreak Mulga
	ECe (mS/m)	1709.4 (2739.3)	3465.5 (3588.7)	18.6 (10.8)
	CEC (meq/100g)	20.0 (22.9)	34.9 (21.7)	7.5 (1.4)
Exchangable cations (meq/100g)	Ca	5.0 (4.3)	13.1 (6.0)	5.0 (1.2)
	Mg	2.9 (2.8)	6.5 (4.5)	1.5 (0.4)
	Na	2.1 (1.4)	3.6 (0.7)	0.9 (0.2)
	K	10.0 (18.6)	11.8 (12.1)	0.1 (0.1)
Partical size distribution (%)	Sand	59.0 (22.2)	34.3 (18.2)	47.2 (6.6)
	Silt	29.6 (18.8)	57.9 (21.3)	27.2 (8.9)
	Clay	11.4 (6.6)	7.8 (4.1)	25.6 (8.4)

The EM38 transects revealed large variation in conductivity readings within the Fortescue Marsh both at Christmas Creek (Fig. 9) and Cloudbreak (Fig. 10); however salinity decreased with increasing distance from the marsh. The EM38 readings in the marsh were very similar, whether in the vertical or horizontal mode, suggesting that EC is relatively uniform with depth. This is confirmed in Table 8. The EM38 readings in the Cloudbreak Mulga area were much lower than the marsh, though also variable (Fig. 11). The EM38 readings in the horizontal mode were always higher in the vertical mode, which means that the surface soil is more saline than soil at depth. A transect completed in the Cloudbreak Drainage area was found to have an intermediate salinity range in comparison with other areas (Fig. 12). West to East transects completed at Christmas Creek reinforce the concept that the areas within and near the edge of the Fortescue Marsh are extremely variable in terms of salinity (Fig.13).

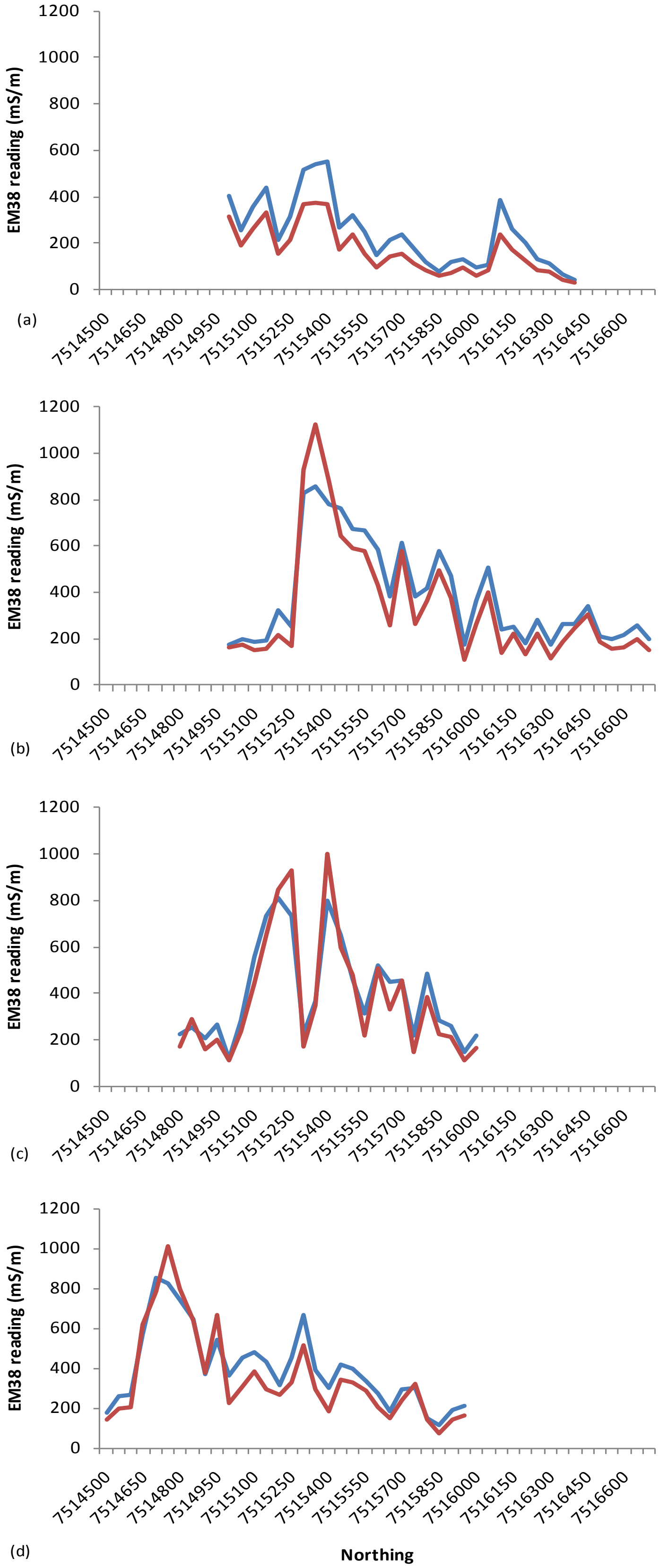

Figure 9. EC (mS m^{-1}) measured by EM38 along transects in the Christmas Creek Marsh area. The blue line represents the EM38 in the vertical position, and the red line in the horizontal position. (a): transect 1, (b): transect 2, (c): transect 12 and (d): transect 14. Figures are arranged from the most western (top) to the most eastern (bottom). From left to right on the x-axis is from south (within Marsh) to north (away from Marsh).

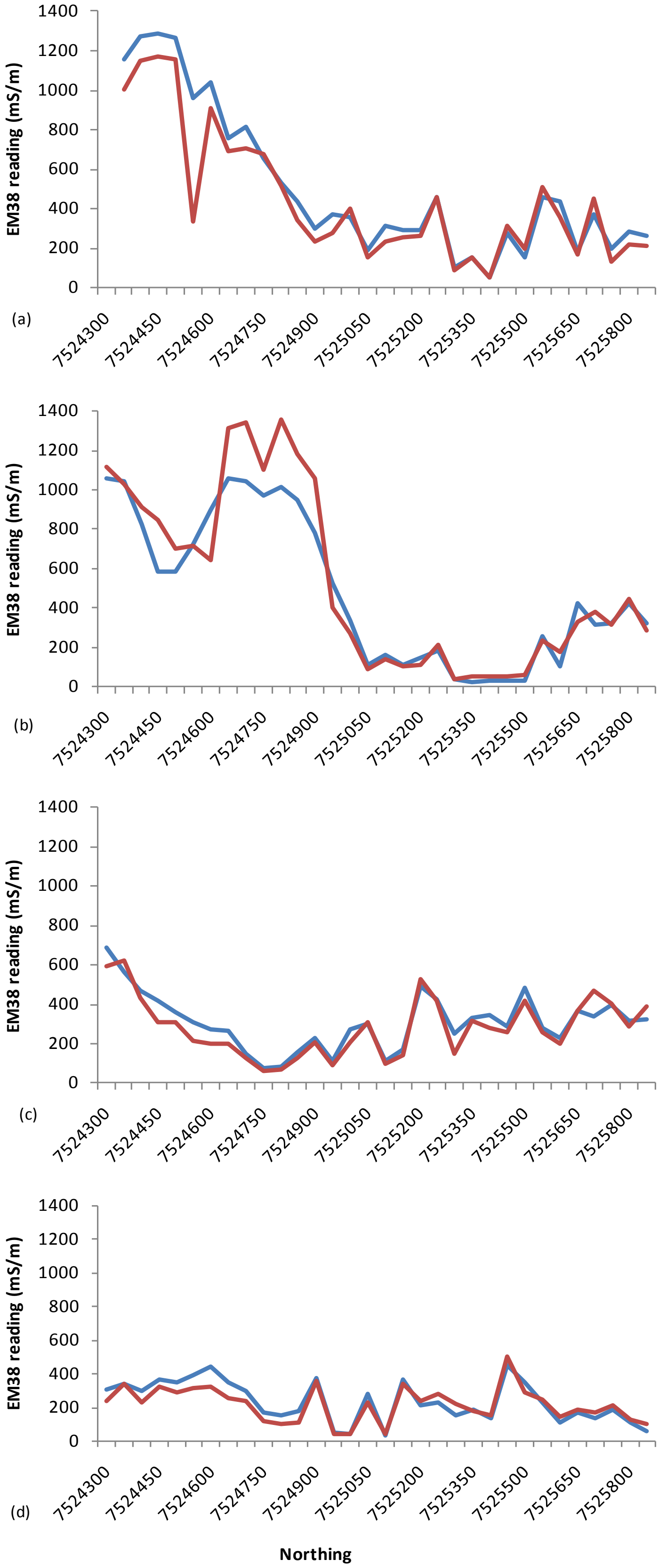

Figure 10. EC (mS m^{-1}) measured by EM38 along transects in the Cloudbreak Marsh area. The blue line represents the EM38 in the vertical position, and the red line in the horizontal position. (a): transect 3, (b): transect 4, (c): transect 5 and (d): transect 6. Figures are arranged from the most western (top) to the most eastern (bottom). From left to right on the x-axis is from south (within Marsh) to north (away from Marsh).

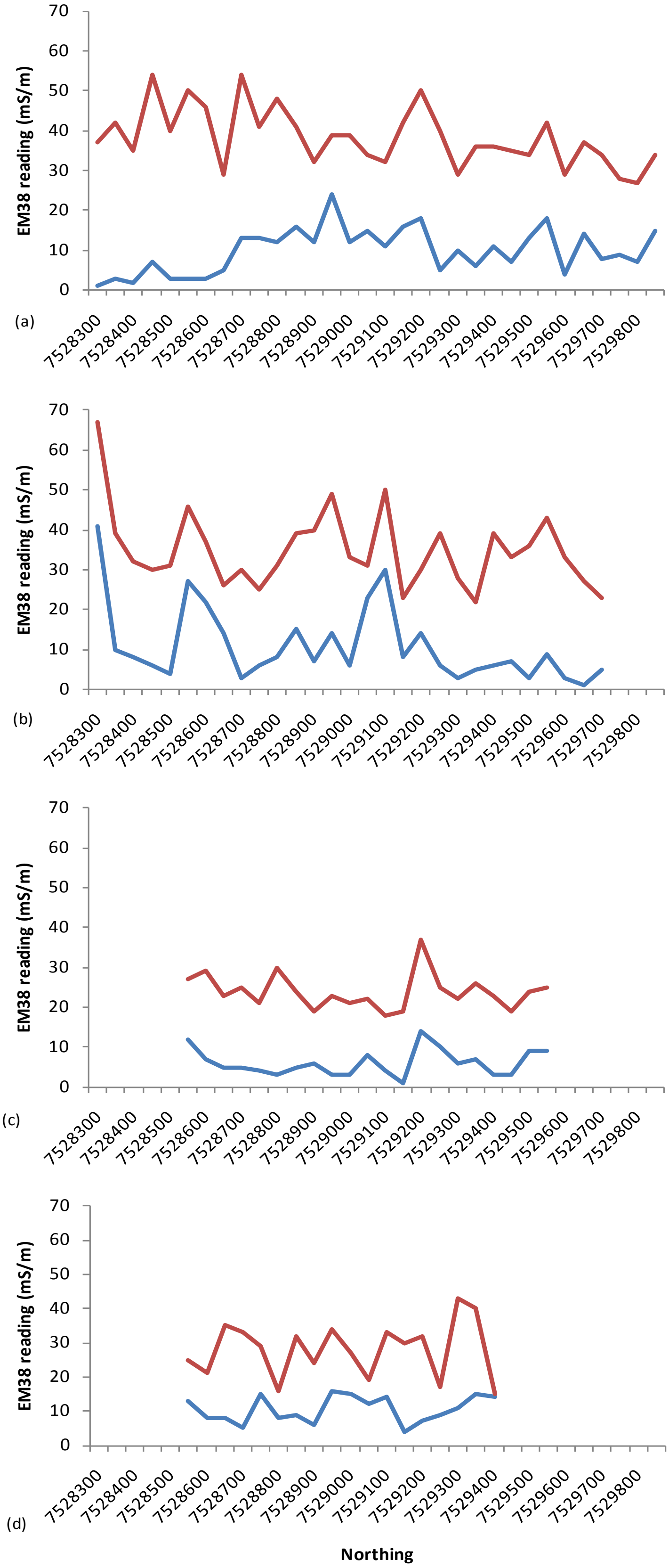

Figure 11. EC (mS m^{-1}) measured by EM38 along transects in the Cloudbreak Mulga area. The blue line represents the EM38 in the vertical position, and the red line in the horizontal position. (a): transect 7, (b): transect 8, (c): transect 9 and (d): transect 10. Figures are arranged from the most western (top) to the most eastern (bottom). From left to right on the x-axis is from south to north (moving away from the Marsh).

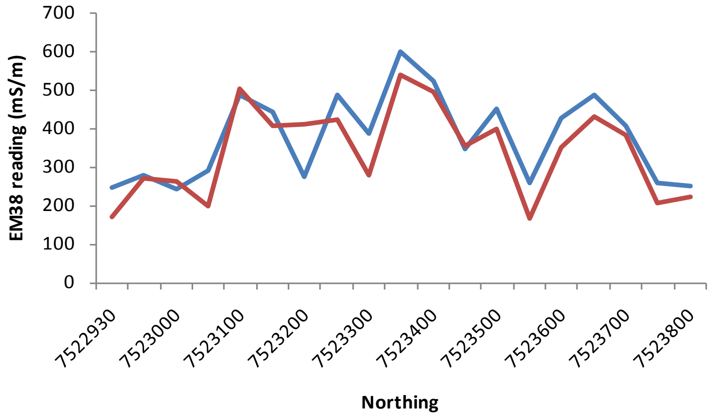

Figure 12. EC (mS m[-1]) measured by EM38 along a transect in the Cloudbreak Drainage area. The blue line represents the EM38 in the vertical position, and the red line in the horizontal position. From left to right of the x-axis is from south to north (moving away from the Marsh).

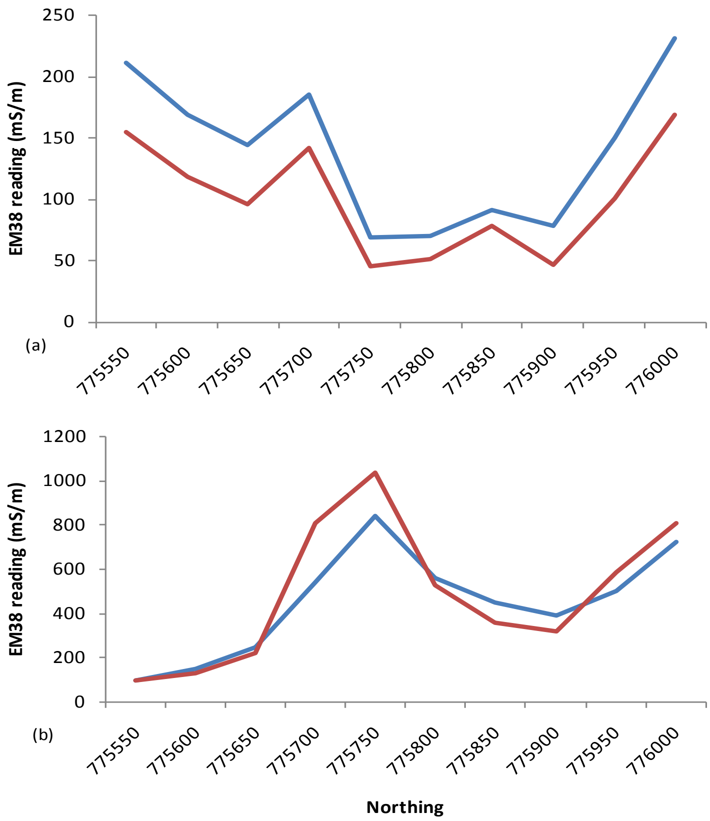

Figure 13. EM38 reading measured by EM38 along transects in the Christmas Creek Marsh area. The blue line represents the EM38 in the vertical position, and the red line in the horizontal position. (a): transect 13 and (b): transect 15. Figures are arranged from north (top – outside the Marsh) to south (bottom – in the Marsh). From left to right on the x-axis is from west to east.

4 Discussion

4.1 EM38 Calibration and Suitability

The EM38 is a suitable tool for use in monitoring salt levels around haul roads. Salt movement from haul roads will be initially evident in the surface (0-0.1 m) profile of the soil. Correlation between the EM38 reading and EC(1:5) in surface salinity was initially much lower than correlations with other depths; however, this was primarily due to a single outlying data point from in the Fortescue Marsh where a visible, thin layer of salt crust was present on the surface of the soil. Removing this outlier from the linear regression resulted in a much stronger correlation, though removing the outlier did not influence the outcome of other parameters tested in the model. Use of the EM38 on areas where salt is crusting on the surface will probably still indicate a high level of salt is present, but may result in an underestimation of EC because the EM38 measure the conductivity within the soil bulk to 1.5 m. Extensive salt crusting is not be expected to occur as a result of application of saline water for dust suppression of haul roads in operational areas because soil salinity levels are not anticipated to be as elevated as in the Fortescue Marsh. Infiltration, particularly around banded mulga, should also leach salt to depth. Consequently, this finding should not be considered a limitation to future monitoring programs, unless future programs are assessing salt levels well within the Fortescue Marsh. If a layer of salt is present on the soil surface in operational areas it should be noted in addition to taking an EM38 reading during future monitoring programs. The biological consequences of a surface encrustation of salt above a soil profile that is low in salt are not known, but would be expected to impact on germination rather than the health of existing plants.

The robustness of a single EM38 sample point being representative of a larger area of the landscape was assessed by regression modelling of the EC of samples from the soil pits with EM38 readings taken from within a 10 m radius of each of the soil pits. The models determined that a single reading provides a good representation of the surrounding area, so taking multiple readings when completing an EM38 transect is unnecessary.

The strongest correlation between the EC(1:5) measured by laboratory analysis and the EM38 readings was for EC(1:5) at profile depth 0.2-0.35 m in the horizontal mode and 0.35-5 m in the vertical mode. In the future, if soil samples are taken for proofing the EM38 readings, taking a sample from 0.2-0.35 m deep in the soil profile can be considered a sufficient representation of the profile. Whilst not as accurate, taking samples from the surface (0-0.1 m) also provides a fair representation of the profile and would be more relevant to assessing salt accumulation resulting from surface application.

After EC(1:5), soil moisture had the most influence on EM38 readings, but this accounted for only an additional 2.5-2.7% of variation explained by the models; all other variables were not significant. In future monitoring programs it will not be worthwhile to sample and analyse for other variables including pH, cation exchange capacity, exchangeable cations (Na, K, Ca, Mg) and particle size distribution because they have only a minor influence on the EM38 reading. This will reduce the cost of future monitoring programs significantly.

4.2 Baseline status of salt in the landscape

The Fortescue Marsh is known as a saline environment, and this investigation confirmed that it was at the time of the survey; however, salinity levels in the marsh are highly variable. The drainage area and areas in close proximity to the marsh are characterised by a moderate level of salinity and presumably are flushed during occasional heavy, cyclonic rainfall events. Low levels of salt were detected in the regions of banded mulga and mulga growing on shallow drainage lines away from the Marsh; many plant species that exist in this environment may not be poorly adapted to tolerating salt. Mulga can be found extending on 'fingers' into the marsh suggesting that mulga possess some tolerance to moderate concentrations of salt, or that these mulga are a more salt tolerant ecotype. Low baseline salinity found in the Cloudbreak Mulga area should allow for detection of a salt signature if salinity was to increase as a result of saline water dust suppression activities.

4.3 Recommendations for future monitoring

Future monitoring programs can use the EM38 as a tool for monitoring whether salt is accumulating in areas where frequent use of saline water for dust suppression is occurring. Soil sampling to verify the EM38 readings is recommended; however, analysis for EC(1:5) is the only critical factor to truth the EM38. Sampling from 0.2-0.35 m for EC(1:5) is optimal for best correlation with EM38 readings; however, sampling from 0-0.1 m also provided a strong correlation. If soil samples are taken from 0-0.15 m, an excavation permit is not required, allowing for greater freedom for selection of sample points. Sampling from 0-0.1 m would also capture any surface salt crusting otherwise not detected by the EM38. Therefore it may be better, albeit less accurate, to truth the samples using calibration with the 0-0.1 m profile.

Comparison of measuring EC by a field-type 1:5 hand extraction or by laboratory analysis found that field type extraction is much less accurate than laboratory analysis. In future monitoring programs it would be better to rely on laboratory analysis both for accuracy and because all modelling and calibration regression during this study relied on data produced by laboratory EC(1:5) analysis.

To determine a mass balance for salt being deposited on haul roads, it would be essential to monitor and maintain records on the salt concentration and volume of water used for dust suppression. Astron suggests water carts maintain a log of the number of times a shift they are filled and that Fortescue environmental staff frequently record the EC of water from standpipes to ensure that a mass balance can be calculated and that changes in the level of salinity in water being used for dust suppression can be detected.

Discussion with mining engineers whilst on site revealed that many of the existing haul roads at Cloudbreak are returned to the pit as infill as the ore body is mined. The EPA recommended the following: "soil contaminated by salt accumulation from dust suppression will be encapsulated within waste dumps and /or buried above the water table in pits during backfilling." (EPA 2012). Haul road material should therefore be buried deep enough during infilling of the pit that it does not create a problem during restoration of plant communities. Drainage from haul roads should either be captured or directed back into operational areas rather than into adjacent vegetation or natural drainage lines.

Areas surrounding roads that require frequent use of saline water for dust suppression should be monitored to detect if salt levels are accumulating to levels that may cause environmental harm. Particularly, areas surrounding standpipes frequently used for refilling water carts should be monitored and spillage should be minimised as much as possible. Areas surrounded standpipes should be contained by a bund wall to ensure saline water does not flow into the surrounding environment.

If haul roads become accessible due to site maintenance or diversion of haul lines for other reasons, Astron recommends this opportunity be seized to take soil samples to gain an understanding of the level of accumulation of salts on haul roads, and immediately adjacent to them. Depth of penetration of salt into haul roads would also provide and understanding of how mobile the salt is through the haul road profile, or whether it accumulates on the surface and is then dispersed during cyclonic flooding events into the natural environment and potentially washed into the already saline marsh.

5 Conclusions

The EM38 can provide a quick, cost-effective and accurate assessment of salt levels in soil in areas surrounding Fortescue operations where saline water is frequently used for dust suppression. The EM38 may not be accurate where a visible, thin layer of salt crust has formed on the surface of the soil, as was found in patches within the Fortescue Marsh. In these situations the salt level will be underestimated. Given the low levels of salt found in soils found where banded mulga occur, any accumulation of salt in the soil resulting from saline water dust suppression activities should be detectable if using the EM38 as a salt monitoring tool.

6 References

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Appendix A: Soil Calibration Pit Raw Data

Table 1: Calibration pit % moisture, pH 1:5 ($CaCl_2$) and EC 1:5 (mS m^{-1}).

			% Moisture (g g^{-1})				pH 1:5 ($CaCl_2$)				EC 1:5 (mS m^{-1})			
Pit no.	**Location**	**Area**	**0.0-0.1**	**0.1-0.2**	**0.2-0.35**	**0.35-0.5**	**0.0-0.1**	**0.1-0.2**	**0.2-0.35**	**0.35-0.5**	**0.0-0.1**	**0.1-0.2**	**0.2-0.35**	**0.35-0.5**
Cal 1	Christmas Creek	Marsh	3.1	9.5	13.0	15.9	6.0	6.9	7.3	7.9	3.5	2.9	4.3	11.8
Cal 2	Christmas Creek	Marsh	3.9	10.4	15.8	17.9	6.4	7.7	8.2	8.3	6.3	7.6	18.0	73.0
Cal 3	Christmas Creek	Marsh	3.8	13.7	16.5	17.3	7.8	8.2	8.4	8.4	328.0	294.0	349.0	370.0
Cal 4	Christmas Creek	Marsh	4.3	14.4	17.0	18.4	7.6	7.4	7.9	8.2	229.0	330.0	360.0	247.0
Cal 5	Christmas Creek	Marsh	6.1	16.9	18.5	19.2	8.0	8.2	8.3	8.9	183.0	321.0	388.0	428.0
Cal 6	Christmas Creek	Marsh	14.6	16.9	19.9	22.6	8.2	8.3	8.3	8.2	1923.0	653.0	735.0	662.0
Cal 7	Christmas Creek	Marsh	13.0	18.6	21.2	24.2	8.1	8.2	8.2	8.2	565.0	367.0	365.0	403.0
Cal 8	Christmas Creek	Marsh	1.2	3.5	4.6	5.2	4.9	5.3	5.2	6.1	2.0	1.3	0.9	2.2
Cal 9	Cloudbreak	Marsh	3.5	7.9	17.5	21.7	6.9	7.3	8.1	8.3	208.0	167.0	379.0	534.0
Cal 10	Cloudbreak	Marsh	7.8	14.4	16.7	25.6	7.8	7.5	7.4	7.6	759.0	706.0	796.0	1144.0
Cal 11	Cloudbreak	Marsh	21.3	13.3	20.4	30.7	7.7	7.8	7.8	7.5	860.0	466.0	646.0	834.0
Cal 12	Cloudbreak	Marsh	6.4	15.6	17.0	17.6	8.0	7.8	7.9	7.8	272.0	93.5	70.5	230.0
Cal 13	Cloudbreak	Mulga	3.0	8.2	10.3	9.5	6.2	6.3	7.4	7.8	2.2	3.7	15.6	31.2

			% Moisture (g g^{-1})				pH 1:5 (CaCl2)				EC 1:5 (mS/m)			
Pit no.	**Location**	**Area**	**0.0-0.1**	**0.1-0.2**	**0.2-0.35**	**0.35-0.5**	**0.0-0.1**	**0.1-0.2**	**0.2-0.35**	**0.35-0.5**	**0.0-0.1**	**0.1-0.2**	**0.2-0.35**	**0.35-0.5**
Cal 14	Cloudbreak	Mulga	2.1	5.0	7.2	8.5	4.8	5.3	6.3	7.1	2.3	0.9	4.0	9.0
Cal 15	Cloudbreak	Mulga	3.5	7.2	8.3	7.5	5.5	5.8	5.8	5.7	1.6	1.2	1.2	1.3
Cal 16	Cloudbreak	Mulga	3.7	7.9	10.5	8.0	5.4	5.5	6.2	7.3	3.3	3.4	4.4	9.2
Cal 17	Cloudbreak	Mulga	5.0	8.2	10.1	10.3	6.1	6.2	6.0	5.9	1.9	1.7	1.3	1.6
Cal 18	Cloudbreak	Mulga	3.8	7.7	8.4	8.4	5.3	4.9	5.0	5.0	5.3	3.8	4.0	2.6
Cal 19	Cloudbreak	Mulga	2.4	6.2	6.8	9.9	5.9	5.9	5.7	5.8	2.3	1.5	1.5	1.5
Cal 20	Cloudbreak	Mulga	2.2	6.2	8.5	8.6	5.7	6.1	6.9	7.0	3.9	8.7	5.2	5.6
Cal 21	Christmas Creek	Marsh	0.6	10.3	9.8	9.8	5.4	7.4	7.6	8.2	37.2	254.0	265.0	0.3
Cal 22	Christmas Creek	Marsh	1.6	6.0	14.3	14.0	7.2	7.8	8.0	8.1	67.4	115.9	247.0	212.0
Cal 23	Christmas Creek	Marsh	1.6	2.7	9.9	14.2	6.5	6.4	7.5	7.6	24.4	11.7	147.1	306.0
Cal 24	Christmas Creek	Marsh	7.7	9.9	11.7	10.2	8.0	8.0	8.0	8.0	19.8	18.2	18.2	17.6

Table 2: Calibration pit 0-0.1 m ECe, cation exchange capacity (CEC), exchangeable cations and particle size distribution.

					Exchangeable Cations (meq/100g)				Particle Size Distribution (%)		
Pit no.	**Location**	**Area**	**ECe (mS m^{-1})**	**CEC (meq/100g)**	**Ca**	**Mg**	**Na**	**K**	**Sand**	**Silt**	**Clay**
Cal 1	Christmas Creek	Marsh	23.0	10.0	6.2	2.3	1.2	0.3	52.7	32.1	15.2
Cal 2	Christmas Creek	Marsh	53.0	11.5	7.4	2.4	1.2	0.7	41.7	37.5	20.7
Cal 3	Christmas Creek	Marsh	3190.0	17.6	1.7	1.9	2.4	11.6	73.0	20.3	6.7
Cal 4	Christmas Creek	Marsh	283.0	16.9	14.3	0.8	1.5	0.3	59.6	28.7	11.6
Cal 5	Christmas Creek	Marsh	1941.0	17.5	0.8	2.4	3.0	11.3	68.8	23.0	8.2
Cal 6	Christmas Creek	Marsh	8950.0	85.9	4.6	10.1	5.8	65.4	42.8	53.5	3.8
Cal 7	Christmas Creek	Marsh	4760.0	40.6	10.2	6.8	2.4	21.2	6.0	71.9	22.2
Cal 8	Christmas Creek	Marsh	27.0	3.4	1.8	0.9	0.6	0.1	86.7	8.0	5.3
Cal 9	Cloudbreak	Marsh	528.0	16.2	8.0	3.3	2.5	2.4	28.7	63.1	8.2
Cal 10	Cloudbreak	Marsh	5380.0	44.5	12.4	6.5	4.2	21.4	31.4	57.9	10.8
Cal 11	Cloudbreak	Marsh	7570.0	61.0	21.8	12.8	3.6	22.9	17.2	81.0	1.9
Cal 12	Cloudbreak	Marsh	384.0	17.8	10.3	3.3	3.9	0.2	60.1	29.6	10.4
Cal 13	Cloudbreak	Mulga	17.0	6.3	3.7	1.8	0.7	0.2	53.0	27.6	19.4
Cal 14	Cloudbreak	Mulga	8.0	5.1	3.0	1.3	0.7	0.1	39.5	47.3	13.2
Cal 15	Cloudbreak	Mulga	7.0	7.7	5.6	1.2	0.8	0.0	45.3	25.9	28.8
Cal 16	Cloudbreak	Mulga	25.0	7.5	5.1	1.3	1.0	0.1	54.0	21.4	24.5
Cal 17	Cloudbreak	Mulga	13.0	9.5	6.7	1.5	1.2	0.0	38.7	29.1	32.2
Cal 18	Cloudbreak	Mulga	26.0	7.5	5.6	1.1	0.8	0.0	41.7	17.5	40.8
Cal 19	Cloudbreak	Mulga	14.0	8.1	5.0	2.1	1.0	0.1	52.0	24.3	23.8
Cal 20	Cloudbreak	Mulga	39.0	8.6	5.3	2.0	1.1	0.2	53.2	24.4	22.4
Cal 21	Christmas Creek	Marsh	356.0	5.1	1.2	0.3	1.7	1.9	71.8	22.7	5.5
Cal 22	Christmas Creek	Marsh	829.0	8.2	1.2	1.1	1.6	4.3	75.8	19.1	5.0
Cal 23	Christmas Creek	Marsh	40.0	6.2	3.1	1.8	0.9	0.4	79.2	3.8	17.0
Cal 24	Christmas Creek	Marsh	61.0	16.7	8.0	3.9	2.7	2.1	49.4	34.7	15.9

Appendix B: Soil Profile Logs

BOREHOLE NUMBER Cal 1

Astron Soil and Water

CLIENT Fortescue Metals Group Limited

PROJECT NAME Salt Movement from Dust Suppression

PROJECT NUMBER 90940

PROJECT LOCATION Christmas Creek Marsh

DATE STARTED 25/4/12 **COMPLETED** 25/4/12

R.L. SURFACE

DATUM

DRILLING CONTRACTOR Astron Environmental Services

EASTING 774614

NORTHING 7516186

EQUIPMENT Hand Shovel

HOLE LOCATION Marsh

HOLE SIZE 0.5

LOGGED BY T.D.

CHECKED BY T.D.

NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					GP-GC	Silty, gravelly clay, brown/red 10R 3/4, very fine to coarse grained, poorly sorted, poorly graded, few organics, gravel partially rounded. Silty Loam (ZL).	Cal 1 - 0.0 - 0.1	No odour at any depth. Landscape: Stoney, samphire flat. EM38 V:116/H:97
					CLS	Silty, gravelly clay, very fine to coarse grained, moderately sorted, well graded, minor organics, small gravel grading to larger at depth, gravel slightly rounded. Clay Loam, Sandy (CLS).	Cal 1 - 0.1 - 0.2	
							Cal 1 - 0.2 - 0.35	
			0.5				Cal 1 - 0.35 - 0.5	

Borehole Cal 1 terminated at 0.5m

BOREHOLE NUMBER Cal 2

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Salt Movement from Dust Suppression
PROJECT NUMBER 90940
PROJECT LOCATION Christmas Creek Marsh

DATE STARTED 25/4/12 **COMPLETED** 25/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Astron Environmental Services
EASTING 774569
NORTHING 7516123
EQUIPMENT Hand Shovel
HOLE LOCATION Marsh
HOLE SIZE 0.5
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					GW-GC	Silty, gravelly clay, brown/red 2.5YR 3/4, very fine to coarse grained, moderately sorted, well graded, abundant organics, gravel partially rounded. Silty Clay Loam (ZCL).	Cal 2 - 0.0 - 0.1	No odour at any depth. Landscape: Sparsely vegetated stoney flat. EM38 V:344/H:205.
					CLS	Silty, gravelly clay, brown/red 10R 3/4, very fine to coarse grained, poorly sorted, well graded, few organics, gravel partially rounded. Clay Loam, Sandy (CLS).	Cal 2 - 0.1 - 0.2	
							Cal 2 - 0.2 - 0.35	
			0.5				Cal 2 - 0.35 - 0.5	

Borehole Cal 2 terminated at 0.5m

BOREHOLE NUMBER Cal 3

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Salt Movement from Dust Suppression
PROJECT NUMBER 90940
PROJECT LOCATION Christmas Creek Marsh

DATE STARTED 25/4/12 **COMPLETED** 25/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Astron Environmental Services
EASTING 774697
NORTHING 7516070
EQUIPMENT Hand Shovel
HOLE LOCATION Marsh
HOLE SIZE 0.5
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					MLS	Silty clay, brown/red 2.5YR 5/4, very fine to fine grained, well sorted, well graded, few organics. Silty Loam (SL).	Cal 3 - 0.0 - 0.1	No odour at any depth. Landscape: Flat, sparse stoney plain. EM38 V:434/H:363.
					CL-ML	Silty clay with minor gravel, brown/red 2.5 YR 4/5, very fine to fine grained, well sorted, moderately graded, no organics. Sandy Clay Loam (SCL).	Cal 3 - 0.1 - 0.2	
							Cal 3 - 0.2 - 0.35	
			0.5				Cal 3 - 0.35 - 0.5	

Borehole Cal 3 terminated at 0.5m

BOREHOLE NUMBER Cal 4

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Salt Movement from Dust Suppression
PROJECT NUMBER 90940
PROJECT LOCATION Christmas Creek Marsh

DATE STARTED 25/4/12 **COMPLETED** 25/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Astron Environmental Services
EASTING 774966
NORTHING 7515916
EQUIPMENT Hand Shovel
HOLE LOCATION Marsh
HOLE SIZE 0.5
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					CL	Silty Clay with some gravel, brown/red 2.5YR 2.5/4, very fine to coarse grained, moderately sorted, moderately graded, few organics, gravel slightly rounded. Clay Loam (CL).	Cal 4 - 0.0 - 0.1	No odour at any depth. Landscape: Sparse cobbly flat, some samphire. EM38 V:246/H:168
					CL-CH	Silty clay with some gravel, brown/red 2.5YR 3/6, very fine to coarse grained, poorly sorted, well graded, few organics, gravel partially rounded. Light Clay (LC).	Cal 4 - 0.1 - 0.2	
							Cal 4 - 0.2 - 0.35	
			0.5				Cal 4 - 0.35 - 0.5	

Borehole Cal 4 terminated at 0.5m

BOREHOLE NUMBER Cal 5

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Salt Movement from Dust Suppression
PROJECT NUMBER 90940
PROJECT LOCATION Christmas Creek Marsh

DATE STARTED 25/4/12 **COMPLETED** 25/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Astron Environmental Services
EASTING 775019
NORTHING 7515871
EQUIPMENT Hand Shovel
HOLE LOCATION Marsh
HOLE SIZE 0.5
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					SP-SM	Silty clay with minor gravel, brown/red 2.5YR2.5/4, very fine to fine grained, well sorted, poorly graided, no organics. Silty Loam (ZL).	Cal 5 - 0.0 - 0.1	No odour at any depth. Landscape: very sparce- cobbely/gravelly flat. Soil slightly moist to touch. EM38 V:429/H:400.
					CL	Silty clay, brown/red 2.5YR 2.5/4, very fine to medium grained, well sorted, well graided, no organics. Silty Clay Loam (ZCL).	Cal 5 - 0.1 - 0.2	
							Cal 5 - 0.2 - 0.35	
			0.5				Cal 5 - 0.35 - 0.5	

Borehole Cal 5 terminated at 0.5m

BOREHOLE NUMBER Cal 6

astron soil and water pty ltd

Astron Soil and Water

CLIENT Fortescue Metals Group Limited

PROJECT NAME Salt Movement from Dust Suppression

PROJECT NUMBER 90940

PROJECT LOCATION Christmas Creek Marsh

DATE STARTED 25/4/12 **COMPLETED** 25/4/12

R.L. SURFACE

DATUM

DRILLING CONTRACTOR Astron Environmental Services

EASTING 775346

NORTHING 7515591

EQUIPMENT Hand Shovel

HOLE LOCATION Marsh

HOLE SIZE 0.5

LOGGED BY T.D.

CHECKED BY T.D.

NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					CH	Silty clay with very minor gravel, brown/red 10R 4/4, very fine to fine grained, well sorted, well graded, minor organics. Medium Clay.	Cal 6 - 0.0 - 0.1	No odour at any depth. Landscape: visable salt crust on surface, moderate to sparse samphire flat. EM38 V:800/H:960.
							Cal 6 - 0.1 - 0.2	
							Cal 6 - 0.2 - 0.35	
			0.5				Cal 6 - 0.35 - 0.5	

Borehole Cal 6 terminated at 0.5m

BOREHOLE NUMBER Cal 7

Astron Soil and Water

CLIENT	Fortescue Metals Group Limited	**PROJECT NAME**	Salt Movement from Dust Suppression
PROJECT NUMBER	90940	**PROJECT LOCATION**	Christmas Creek Marsh

DATE STARTED 25/4/12	**COMPLETED** 25/4/12	**R.L. SURFACE**		**DATUM**	
DRILLING CONTRACTOR	Astron Environmental Services	**EASTING**	775479	**NORTHING**	7515463
EQUIPMENT	Hand Shovel	**HOLE LOCATION**	Marsh		
HOLE SIZE	0.5	**LOGGED BY**	T.D.	**CHECKED BY**	T.D.
NOTES					

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					CL-CH	Silty clay, brown/red 2.5YR 3/4, very fine to medium grained, well sorted, well graded, some organics. Light Medium Clay (LMC).	Cal 7 - 0.0 - 0.1 Cal 7 - 0.1 - 0.2	No odour at any depth. Landscape: Dense samphire plain, isolated salt crusting. EM38 V:694/H:586.
			0.5		CH	Silty Clay, brown/red 10R 3/4, very fine to fine grained, well sorted, well graded, few organics. Medium Clay (MC).	Cal 7 - 0.2 - 0.35 Cal 7 - 0.35 - 0.5	

Borehole Cal 7 terminated at 0.5m

BOREHOLE NUMBER Cal 8

Astron Soil and Water

CLIENT Fortescue Metals Group
PROJECT NAME Salt Movement from Dust Suppression
PROJECT NUMBER 90940
PROJECT LOCATION Christmas Creek Marsh

DATE STARTED 25/4/12 **COMPLETED** 25/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Astron Environmental Services
EASTING 775415
NORTHING 7517271
EQUIPMENT Hand Shovel
HOLE LOCATION Marsh
HOLE SIZE 0.5
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					SW-SM	Gravelly, sandy, silty clay, brown/red 2.5YR 3/4, very fine to coarse grained, moderately sorted, well graded, few organics, gravel partially to well rounded. Sandy Loam (SL).	Cal 8 - 0.0 - 0.1	No odour at any depth. Landscape: Flat, sparse mulga grove, some ground cover present (Root Architecture Location). EM38 V:61/H:60.
					SP-SC	Silty sandy, gravelly loam, brown/red to rust 2.5YR 3/4, very fine to coarse grained, well graded, moderately sorted, very minor organics. Sandy Clay Loam (SCL).	Cal 8 - 0.1 - 0.2 Cal 8 - 0.2 - 0.35	
			0.5		SP-SC	Silty Clay Loam with gravel/cobbles, brown/red 2.5YR 3/6, very fine to coarse grained, moderately sorted, well graded. Sandy Clay Loam (SCL).	Cal 8 - 0.35 - 0.5	

Borehole Cal 8 terminated at 0.5m

BOREHOLE NUMBER Cal 9

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Astron Soil and Water

CLIENT Fortescue Metals Group Limited

PROJECT NAME Salt Movement from Dust Suppression

PROJECT NUMBER 90940

PROJECT LOCATION Cloudbreak Marsh

DATE STARTED 26/4/12 **COMPLETED** 26/4/12

R.L. SURFACE

DATUM

DRILLING CONTRACTOR Astron Environmental Services

EASTING 740741

NORTHING 7524903

EQUIPMENT Hand Shovel

HOLE LOCATION Marsh

HOLE SIZE 0.5

LOGGED BY T.D.

CHECKED BY T.D.

NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					ML	Silty clay with minor gravel, brown/red 2.5YR 4/4, well sorted, well graded, some organics, gravel partially rounded. Loam (L).	Cal 9 - 0.0 - 0.1	No odour at any depth. Landscape: minimal gravel, *Tecticornia indica* (samphire), UWA site A. Marsh Bore 6 access track, sample from western side. EM38 V:640/H:504.
							Cal 9 - 0.1 - 0.2	
					CL-CH	Silty, sandy clay, brown/red to rust 2.5YR 2.5/4, very fine to coarse grained, brown red to rust, few organics. Light Clay (LC).	Cal 9 - 0.2 - 0.35	
			0.5				Cal 9 - 0.35 - 0.5	

Borehole Cal 9 terminated at 0.5m

BOREHOLE NUMBER Cal 10

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Salt Movement from Dust Suppression
PROJECT NUMBER 90940
PROJECT LOCATION Cloudbreak Marsh

DATE STARTED 26/4/12 **COMPLETED** 26/4/12 **R.L. SURFACE** **DATUM**
DRILLING CONTRACTOR Astron Environmental Services **EASTING** 740611 **NORTHING** 7524756
EQUIPMENT Hand Shovel **HOLE LOCATION** Marsh
HOLE SIZE 0.5 **LOGGED BY** T.D. **CHECKED BY** T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					CL-ML	Silty clay, brown/red 2.5YR 3/4, very fine to fine grained, well sorted, well graded, some organics. Silty Clay Loam (ZCL).	Cal 10 - 0.0 - 0.1	No odour at any depth. Landscape: Surface flakey, some salt crusting. Marsh bore 6 access track, sample from western side. *Tectacornia auriculata* Samphire. UWA site A. Gypsum crystals from 0.2 to 0.5 m. EM38 V:997/H:825.
					CL	Silty loam with minor gravel, brown/red 10R 3/2, fine to medium grained, poorly sorted, poorly graded, few organics, gravel slightly rounded. Clay loam (CL).	Cal 10 - 0.1 - 0.2	
					CL-CH	Silty Loam with some gravel, dark brown/red 10R 3/4, fine to medium grained, moderately sorted, moderate to poorly graded, no organics, clear crystal inclusions (likley Gypsum). Light Clay (LC).	Cal 10 - 0.2 - 0.35	
			0.5				Cal 10 - 0.35 - 0.5	

Borehole Cal 10 terminated at 0.5m

BOREHOLE NUMBER Cal 11

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Salt Movement from Dust Suppression
PROJECT NUMBER 90940
PROJECT LOCATION Cloudbreak Marsh

DATE STARTED 26/4/12 **COMPLETED** 26/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Astron Environmental Services
EASTING 740463
NORTHING 7524583
EQUIPMENT Hand Shovel
HOLE LOCATION Marsh
HOLE SIZE 0.5
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					CL-CH	Silty clay, brown/red 2.5YR 4/4, very fine to fine grained, well sorted, well graded, some organics, dessicated algal layer on surface. Light Medium Clay (LMC).	Cal 11 - 0.0 - 0.1	No odour at any depth. Landscape: Dominated by *Tecicornia indica*, some *T. uriculata,* possible dessicated algal layer on surface, some white crusting on surface, Marsh Bore 6 access track, UWA site 6, sample from western side
					CL-CH	Silty clay, brown/red 2.5YR 4/4, very fine to fine grained, well sorted, well graded, no organics, clear crystal inclusions (likely Gypsum). Light Medium Clay (LMC).	Cal 11 - 0.1 - 0.2	
							Cal 11 - 0.2 - 0.35	
			0.5				Cal 11 - 0.35 - 0.5	

Borehole Cal 11 terminated at 0.5m

BOREHOLE NUMBER Cal 12

Astron Soil and Water

CLIENT	Fortescue Metals Group Limited	**PROJECT NAME**	Salt Movement from Dust Suppression
PROJECT NUMBER	90940	**PROJECT LOCATION**	Cloudbreak Marsh

DATE STARTED	26/4/12	**COMPLETED**	26/4/12	**R.L. SURFACE**	
DATUM					
DRILLING CONTRACTOR	Astron Environmental Services	**EASTING**	740496	**NORTHING**	7525137
EQUIPMENT	Hand Shovel	**HOLE LOCATION**	Marsh		
HOLE SIZE	0.5	**LOGGED BY**	T.D.	**CHECKED BY**	T.D.
NOTES					

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					GM	Silty clay with some gravel, brown/red 2.5YR 3/4, very fine to coarse grained, poorly sorted, poorly graded, some organics. Loam (L).	Cal 12 - 0.0 - 0.1	No odour at any depth. Landscape: Marsh, approximately 50 m from Mulga, grass, Tecticornia mixed, marsh access road, stones on surface ironstone, churt. EM38 V:122/H:118.
					CL-ML	Silty loam with minor gravel, brown/red 10R 3/4, very fine to fine grained, moderately sorted, moderately graded, few organics. Silty Clay Loam (ZCL).	Cal 12 - 0.1 - 0.2	
							Cal 12 - 0.2 - 0.35	
			0.5				Cal 12 - 0.35 - 0.5	

Borehole Cal 12 terminated at 0.5m

BOREHOLE NUMBER Cal 13

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Salt Movement from Dust Suppression
PROJECT NUMBER 90940
PROJECT LOCATION Cloudbreak - Test Area 9

DATE STARTED 28/4/12 **COMPLETED** 28/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Astron Environmental Services
EASTING 738646
NORTHING 7527793
EQUIPMENT Hand Shovel
HOLE LOCATION Marsh
HOLE SIZE 0.5
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					ML	Silty gravelly clay, brown/red 10R3/4, very fine to coarse grained, well graded, poorly sorted, gravel moderately rounded, no organics. Sandy Loam/Loam (SL/L).	Cal 13 - 0.0 - 0.1	No odour at any depth. Landscape: Inter-Mulga flat. Soil: cobbles and gravel over sandy, silty clay loam. EM38 V:22/H:49.
					ML	Silty Clay with some gravel, brown/red 10R 3/2, very fine to coarse grained, well graded, moderately sorted, gravel slightly rounded, no organics. Silty Loam (SL).	Cal 13 - 0.1 - 0.2	
							Cal 13 - 0.2 - 0.35	
			0.5				Cal 13 - 0.35 - 0.5	

Borehole Cal 13 terminated at 0.5m

BOREHOLE NUMBER Cal 14

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Salt Movement from Dust Suppression
PROJECT NUMBER 90940
PROJECT LOCATION Cloudbreak - Test Area 9

DATE STARTED 28/4/12 **COMPLETED** 28/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Astron Environmental Services
EASTING 738667
NORTHING 7527779
EQUIPMENT Hand Shovel
HOLE LOCATION Test Area 3
HOLE SIZE 0.5
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					ML	Silty Loam with minor gravel, brown/red 10R 3/3, very fine to medium grained, moderately sorted, well graded, some organics, gravel moderately rounded, surface flakes. Loam (L).	Cal 14 - 0.0 - 0.1 Cal 14 - 0.1 - 0.2	No odour at any depth. Landscape: Mulga grove, isolated grasses/small seedlings in understory. Soil: clayey, silty loam, some surface flakes. EM38 V:22/H43.
			0.5		SW-SC	Silty clay with some minor gravel, brown/red 10R 3/4, very fine to coarse grained, well graded, moderately sorted, some organics, minor concretion, gravel slightly rounded. Sandy Clay Loam (SCL).	Cal 14 - 0.2 - 0.35 Cal 14 - 0.35 - 0.5	

Borehole Cal 14 terminated at 0.5m

BOREHOLE NUMBER Cal 15

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Salt Movement from Dust Suppression
PROJECT NUMBER 90940
PROJECT LOCATION Cloudbreak - Test Area 8

DATE STARTED 28/4/12 **COMPLETED** 28/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Astron Environmental Services
EASTING 739878
NORTHING 7528367
EQUIPMENT Hand Shovel
HOLE LOCATION Test Area 4 - Drainage
HOLE SIZE 0.5
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					ML	Silty clay loam with minor gravel, brown/red 10R 3/3, very fine to coarse grained, moderately sorted, well graded, few organics, gravel partial-to-well rounded. Silty Loam (ZL).	Cal 15 - 0.0 - 0.1	No odour at any depth. Landscape: Drainage line located within Mulga Grove, grassy understory. Soil: Hard, sandy clay, minor gravel. EM38 V:14/H:23.
					CL-ML	Silty clay loam with some gravel, brown/red 10R 3/3, very fine to coarse grained, moderately sorted, well graded, gravel partial-to-well rounded. Silty Clay Loam (ZCL).	Cal 15 - 0.1 - 0.2	
							Cal 15 - 0.2 - 0.35	
			0.5				Cal 15 - 0.35 - 0.5	

Borehole Cal 15 terminated at 0.5m

BOREHOLE NUMBER Cal 16

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Salt Movement from Dust Suppression
PROJECT NUMBER 90940
PROJECT LOCATION Cloudbreak Test Area 4

DATE STARTED 28/4/12 **COMPLETED** 28/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Astron Environmental Services
EASTING 739883
NORTHING 7528370
EQUIPMENT Hand Shovel
HOLE LOCATION Test Area 4 - next to drainage
HOLE SIZE 0.5
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					SW-SM	Silty gravelly clay, brown/red 10R 3/4, very fine to coarse grained, moderately sorted, well graded, gravel slight-to-well rounded, few organics. Sandy Loam (SL).	Cal 16 - 0.0 - 0.1	No odour at any depth. Landscape: Adjacent to drainage line, some grass and low shrubs with sparse Mulga canopy. Soil: sandy/gravelly silty clay.
					CLS	Silty, gravelly clay, brown/red 10R 3/4, fine to coarse grained, poorly sorted, well graded, few organics, gravel partial-to-well rounded. Sandy Clay Loam (SCL).	Cal 16 - 0.1 - 0.2	
							Cal 16 - 0.2 - 0.35	
			0.5				Cal 16 - 0.35 - 0.5	

Borehole Cal 16 terminated at 0.5m

BOREHOLE NUMBER Cal 17

Astron Soil and Water

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CLIENT Fortescue Metals Group Limited

PROJECT NAME Salt Movement from Dust Suppression

PROJECT NUMBER 90940

PROJECT LOCATION Cloudbreak - Test Area 8

DATE STARTED 28/4/12 **COMPLETED** 28/4/12

R.L. SURFACE

DATUM

DRILLING CONTRACTOR Astron Environmental Services

EASTING 739923

NORTHING 7528406

EQUIPMENT Hand Shovel

HOLE LOCATION Test Area 4 - Drainage/wash area

HOLE SIZE 0.5

LOGGED BY T.D.

CHECKED BY T.D.

NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					MLS	Silty Clay with minor gravel, Brown/red 10R 3/2, fine to coarse grained, moderately sorted, well graded, few organics, gravel partially rounded. Silty Loam (ZL).	Cal 17 - 0.0 - 0.1	No odour at any depth. Landscape: Drainage/wash area, some Mulga close by, shrubs/grasses in understory. EM38 V:2/H:32.
					MLS	Silty clay loam with some gravel, brown/red 10R 3/3, very fine to coarse grained, moderately sorted, moderately graded, few organics, gravel partially to well rounded. Silty Loam (ZL).	Cal 17 - 0.1 - 0.2	
							Cal 17 - 0.2 - 0.35	
			0.5				Cal 17 - 0.35 - 0.5	

Borehole Cal 17 terminated at 0.5m

BOREHOLE NUMBER Cal 18

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Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Salt Movement from Dust Suppression
PROJECT NUMBER 90940
PROJECT LOCATION Cloudbreak - Test Area 8

DATE STARTED 28/4/12 **COMPLETED** 28/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Astron Environmental Services
EASTING 739866
NORTHING 7528472
EQUIPMENT Hand Shovel
HOLE LOCATION Test Area 4 - Mulga Grove
HOLE SIZE 0.5
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					CL	Silty, gravelly clay, brown/red 10R 3/4, very fine to coarse grained, well graded, poorly sorted, some organics, gravel moderately rounded, minor white clay inclusions. Light Clay (LC).	Cal 18 - 0.0 - 0.1	No odour at any depth. Landscape: Flat Mulga grove, understory consisting of grass and small shrubs. Soil: silty clay. EM38 V:12/H:19.
					CL	Silty loamy clay, brown/red 10R 3/4, very fine to coarse grained, well graded, poorly sorted, some organics, gravel partially rounded, some minor concretion. Light Clay (LC).	Cal 18 - 0.1 - 0.2	
							Cal 18 - 0.2 - 0.35	
			0.5				Cal 18 - 0.35 - 0.5	

Borehole Cal 18 terminated at 0.5m

BOREHOLE NUMBER Cal 19

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Salt Movement from Dust Suppression
PROJECT NUMBER 90940
PROJECT LOCATION Cloudbreak - Test Area 7

DATE STARTED 28/4/12 **COMPLETED** 28/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Astron Environmental Services
EASTING 737360
NORTHING 7530497
EQUIPMENT Hand Shovel
HOLE LOCATION Test Area 5 - Mulga
HOLE SIZE 0.5
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					CLS	Silty, gravelly clay, brown/red 10R2.5/2, very fine to medium grained, moderately sorted, moderately graded, some organics, gravel well to partially rounded. Sandy Clay Loam (SCL).	Cal 19 - 0.0 - 0.1	No odour at any depth. Landscape: Next to Mulga and bordered by open stoney flat, located in small depressions around vegetation (appear to be sink-hole like). soil: Hard clay. EM38 V:26/H:38.
					CL	Silty gravelly clay, very fine to coarse grained, few organics, moderately sorted, brown/red 10R3/4, well graded, partially concreted to concreted at depth. Clay Loam (CL).	Cal 19 - 0.1 - 0.2	
							Cal 19 - 0.2 - 0.35	
			0.5				Cal 19 - 0.35 - 0.5	

Borehole Cal 19 terminated at 0.5m

BOREHOLE NUMBER Cal 20

Astron Soil and Water

CLIENT Fortescue Metals Group Limited		**PROJECT NAME** Salt Movement from Dust Suppression	
PROJECT NUMBER 90940		**PROJECT LOCATION** Cloudbreak - Test Area 7	
DATE STARTED 28/4/12	**COMPLETED** 28/4/12	**R.L. SURFACE**	**DATUM**
DRILLING CONTRACTOR Astron Environmental Services		**EASTING** 737322	**NORTHING** 7530513
EQUIPMENT Hand Shovel		**HOLE LOCATION** Test Area 5	
HOLE SIZE 0.5		**LOGGED BY** T.D.	**CHECKED BY** T.D.
NOTES			

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					CL	Silty, gravelly clay, brown/red 10R3/4, very fine to coarse grained, some organics, moderately sorted, well graded, gravel partially rounded. Clay Loam (CL).	Cal 20 - 0.0 - 0.1 Cal 20 - 0.1 - 0.2	No odour at any depth. Landscape: stoney flat locatedbetween several Mulgas, no ground cover present. EM38 V:20/H:35.
			0.5		ML	Silty gravelly clay, brown/red to rust 10R 3/4, very fine to coarse grained, well graded, poorly sorted, no organics, partially concreted. Loam (L).	Cal 20 - 0.2 - 0.35 Cal 20 - 0.35 - 0.5	

Borehole Cal 20 terminated at 0.5m

BOREHOLE NUMBER Cal 21

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Salt Movement from Dust Suppression
PROJECT NUMBER 90940
PROJECT LOCATION Christmas Creek Marsh

DATE STARTED 29/4/12 **COMPLETED** 29/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Astron Environmental Services
EASTING 774914
NORTHING 7516618
EQUIPMENT Hand Shovel
HOLE LOCATION Marsh
HOLE SIZE 0.5
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					SM	Silty, gravelly clay, brown/red 2.5YR 3/4, very fine to medium grained, moderately sorted, poorly graided, no organics, gravel partially rounded. Sandy Loam (SL).	Cal 21 - 0.0 - 0.1	No odour at any depth. Landscape: Open, stoney flat, very sparce shrubs, no larger vegetation. Soil: gravelly/cobbely, silty clay. EM38 V:281/H:229.
							Cal 21 - 0.1 - 0.2	
					CLS	Gravelly, sandy clay, brown/red 2.5YR 2.5/4, very fine to coarse grained, moderately sorted, well graided, no organics. Sandy Clay Loam (SCL).	Cal 21 - 0.2 - 0.35	
			0.5				Cal 21 - 0.35 - 0.5	

Borehole Cal 21 terminated at 0.5m

BOREHOLE NUMBER Cal 22

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Salt Movement from Dust Suppression
PROJECT NUMBER 90940
PROJECT LOCATION Christmas Creek Marsh

DATE STARTED 29/4/12 **COMPLETED** 29/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Astron Environmental Services
EASTING 776869
NORTHING 7514897
EQUIPMENT Hand Shovel
HOLE LOCATION Marsh adjacent to drainage line
HOLE SIZE 0.5
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					CLS	Silty, gravelly clay, brown/red 2.5 YR 3/6, very fine to coarse grained, moderately sorted, poorly graded, no organics, gravel partially rounded. Sandy Clay Loam (SCL).	Cal 22 - 0.0 - 0.1	No odour at any depth. Landscape: Stoney flat, sparse, low shrubs. Soil: cobbly/gravelly clay/loam.
							Cal 22 - 0.1 - 0.2	
					CLS	Silty, gravelly clayloam, brown/red 2.5YR 4/6, very fine to coarse grained , well sorted, well graded, no organics, gravel partially rounded, minor concretion. Clay Loam, Sandy (CLS)	Cal 22 - 0.2 - 0.35	
			0.5				Cal 22 - 0.35 - 0.5	

Borehole Cal 22 terminated at 0.5m

BOREHOLE NUMBER Cal 23

Astron Soil and Water

CLIENT	Fortescue Metals Group Limited	**PROJECT NAME**	Salt Movement from Dust Suppression
PROJECT NUMBER	90940	**PROJECT LOCATION**	Christmas Creek Marsh

DATE STARTED	29/4/12	**COMPLETED**	29/4/12	**R.L. SURFACE**	
DATUM					
DRILLING CONTRACTOR	Astron Environmental Services	**EASTING**	776895	**NORTHING**	7514886
EQUIPMENT	Hand Shovel	**HOLE LOCATION**	Marsh, adjacent to drainage.		
HOLE SIZE	0.5	**LOGGED BY**	T.D.	**CHECKED BY**	T.D.
NOTES					

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					MLS	Silty, gravelly clay, brown/red to rust 2.5YR 2.5/3, very fine to coarse grained, moderately sorted, poorly graded, few organics, gravel partially rounded. Sandy Loam (SL).	Cal 23 - 0.0 - 0.1	No odour at any depth. Landscape: South East of drainage line (~5 m away), low shrubland, samphire and other small hardy plants. Soil: sandy clay loam. EM38 V:379/H:232.
							Cal 23 - 0.1 - 0.2	
					CL-CH	Silty, gravelly clay, brown/red 2.5YR 3/4, very fine to mediunm grained, well sorted, poorly graded, few organics, gravel partially rounded. Light Medium Clay (LMC).	Cal 23 - 0.2 - 0.35	
			0.5				Cal 23 - 0.35 - 0.5	

Borehole Cal 23 terminated at 0.5m

BOREHOLE NUMBER Cal 24

Astron Soil and Water

CLIENT Fortescue Metals Group Limited
PROJECT NAME Salt Movement from Dust Suppression
PROJECT NUMBER 90940
PROJECT LOCATION Christmas Creek

DATE STARTED 29/4/12 **COMPLETED** 29/4/12
R.L. SURFACE
DATUM
DRILLING CONTRACTOR Astron Environmental Services
EASTING 776245
NORTHING 7515030
EQUIPMENT Hand Shovel
HOLE LOCATION Observed change in vegetation type.
HOLE SIZE 0.5
LOGGED BY T.D.
CHECKED BY T.D.
NOTES

Method	Water	RL (m)	Depth (m)	Graphic Log	Classification Symbol	Material Description	Samples Tests Remarks	Additional Observations
HA					CL-ML	Silty clay with minor gravel, brown/red 2.5YR 4/4, very fine to fine grained, well sorted, well graded, some organics, gravel partially rounded. Silty Clay Loam (ZCL).	Cal 24 - 0.0 - 0.1 Cal 24 - 0.1 - 0.2 Cal 24 - 0.2 - 0.35	No odour at any depth. Landscape: transition between elevated samphire and drainage area - different vegetation type - dominated by green shrubs to 70 cm, some samphire. Soil Silty, clayey loam, some minor gravel.
			0.5		CL-CH	Silty, gravelly loam, brown/red 10R 4/4, fine to coarse grained,moderately sorted, moderately graded, no organics, gravel partially rounded. Light Clay (LC).	Cal 24 - 0.35 - 0.5	

Borehole Cal 24 terminated at 0.5m

UNSATURATED ZONE MODELLING – Fortescue Marsh Investigations

Stage 2

June 2012

Prepared for
Fortescue Metals Group

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Revision Status

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Draft A	25/07/2011	Draft for Internal Review	Dan Jarvis	Cameron Baldock	
Draft B	03/11/2011	Draft for Client Review	Dan Jarvis	Cameron Baldock	Cameron Baldock
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Text	IR
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Tabulations	IR
Calculations	NR
Statistics	NR

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1 Introduction

Fortescue Metals Group (Fortescue) is proposing to expand its iron ore mining operations at Christmas Creek and Cloudbreak, located approximately 120 kilometres north of Newman. These mining areas are collectively referred to as the Chichester Operations.

The mine expansions will require large scale dewatering to provide access to below watertable ore reserves. Mine pit dewatering creates zones of lowered watertables (drawdown zones) that extend beyond the mine pit boundaries. Groundwater injection can create zones of elevated watertables (mounding zones) centred around the injection bores. Collectively these effects can impact vegetation due to interactions between groundwater levels and vegetation water uptake.

The effects of dewatering have the potential to extend to the fringes of the Fortescue Marsh, an episodically inundated wetland with important conservation values. The Marsh includes a variety of plant communities dominated by samphire (*Tecticornia*) species. Fortescue has initiated a research program to improve understanding of the eco-hydrology of the Marsh vegetation.

Fortescue has contracted Astron Environmental Services Pty Ltd (in its capacity as Astron Soil and Water Pty Ltd) to provide unsaturated zone water balance modelling for the Fortescue Marsh for the purposes of:

- Improving understanding of soil moisture dynamics in the unsaturated zone profile, under different soil profile and climate scenarios.
- Identifying the potential contribution of groundwater to meeting vegetation water use requirements.
- Evaluating the potential impacts of modified watertable depth on plant available soil moisture.

Groundwater modelling of the proposed dewatering for the expansion of the Cloudbreak mine identified some areas along the fringe of the marsh that are likely to be within the zone of modelled groundwater drawdown. The extent to which samphire rely on groundwater must be understood to assess the impact that the proposed dewatering could have on the marsh ecology.

Tecticornia indica (*T. indica*) has been identified as the predominant samphire vegetation on the fringe of the marshes that may be affected by mine site dewatering activities and is the primary focus of this investigation.

The primary aim of the modelling assessment is to:

> ***"Determine whether surface water and groundwater interactions are vital to the sustainability of the marshes and evaluate the dynamics of stored soil water replenishment and water table fluctuations on water availability for samphire."***

And to test the hypothesis:

"The water requirements of the Fortescue Marsh vegetation can be met by surface water inputs under most climatic regimes, including areas potentially exposed to modified groundwater depth."

The Stage 2 unsaturated zone modelling simulations were run using HYDRUS1D-4.14 software (Šimůnek *et al*, 2009).

The Stage 2 unsaturated zone modelling follows on from preliminary Stage 1 modelling that was based on more generalised data (not site-specific as in Stage 2). Stage 1 modelling was an assessment of soil moisture content based on the current seasonal regime of rainfall and evapotranspiration from October 2008 to May 2011 (based on Newman Aero data), with the simulation period extended to include a worst case scenario "dry season" from June 2011 to May 2012 (modelled using 2009-2010 evaporation data with no rainfall). At various times throughout Stage 1, data from UWA field and laboratory investigations became available to help guide and refine the preliminary assessment. This Stage 2 investigation includes all available UWA data including the on-site weather station data for rainfall and evapotranspiration for a simulation period of 950 days (1st October 2008 to 8th May 2011).

The site specific data is part of the ARC Linkage project "Ecophysiology of stem succulent halophytes subject to changes in salinity and water availability: distinguishing natural dynamics from potential mine related impacts" being managed by the University of Western Australia (UWA) with funding support from Fortescue (ARC Linkage project LP0882350).

The Stage 1 report is presented in Appendix 1.

2 Stage 2 Scope of Work

Astron Soil and Water have completed Stage 2 of the groundwater and unsaturated zone modelling based on site-specific data to test the following hypothesis:

> *"The water requirements of the Fortescue Marsh vegetation can be met by surface water inputs under most climatic regimes, including areas potentially exposed to modified groundwater depth."*

The tasks identified in the Stage 2 scope of works are as follows:

1. Review all site-specific UWA field and laboratory data and incorporate it into the HYDRUS1D model developed in Stage 1 (Appendix 1).
2. Update the model's Main Processes to include Root Water Uptake. Provide suitable parameter values for the Water Uptake Reduction Model (i.e. Feddes' parameters).
3. Update the model to include output at the times that match the nine sample event dates for UWA field soil moisture data taken between October 2008 and May 2011. Compare the different scenarios' soil moisture profiles at each of these times for:
    - No Root Water Uptake
    - Root Water Uptake
    - Comparison with UWA field soil moisture data
4. Compare time-series modelled output for Root Water Uptake, Soil Water Storage and other fluxes. Compare modelled average daily values and changes in these fluxes to estimates calculated from the recorded soil moisture values.
5. Update the model to include observation nodes at depths of 10cm, 20cm, 30cm and 50cm to match UWA profile data (0-10cm, 10-20cm, 20-30cm, 30-50cm). Compare the time-series values for modelled and recorded soil moisture at each of these observation nodes.
6. Provide a qualitative assessment of the effects of salinity on the soil moisture profile.
7. Undertake an Uncertainty and Sensitivity Analysis including key parameters for Root Water Uptake.
8. Provide an analysis of all the results to satisfy the primary aim of the modelling:

    "Determine whether surface water and groundwater interactions are vital to the sustainability of the marshes and evaluate the dynamics of stored soil water replenishment and water table fluctuations on water availability for samphire."

    And assess hypothesis:

    "The water requirements of the Fortescue Marsh vegetation can be met by surface water inputs under most climatic regimes, including areas potentially exposed to modified groundwater depth."

Various scenarios were developed for evaluation using the HYDRUS1D-4.14 model to obtain outputs for differing situations based on water input to the system and the interactions of groundwater and different soil profile characteristics.

The modelled scenarios were based on:

- Recent rainfall and evapotranspiration data recorded from October 2008 to May 2011 (UWA weather station).

- Soil and plant water use parameters based on recent soil profile descriptions and analysis (Kew Wetherby Soil Survey Pty/Ltd).

A detailed discussion of the scenarios and inputs to the model and are described in Section 5 and Section 6.

The target outputs from Stage 2 were:

- a working model that produces understandable outputs and is capable of being used for testing parameter sensitivities and scenarios; and
- Model scenario simulation results using recent soil data, water use data and rainfall/evapotranspiration data recorded from October 2008 to May 2011.

- An assessment of the model calibration and validity based on comparisons with field measured soil moisture data (UWA) for the modelling period.

3 Methodology

3.1 Model Selection

HYDRUS1D (version 4.14) was selected as the preferred model to be used to assess the water requirements of the Fortescue Marsh vegetation. HYDRUS1D was chosen based on the following features:

- HYDRUS1D has a user friendly Graphical User Interface (GUI), HYDRUS1D vs 4.14.
- HYDRUS1D provides report ready graphs, tables and data via the GUI.
- HYDRUS1D has an option to "save as input to MODFLOW".

For further details regarding model selection refer to Appendix 1.

3.2 Parameter List Development

A parameter list was developed based on a simulation involving all the Main Processes available in HYDRUS1D. The list was provided to the relevant personnel at UWA and FMG who are involved in the Fortescue Marsh research program.

Within the HYDRUS1D-4.14 interface, default values are available for many of the parameter inputs that are required and were used where other data was unavailable. Default values considered most appropriate for the current understanding of the Marsh soil profile were used in the assessment.

For further details regarding the parameter list refer to Appendix 1.

3.3 Stage 2 Methodology

- Modify the model to span the UWA soil moisture data period (Oct-08 to May-11).
- Incorporate UWA weather station (and CB station) data. Where data is absent, Newman Aero data was used.
- Update the model to include Root Water Uptake. Determine how ETo (Potential Evapotranspiration, from UWA weather data) is partitioned into Evaporation from soil and Transpiration from plants.
- Update the model to include observation pts at 5cm, 15cm, 25cm and 40cm to match UWA profile data.
- Update the model to include output times to match UWA time series sample data (9 dates).
- Soil parameters and Root Water Uptake parameters (Feddes' parameters) will be based on the Kew soil report, with reference to other literature.
- The following scenarios will be presented.
    - Sc 1a and Sc1b (T. indica) – 1m to hardpan, no GW
    - Sc2a and Sc2b (T. indica) – 3m to GW, no hardpan
- Comparison will be made to scenarios with no Root Water Uptake.
- Depth profiles and time series graphs of modelled versus observed soil moisture will be presented with an analysis of data for each of the scenarios.

- Determine the most likely scenario(s) based on the modelling and field results.
- Provide an analysis the modelled versus observed change in soil moisture between June 09 and May 10.
- Compare model results with UWA sapflow data.
- Determining whether measured changes in soil moisture are consistent with Scenario 1 (1m to hardpan, no GW), thereby lending support the hypothesis that the samphire marsh water requirements are met by rainfall and not reliant on groundwater.
- Comparison of Scenario 1 with Scenario 2 (no hardpan, 3m to GW) will be made to demonstrate the minimal influence of groundwater at this depth.
- Undertake a qualitative analysis of the effects of salinity with reference to UWA salinity data and other recent studies on the effects of salinity.
- A summary of all the modelling to determine which of the scenarios is most likely and provide an assessment of the likely water balance for this scenario. From the water balance analysis, the investigation can determine the validity of the hypothesis:

  "The water requirements of the Fortescue Marsh vegetation can be met by surface water inputs under most climatic regimes, including areas potentially exposed to modified groundwater depth."

4 Assumptions and Limitations

4.1 Mathematical Modelling and Parsimony

The modelling was undertaken with the intention of providing preliminary estimates of the soil moisture in the profile under a simplified and conservative set of conditions. While there are assumptions and limitations in all modelling, the results from the simulations provide a suitable starting point for further investigations.

It is common for investigations like this one to undertake modelling of various likely scenarios, as well as some level of Sensitivity and Uncertainty Analysis, so as to provide a range of modelled scenarios (e.g. best case scenario, worst case scenario, extreme worst case scenario etc.) that will "capture" the range of scenarios that are likely in nature. The manipulation of model input parameters to precisely replicate actual recorded data is considered to be less than ideal as this approach is not "parsimonious" and can produce erroneous results when the model is used as a predictive tool. This is at odds with one of the fundamental tenets of mathematical modelling; i.e. the notion of "parsimony" (Fowkes and Mahony, 1996). It is considered better to have range of simulations from a more generalised model with the intention of "capturing" the natural scenarios (the approach used in this investigation). This idea is represented conceptually in Figure 1.

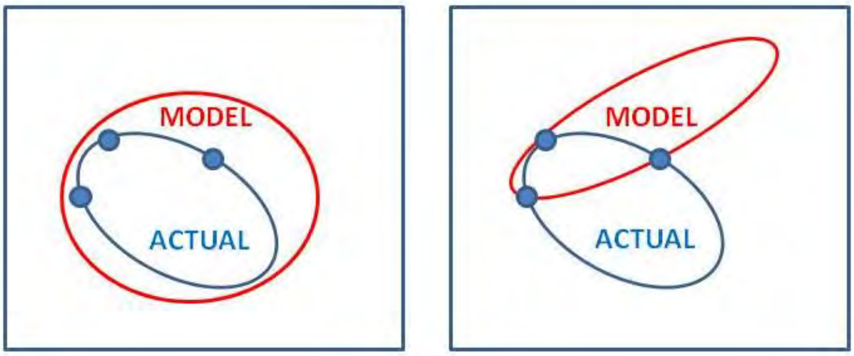


Figure 1: **Model Parsimony.**

The schematic on the left represent the range of results using a more generalised model approach (i.e. parsimonious) with reasonable calibration (3 blue dots) and capturing all "actual" results. The schematic on the right represents the range of results using a highly manipulated model with more precise calibration but with possible erroneous results and failing to capture all "actual" results.

4.2 Conceptual Model

The Conceptual Model for the Scenarios is presented in Figure 2. The three main samphire communities *T. indica, T. auriculata and T. medusa* have been identified in the marsh. As a general rule, these communities extend from the fringe of the marsh (chiefly *T. indica*), to inside the fringe (chiefly *T. auriculata*) and toward the centre (chiefly *T. medusa*). For Stage 1 modelling, only data from the *T. indica* and *T. medusa* communities was used since these represent the extremes of the marsh. Stage 2 modelling investigated the most sensitive of these communities (*T. indica*).

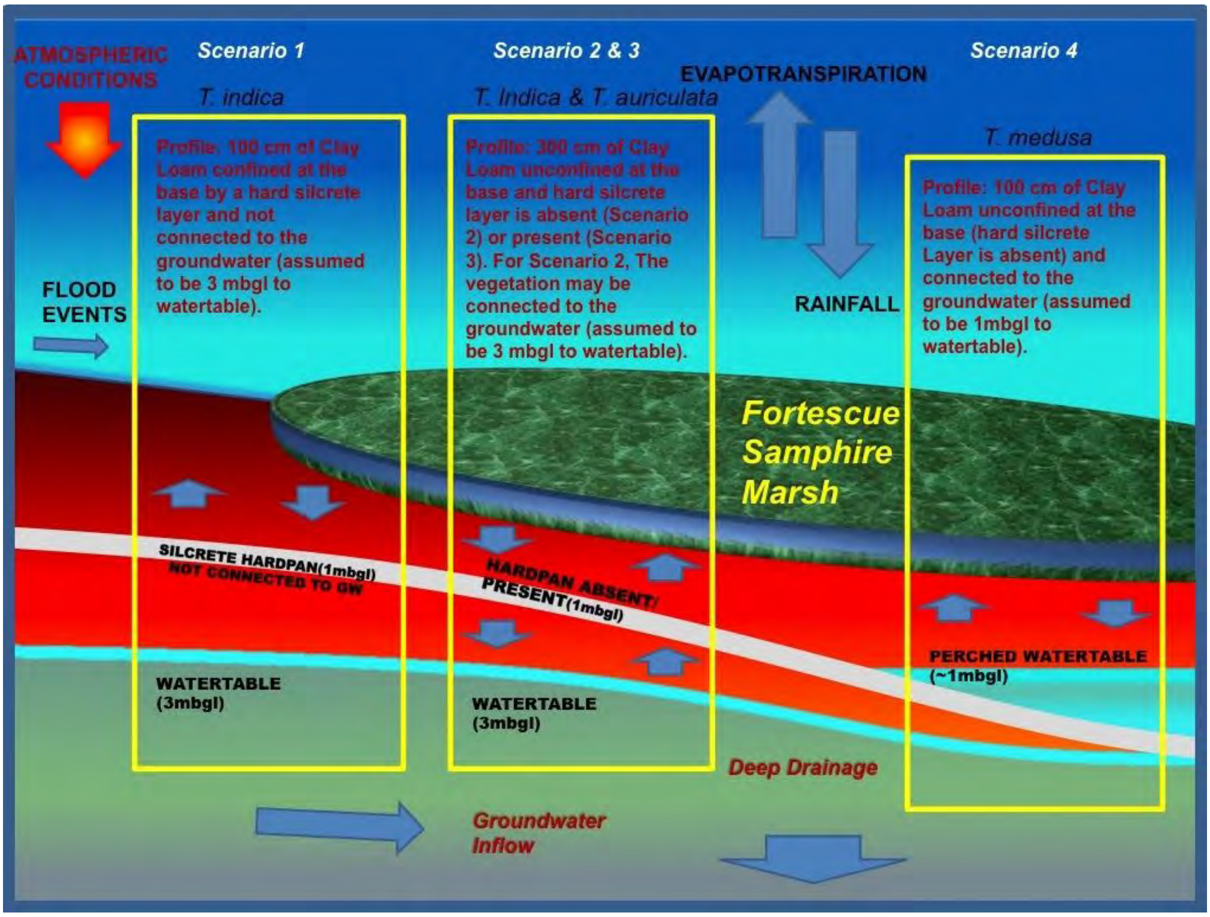


Figure 2: **Conceptual Site Model**

4.3 HYDRUS1D Main Processes -Assumptions

The assessment of moisture content and root water uptake was performed by selecting "Water Flow" and "Root Water Uptake" in the Main Processes menu in HYDRUS1D-4.14. The influence of salinity on moisture content was not included in the HYDRUS1D modelling. A qualitative assessment of salinity is presented in Section 10.

4.4 Hydro-geological Scenarios - Assumptions

The HYDRUS1D model was used to estimate the water content in either a Clay Loam or Clay soil profile under four different groundwater scenarios. In the model, moisture in the soil profile depends on the geometry of the profile, soil hydraulic properties, and the time variable atmospheric boundary conditions of rainfall and evapotranspiration. The following assumptions were made:

- The soil type for the upper soil profile (approximately top 1m) in all four Scenarios is the assumed to be Clay Loam or Clay. This is consistent with the findings of the UWA research project and more recent field results from test pits reported in the *Fortescue Marsh – preliminary soil investigation –Final report* (Kew, 2011). A hardpan including silcrete has been recorded below this depth and is known to be extensive.

- Based on the US Soil Texture Triangle, the bulk density of the Clay Loam soil type ranges from about 1.27 g/cm^3 to 1.35 g/cm^3 (Saxton *et al*., 1986). An upper limit value of 1.35 g/cm^3

was used to convert gravimetric water content values from field measurements (units in g/g) to volumetric moisture content values (units in cm^3/cm^3) for comparison with the model outputs.

- The bulk density for Clay soil types are generally lower, however the methods used to calculate bulk density are unsuitable for well compacted soils high in clay (Saxton *et al.*, 1986). In addition, precipitates of leached minerals (such as silcrete) are likely to occupy some of the pore spaces in the soil due to the cycle of inundation and drying. Clay soils of this nature may have bulk density values that are at the upper end the range given for clay soils of 1.1 g/cm^3 to 1.6 g/cm^3 (ANRA, 2000-2002)

- The soil hydraulic properties for the single porosity van Genuchten – Mualem model for Clay Loam and Clay soils are based on parameters from Carsel and Parrish (1988) and are provided in HYDRUS1D-4.14. An “air entry” value of -2cm was used (recommended for clay soils).

- The modelled period is 950 days (1st October 2008 to 8th May 2011) starting with a saturated soil profile. Rainfall and evapotranspiration (ET) inputs were based on daily values recorded from the UWA weather station.

5 Modelled Scenarios

5.1 Scenarios

The Stage 2 assessment included two groundwater profile scenarios as follows:

1. A shallow (100 cm) soil profile available to plant roots, confined by a hard silcrete (impeding) layer which functions as an aquitard.

2. A deep (300 cm) soil profile available to plant roots, with potential capillary connection to the underlying groundwater.

These scenarios were considered adequate to represent the soil profile near the fringes of the Marsh. The assessment continued by investigating these two scenarios based on soil types identified at the site following recent field results:

(a) Clay Loam soils (comparatively free draining soils)
(b) Clay soils (comparatively high water retaining soils)

There are four model scenarios in total:

- Scenario 1(a) and (b)

- Scenario 2(a) and (b)

6 Model Inputs

6.1 Parameters

The following parameter values were used for the three scenarios. Parameters relating to some of the more technical aspects of the numerical model development have been intentionally left out of this report.

6.1.1 Soil Type

The predominant soil types were identified as Clay Loam and Clay to provide the suitable range of scenarios. The soil descriptions are based on the US Soil Texture Triangle (Figure 3):

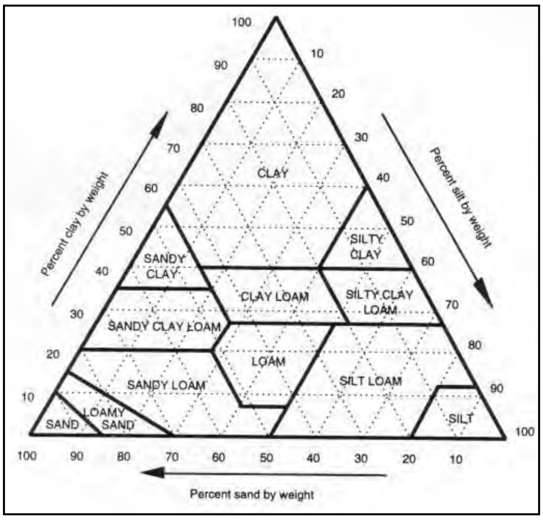


Figure 3: US Soil Texture Triangle

6.1.2 Bulk Density

Based on this classification, the upper limit value for bulk density of Clay Loam soil type was 1.35 g/cm^3 (Saxton *et al.*, 1986 in Šimůnek *et al.*, 2009). Saxon et al (1986) stresses that the methods described for assessing bulk density by are not valid for soils with high clay content. Soils high in clay were identified in the test pits and as such, an estimate for the bulk density must be made. Clay soils that are compacted have bulk density values that are at the upper end the range given for this soil type of 1.1 g/cm^3 to 1.6 g/cm^3(ANRA, 2002). For simulations involving Clay soils, a value of 1.6 g/cm^3 was used. The values used for Clay Loam and Clay soils represent a conservative approach with respect to the effective porosity since a higher bulk density value results in reduced pore water availability.

The different measures of water content are related by the equation:

$$\Theta(\text{Volumetric}) = \text{Bulk Density} \times \Theta(\text{Gravimetric})$$

The higher values used for Bulk Density will result in a higher estimation for ϴ(Volumetric) for field measured moisture (undertaken by UWA).

6.1.3 Soil Hydraulic Properties

The soil hydraulic properties for Clay loam and Clay are presented in Table 1.

Table A: **Soil Hydraulic Properties for the single porosity van Genuchten-Mualem model**

Param.	Description	Clay Loam	Clay
Qr	Residual soil water content, θ_r	0.095	0.068
Qs	Saturated soil water content, θ_s	0.41	0.38
Alpha	Parameter α in the soil water retention function [L^{-1}]	0.019	0.008
n	Parameter *n* in the soil water retention function	1.31	1.09
Ks	Saturated hydraulic conductivity, K_s [LT^{-1}]	6.24	4.8
l	Tortuosity parameter in the conductivity function [-]	0.5	0.5

Source: Values provided in HYDRUS1D-4.14 from Carsel and Parrish (1988)

6.1.4 Upper Boundary Conditions

Atmospheric Boundary Conditions with Surface Layer was chosen to represent the fluxes at the surface of the profile. This allows ponding during heavy rainfall periods. In the model, ponding will be significantly less and for much shorter periods since the model does not include runoff from upper reaches of the river to the Marsh.

This makes the model a conservative representation of the Marsh hydrogeology with respect to water inputs into the soil profile, and therefore appropriate for investigating the potential exposure of vegetation to dry soil conditions.

6.1.5 Rainfall

The transient model period is 950 days (1st October 2008 to 8th May 2011).

Rainfall inputs were based on daily values recorded for the UWA weather station (on site) from October 2008 to May 2011. Where UWA data were missing, data from the Cloudbreak weather station and Newman Aero (BoM ID 007176) were used. The rainfall for the period is presented as a graph in Figure 4.

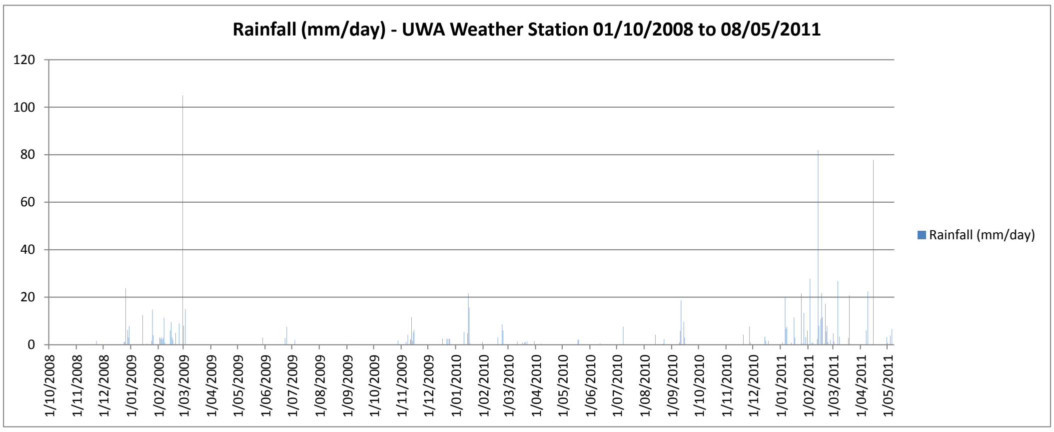


Figure 4: **Rainfall for model period 1st Oct 2008 to 8th May 2011 (UWA Weather Station)**

The three graphs presented in Figure 5 show regional long-term rainfalls trends and indicate that:

- Rainfall conditions for Newman Aero (BoM ID 007176) up to and including the modelled period are marginally drier than the medium to longer term rainfall patterns.
- Longer term rainfall conditions) are currently stable following a steady increase overall since 1998 (exemplified by the Residual Rainfall Mass Curve which shows the moving average for 1972-2010).

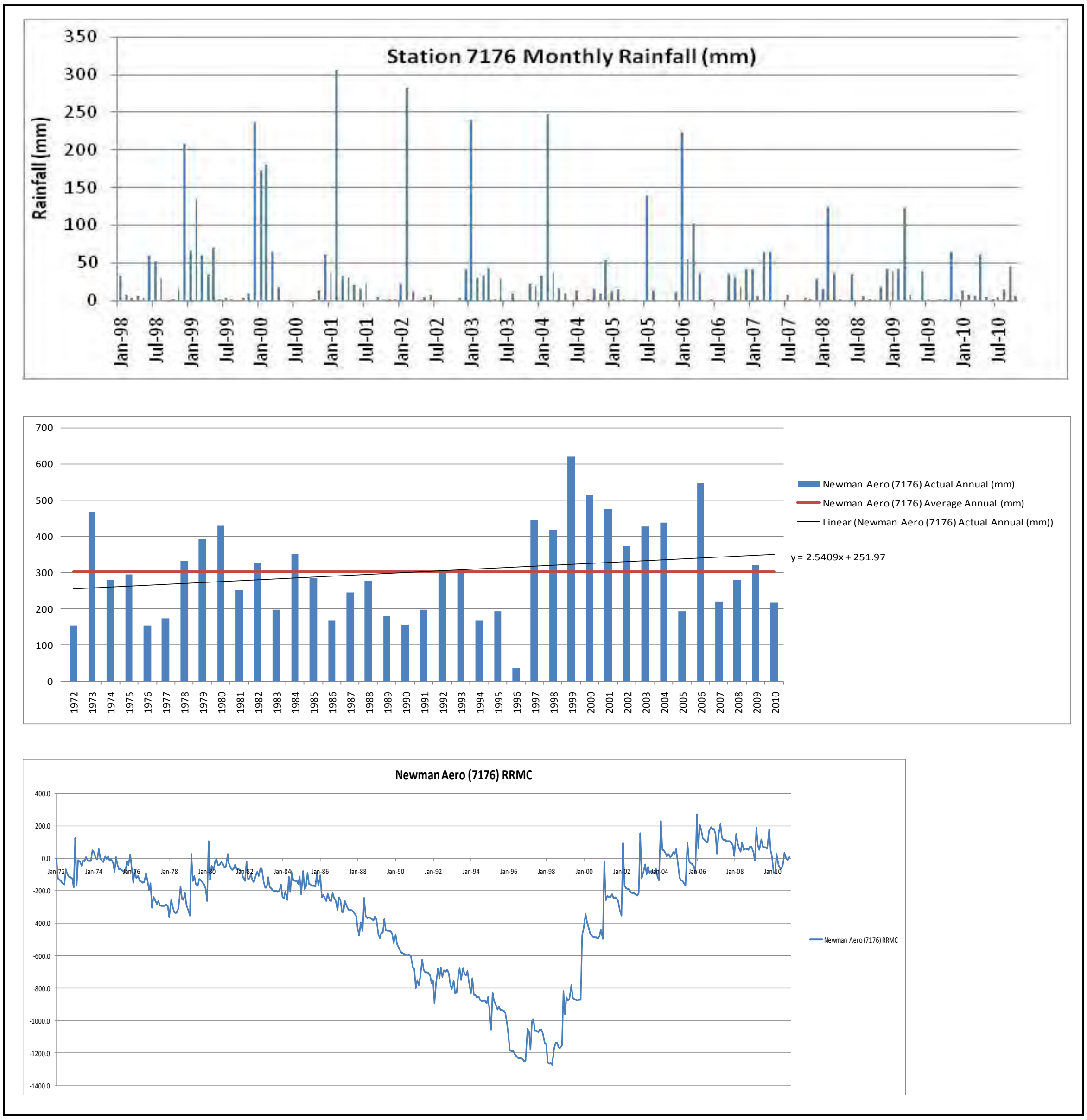


Figure 5: Newman Aero (BoM 7176) Monthly Rainfall (BoM, 1998 to 2010), Annual Rainfall (1972 to 2010) and Long Term Residual Rainfall Mass Curve (1972 to 2010).

6.1.6 Evapotranspiration (ETo)

Potential Evapotranspiration (ETo) were based on daily values recorded for the UWA weather station (on site) from October 2008 to May 2011. Where UWA data were missing, data from the Cloudbreak weather station and Newman Aero (BoM ID 007176) were used. The ETo for the period is presented as a graph in Figure 6.

The values for ET represent a standardised "reference evapotranspiration" used by BoM and described in *Bureau of Meteorology Reference Evapotranspiration Calculations (C.P. Webb, 2010).* The abstract from this document is reprinted below:

> Reference evapotranspiration (ETo) data is valuable for a range of users, including farmers, hydrologists, agronomists, meteorologists, irrigation engineers, project managers, consultants and students. Daily ETo data for 399 locations in Australia will become publicly available on the Bureau of Meteorology's (BoM's) website (www.bom.gov.au) in 2010. A computer program developed in the South Australian Climate Services Centre of the BoM (SACSC) is used to calculate these figures daily. Calculations are made using the adapted Penman-Monteith equation recommended by the United Nations Food and Agriculture Organisation (FAO56-PM equation). Inputs to the equation include temperature, relative humidity and wind speed data from BoM weather stations and satellite derived daily solar radiation data. In the proposed ET_o tables for each weather station, daily evaporation pan (E_{pan}) data are presented alongside ET_o data. Epan data are often used to estimate ET_o and the methods and limitations of doing so are discussed, as is the issue of missing data.

Crop water need, potential evapotranspiration and actual evapotranspiration are related as follows:

Potential Evapotranspiration (ETo) = Transpiration (Samphire) + Evaporation

In the HYDRUS1D model, ETo was partitioned equally (50% transpiration, 50% Evaporation).

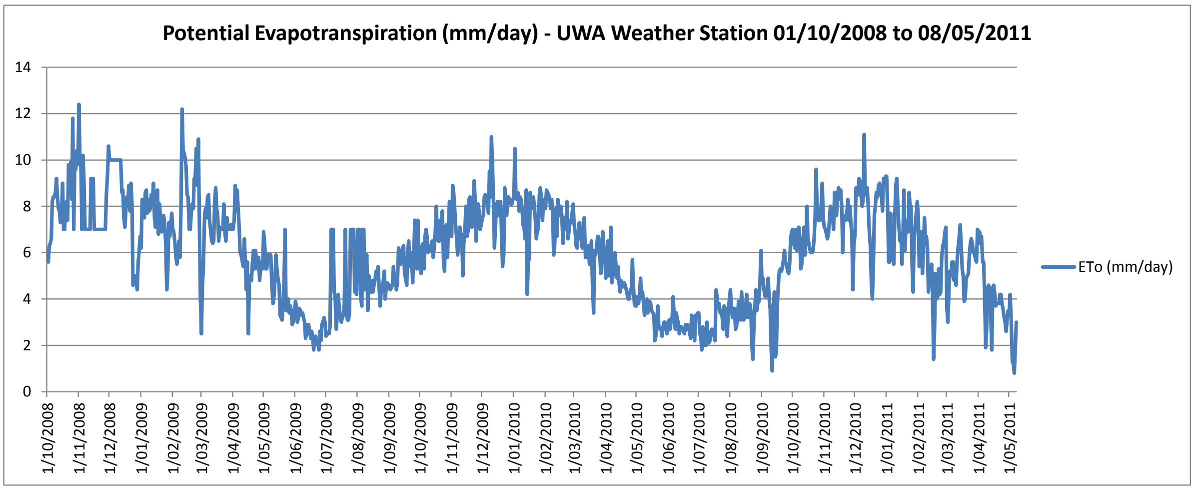


Figure 6: Potential Evapotranspiration for model period 1st Oct 2008 to 8th May 2011 (UWA Weather Station).

6.1.7 Lower Boundary Conditions

Either a *constant flux* or *constant water content* lower boundary condition was used in the model. The values assigned to the lower boundary conditions are described for each scenario.

6.1.8 Root Water Uptake

Root Water Uptake parameters were based on values reported in the *Fortescue Marsh – preliminary soil investigation –Final report* (Kew, 2011). Feddes (1978) (in Šimůnek *et al.*, 2009) describes the parameters presented in Table 2.

The input parameters permit one to make the variable P2 a function of the potential transpiration rate, T_p (P2 presumably decreases at higher transpiration rates).

The manual gives a schematic of the stress response function as used by *Feddes et al.* [1978]. Water uptake is assumed to be zero close to saturation (i.e. wetter than some arbitrary "anaerobiosis point" **P0**). Root water uptake is also zero for pressure heads less than the wilting point (**P3**). Water uptake is considered optimal between pressure heads **Popt** and **P2**, whereas for pressure heads between **P2** and **P3** (or **P0** and **Popt**) water uptake decreases (or increases) linearly with pressure head.

Table B: Root Water Uptake Parameters (Feddes, 1978)

Parameter	Pressure (cm)	Description (Feddes, 1978)
P0	**-10**	Value of the pressure head below which roots start to extract water from the soil.
POpt	**-25**	Value of the pressure head below which roots extract water at the maximum possible rate.
P2H	**-1500**	Value of the limiting pressure head, below which roots cannot longer extract water at the maximum rate (assuming a potential transpiration rate of *r2H*).
P2L	**-1500**	As above, but for a potential transpiration rate of *r2L*.
P3	**-7000**	Value of the pressure head, below which root water uptake ceases (usually taken at the wilting point).
r2H	**0.5**	Potential transpiration rate [LT^{-1}] (currently set at 0.5 cm/day).
r2L	**0.1**	Potential transpiration rate [LT^{-1}] (currently set at 0.1 cm/day).

6.2 Modelled Scenarios

6.2.1 Scenario 1 (a) and (b)

Scenario 1 represented the vegetation community along the fringe of the Fortescue Marsh (primarily *T. indica*) and is considered to be the vegetation community most susceptible to alterations to the hydrogeology/hydrology in the region (i.e. watertable is influenced by dewatering). The profile is described in the model as follows:

- Profile: 100 cm of (a) Clay-Loam soils or (b) Clay soils confined at the base by a hard silcrete layer and not connected to the Groundwater (assumed to be 3mbgl to watertable).

- Lower Boundary Condition: Constant Flux = 0 cm/day for (a) and (b)

6.2.2 Scenario 2 (a) and (b)

Scenario 2 represented the same vegetation community as Scenario 1 (*T. indica*), however the profile is described in the model as follows:

- Profile: 300 cm of (a) Clay-Loam soils or (b) Clay soils unconfined at the base (hard silcrete layer is absent). The vegetation is possibly connected to the groundwater (assumed to be 3mbgl to watertable).

- Lower Boundary Condition: Constant Water Content $\theta_{SATURATED}$ = (a) 0.41 or (b) 0.38

Scenario 2 simulations were run to determine if there was any significant in the upper soil profile (0 - 100cm) when compared to Scenario 1 profiles (not connected to watertable).

7 Field and Laboratory Results

7.1 UWA Sapflow Estimates

Table 3 presents current UWA sapflow estimates based on laboratory data for T. *indica*

Table C: UWA Laboratory Sapflow Data (T. *indica*)

UWA Laboratory Sapflow Data	mm/day
UWA Max. Recorded *(to be reviewed)*	0.35
UWA Ave. Recorded *(to be reviewed)*	<0.05

7.2 Soil Moisture (0cm -50cm) - 1st October 2008 to 1st May 2011

Table 4 presents soil moisture data from nine UWA field trips undertaken between 1st October 2008 to 1st May 2011. Values were converted from gravimetric water content (g/g) to volumetric water content (cm^3/cm^3) by multiplying by the values for Bulk Density (BD). Volumetric water content values were compared to model results for Scenario 1(a) (Clay/Loam, BD=1.35 g/cm^3) and Scenario 1(b) (Clay, BD=1.6 g/cm^3).

Table D: UWA Soil Moisture Data (T. *indica*)

SITE	SPECIES	HORIZON DEPTH (cm)	Depth	1/10/2008 θ (g/g)	1/02/2009 θ (g/g)	1/06/2009 θ (g/g)	1/09/2009 θ (g/g)	1/02/2010 θ (g/g)	1/05/2010 θ (g/g)	1/09/2010 θ (g/g)	1/01/2011 θ (g/g)	1/05/2011 θ (g/g)
A	indica	T	0	-0.003	0.006	0.016	-0.005	0.004	0.009	0.090	0.033	0.006
		1-10	-10	0.017	0.107	0.084	0.023	0.022	0.030	0.142	0.109	0.053
		10-20	-20	0.079	0.101	0.105	0.097	0.077	0.075	0.107	0.076	0.076
		20-30	-30	0.120	0.123	0.140	0.137	0.105	0.105	0.118	0.105	0.127
		30-50	-50	0.130	0.124	0.168	0.152	0.089	0.129	0.128	0.186	0.131
B	indica	T	0	-0.002	0.056	0.018	0.007	0.012	0.007	0.142	0.033	0.021
		1-10	-10	0.095	0.153	0.077	0.021	0.055	0.054	0.191	0.189	0.088
		10-20	-20	0.122	0.157	0.107	0.089	0.075	0.088	0.121	0.115	0.111
		20-30	-30	0.145	0.157	0.132	0.121	0.098	0.109	0.128	0.116	0.130
		30-50	-50	0.148	0.176	0.159	0.145	0.097	0.127	0.141	0.175	0.137

7.3 Soil Water Storage – 1st June 2009 to 1st May 2010

The UWA data for 1st June 2009 to 1st May 2010 (day 244 to 578) was used to estimate net loss in soil water storage observed during the 334 day period. Estimates for the top 50cm could be calculated from the data. Estimates for the lower 50cm were based on the 30cm-50cm (deepest) value multiplied by the 50cm. The HYDRUS1D profiles suggest that the approach was valid. The estimations for soil water content are in Table5.

Table E: Soil Water Content (Based on UWA Field Data)

Site A Depth	Δθ (g/g)	Δθ (g/g)	Net Water Loss (L/m²=mm)	Water Loss (mm/day)
T	0.007			
1-10	0.054			
10-20	0.029	**0.038**	**25.9**	**0.08**
20-30	0.035			
30-50	0.039			
50-100	*0.039*	***0.039***	***26.4***	***0.08***
Site B Depth	**Δθ (g/g)**	**Δθ (g/g)**	**Net Water Loss (L/m²=mm)**	**Water Loss (mm/day)**
T	0.011			
1-10	0.023			
10-20	0.019	**0.025**	**17.1**	**0.05**
20-30	0.023			
30-50	0.032			
50-100	*0.032*	***0.032***	***21.3***	***0.07***

7.4 Soil Survey Data (Kew, 2011)

Table 6 below provides a summary of the soil profiles from seven locations. The topsoil “A” horizon (generally the top 10cm) overlays a “B” horizon and the average rootzone is within the top 50cm of the profile. The “A” and “B” horizons vary between the seven sites and so only a single soil type was modelled (either Clay Loam or Clay).

Table F: Soil Profiles (Kew, 2011)

Site	Easting	Northing	Soil Class	Topsoil cm	Rootzone cm	Depth (cm) upper	Depth (cm) lower	Horizon	Texture	Geology
1	740630	7525004	CHA	10	60	0	10	A1	FCL	Qa-l
						10	80	B2	LMC	Qa-cy
						80	100	B2c	LS	Qa-sh
2	740443	7524506	CHA	10	30	0	10	A1	FCL	Qa-l
						10	40	B2y	LMC	Qa-cy
						40	110	B2c	FSCL	Qa-lh
3	740413	7524529	CHA	10	30	0	10	A1	FCL	Qa-l
						10	40	B2y	CL	Qa-ly
						40	90	B2c	LC	Qa-ch
						90	210	B3c	LC	Qa-ch
						210	250	B3	LMC	Qa-c
4	737956	7525469	DER	10	40	0	10	A1	LC	Qa-c
						10	30	B1	LC	Qa-c
						30	45	B2c	SCL	Qa-lh
5	737985	7525628	CHA	10	80	0	10	A1	FCL	Qw-l
						10	30	B2	FCL	Qw-l
						30	70	B2	CL	Qw-l
						70	80	B2c	LC	Qw-ch
6	738075	7526017	CHA	5	50	0	15	A1	SCL	Qw-l
						15	50	B2	LC	Qw-c
						50	80	B2y	CL	Qw-ly
						80	100	B2	LC	Qw-c
7	741906	7524675	CHA	10	60	0	10	A1	FCL	Qw-l
						10	40	B2	LC	Qw-c
						40	80	B2k	LMC	Qw-ck
						80	100	B2c	SL	Qw-sh

8 Model Calibration and Validation

The HYDRUS1D model developed in Stage 1 (Appendix 1) based on non-site specific rainfall data demonstrate that the model was providing reasonable results when compared with the range of UWA soil moisture data from nine field trips. As such, a single soil type model (Clay Loam or Clay) was considered sufficiently valid as a starting point for Stage 2 modelling. The Stage 2 model outputs based on site-specific rainfall, evaporation and transpiration data are presented in Section 9 and are compared with measured soil moisture profiles under a range of scenario conditions.

The results that follow suggest that that the model is generally well matched to observed data at profile depths of 25cm-50cm. The observed soil moisture values for the upper 25cm of the profile are generally lower than modelled values suggesting one or several of the following:

- The upper 25cm of the profile loses water to evapotranspiration more readily (e.g. sandier).
- The upper 25cm of the profile has precipitated salts, displacing water adsorbent materials.
- The profile is generally anisotropic with respect to soil parameters and/or bulk density.

The Stage 2 modelling approach based on a single soil type was therefore still considered valid since the degree of uncertainty in soil properties was relatively high and that the seven surveyed soil profiles vary in their soil description.

9 Model Outputs & Results

9.1 Sampling Dates & Model Times

Table 7 below shows the simulation day number and its corresponding sample date. HYDRUS1D uses the day number and so this convention is retained for all graphical output.

Table G: Simulation Day Number & Sample Date

Day	Date	Day	Date	Day	Date
1	1/10/2008	336	1/09/2009	701	1/09/2010
124	1/02/2009	489	1/02/2010	823	1/01/2011
244	1/06/2009	578	1/05/2010	943	1/05/2011

9.2 Scenario 1 (a) RWU - Site A and Site B (T. *indica*).

- Profile: 100 cm of Clay-Loam soils confined at the base by a hard silcrete layer and not connected to the groundwater (assumed to be 3 mbgl to watertable).
- Lower Boundary Condition: Constant Flux = 0 cm/day for (a) and (b).

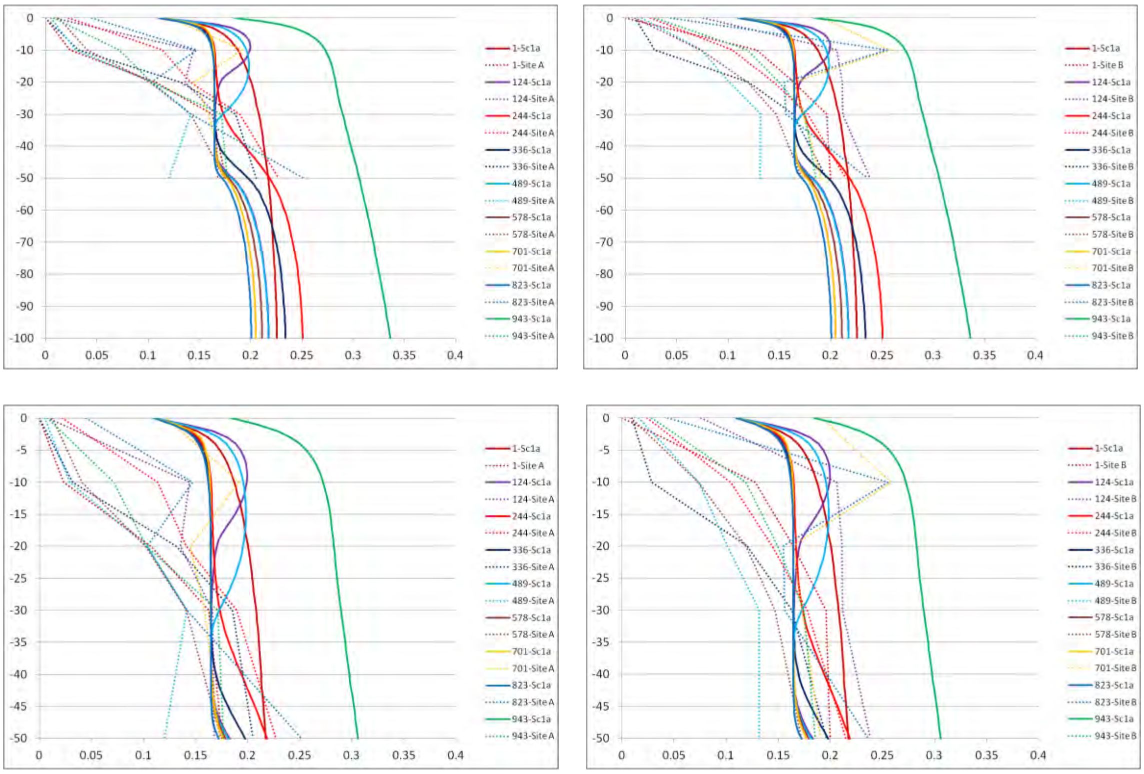


Figure 7: Scenario 1 (a) RWU - Site A and Site B (T. indica). Depth (mbgl) and Water Content (cm^3/cm^3).

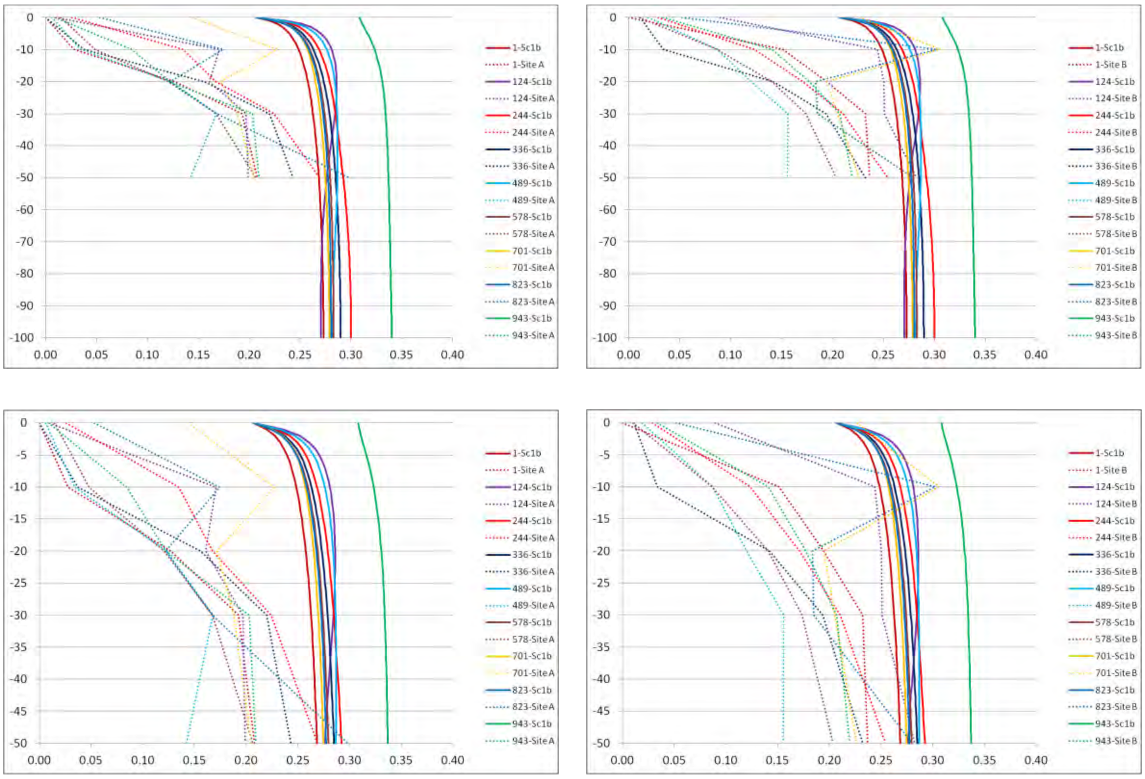
Question: Do the modelled profiles for Scenario 1(a) (Clay Loam) compare well with the UWA field results for Site A and Site B (T. indica)?

Answer: Yes. The model compares well with UWA field data for depths of 25cm-50cm. The UWA field data for the upper 0cm-25cm may be lower due to the reasons detailed in Section 8 (Model Calibration & Validation).

9.3 Scenario 1(b) RWU - Site A and Site B (T. *indica*).

- Profile: 100 cm of Clay soils confined at the base by a hard silcrete layer and not connected to the groundwater (assumed to be 3 mbgl to watertable).

- Lower Boundary Condition: Constant Flux = 0 cm/day for (a) and (b).



Day	Date	Day	Date	Day	Date
1	1/10/2008	336	1/09/2009	701	1/09/2010
124	1/02/2009	489	1/02/2010	823	1/01/2011
244	1/06/2009	578	1/05/2010	943	1/05/2011

Figure 8: **Scenario 1 (b) RWU - Site A and Site B (T. indica). Depth (mbgl) and Water Content (cm^3/cm^3).**

Question: Do the modelled profiles for Scenario 1(b) (Clay) compare well with the UWA field results for Site A and Site B (T. indica).

Answer: No. The modelled values are generally much higher than UWA field data for depths of 0cm-50cm.

9.4 Scenario 1(a) and Scenario 1(b) – Hydraulic Properties

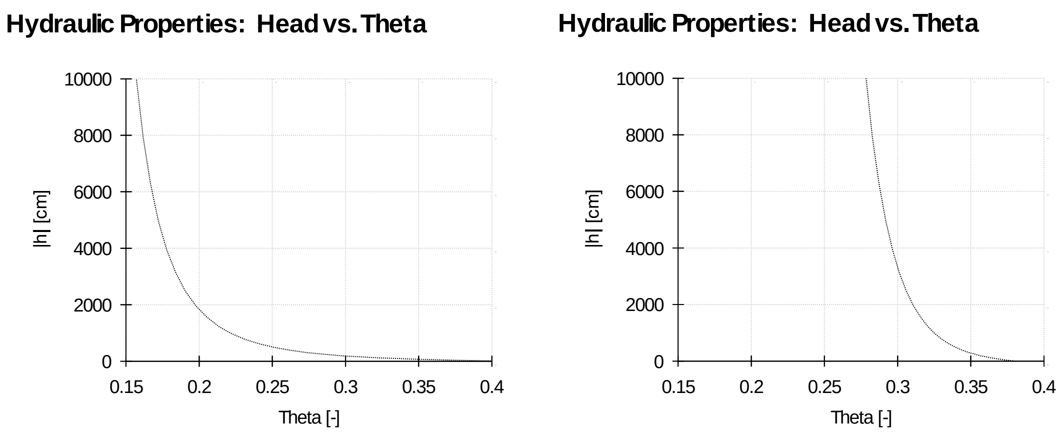


Figure 9: Scenario 1(a) and Scenario 1(b) – Hydraulic Properties

Question: Does the relationship of Soil Pressure Head versus Water Content (theta) provide an indication of the likely soil type (Clay Loam or Clay).

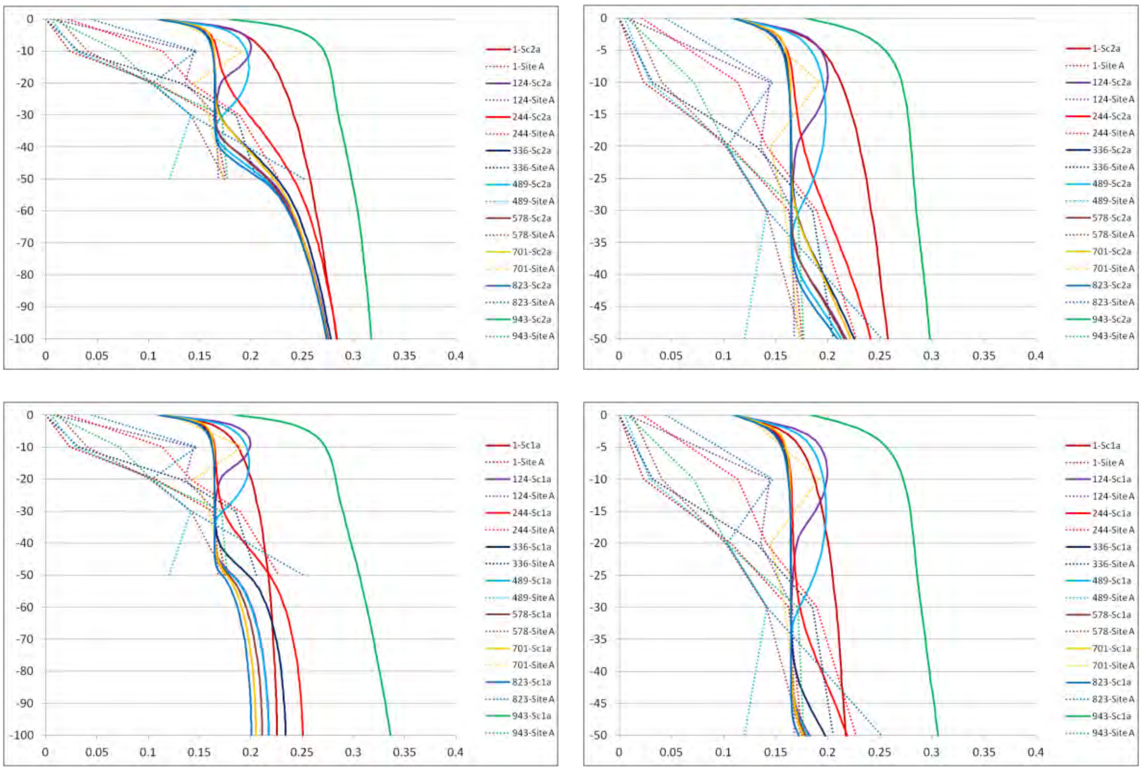
Answer: Yes. Scenario 1(a) provides realistic pressure heads for observed and modelled moisture levels. Scenario 1(b) does not. That is, Clay Loam soils, have a pressure head/water content relationship that is consistent with measured soil moisture and estimated root uptake parameter values (i.e. -1500kPa to as low as -7000kPa, Kew 2011).

All scenarios based on a Clay profiles (i.e. Scenario 1(b), 2(b)) were investigated but have not been included following the implications of the difference in the “head/theta” relationship. All scenarios and simulations with Clay Loam are the more likely of the two soil scenarios.

9.5 Scenario 1(a) RWU compared to Scenario 2(a) RWU.

- Scenario 2a Profile: 300 cm of Clay-Loam soils unconfined at the base (hard silcrete layer is absent). The vegetation is possibly connected to the groundwater (assumed to be 3 mbgl to watertable).

- Lower Boundary Condition: Constant Water Content $\Theta_{SATURATED}$ = (a) 0.41



Sc2a - Sc1a	Aver. Δ (θ)	Standard Error
100cm	0.0238	0.0008
50cm (root zone)	0.0008	0.0006

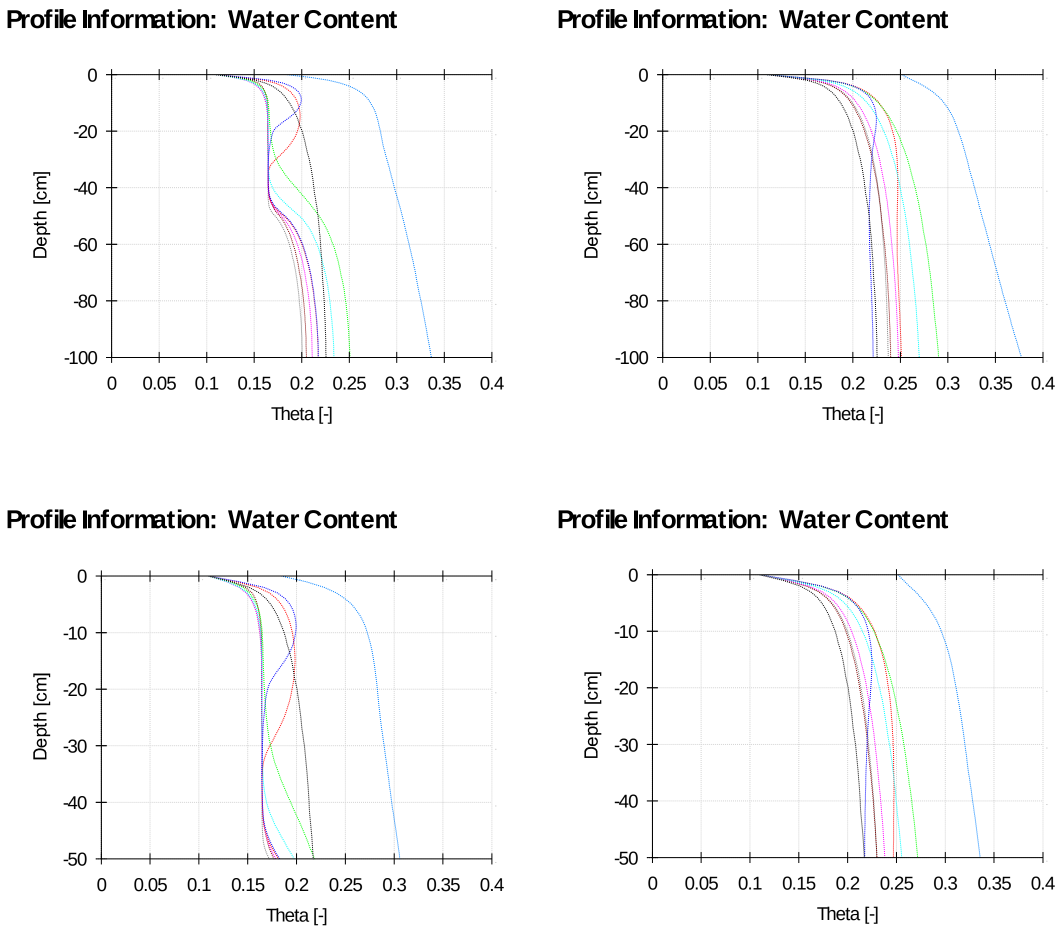
Day	Date	Day	Date	Day	Date
1	1/10/2008	336	1/09/2009	701	1/09/2010
124	1/02/2009	489	1/02/2010	823	1/01/2011
244	1/06/2009	578	1/05/2010	943	1/05/2011

Figure 10: Scenario 1(a) RWU compared to Scenario 2(a) RWU (Upper 100cm). Depth (mbgl) and Water Content (cm^3/cm^3).

Question: Do the modelled profiles for Scenario 1(a) (Clay Loam, hardpan at 1mbgl, no GW) and Scenario 2(a) (Clay Loam, hardpan absent, GW at 3mbgl) differ significantly for the rootzone (0cm-50cm)

Answer: No. The moisture levels for Scenario 2(a) are marginally higher than for Scenario 1(a) in the rootzone. This difference is, on average, 0.0008 cm^3/cm^3 (very marginal).

9.6 Scenario 1(a) RWU compared to Scenario 1(a) No RWU



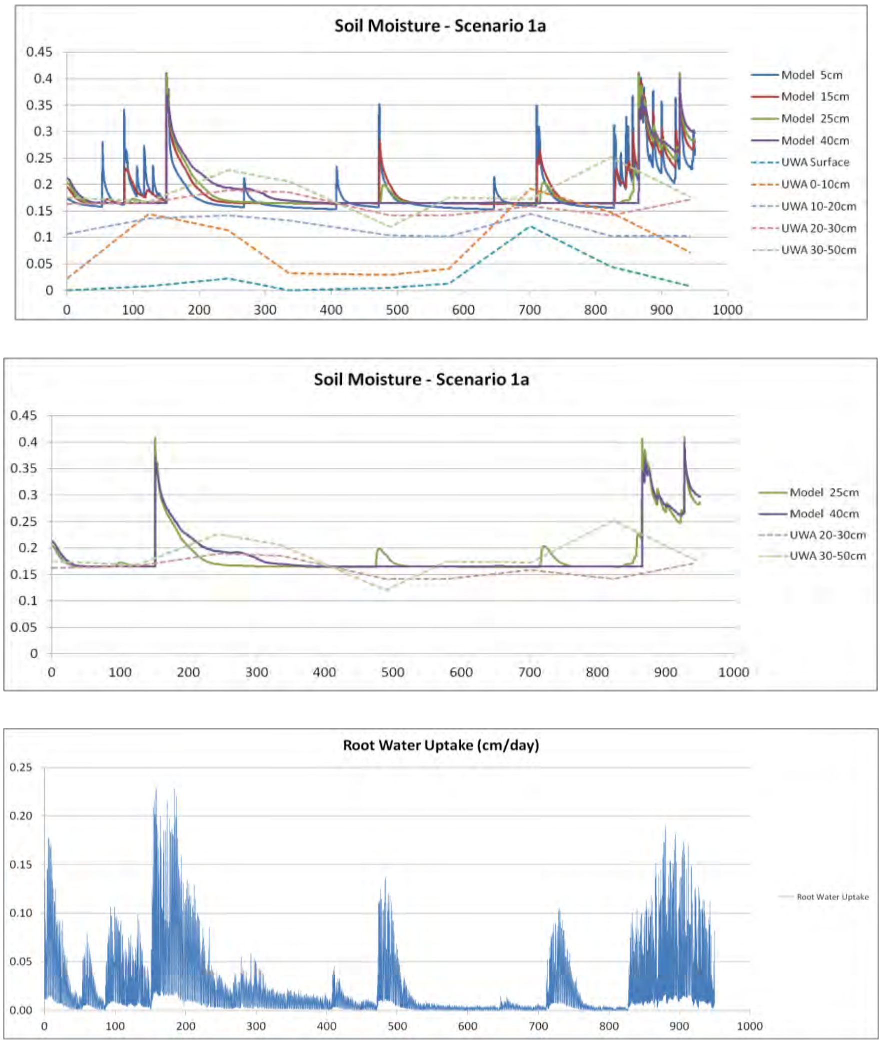
Sc1a: No RWU - RWU	Aver. Δ (θ)	Standard Error
100cm (to hardpan)	0.0432	0.0006
50cm (root zone)	0.0505	0.0010

Figure 11: Scenario 1(a) RWU compared to Scenario 1(a) No RWU (HYDRUS1D Graphical Output). Depth (mbgl) and Water Content (cm^3/cm^3).

Question: Do the modelled profiles for Scenario 1(a) and Scenario 1(a) (without Root Water Uptake)) differ significantly for the rootzone (0cm-50cm)?

Answer: Yes. The moisture levels for Scenario 1(a)-No RWU are higher than for Scenario 1(a)-RWU in the rootzone (as expected). This difference is, on average, 0.05 cm^3/cm^3.The difference for the top 100cm of the profile is lower (0.04 cm^3/cm^3) indicating the Root Water Uptake parameters (Feddes) are reasonable and supports the inference that the Scenario 1(a) soil type (Clay Loam) is representative of the site. (Note: Scenario 1(b) using Clay did not show any significant difference and as such could be considered unrealistic as a soil type).

9.7 Scenario 1(a) RWU – Soil Moisture and Root Water Uptake (950 days)



UWA Laboratory Sapflow Data	cm/day	mm/day
UWA Max. Recorded *(to be reviewed)*	0.035	0.35
UWA Ave. Recorded *(to be reviewed)*	<0.005	<0.05
Model Sc1a: RWU	**RWU cm/day**	**RWU mm/day**
Max RWU	0.23	2.30
Ave. RWU	0.02	0.20
Median RWU	0.01	0.10
Max RWU over 1 day	0.12	1.24
% RWU values <0.05mm/day	36%	36%

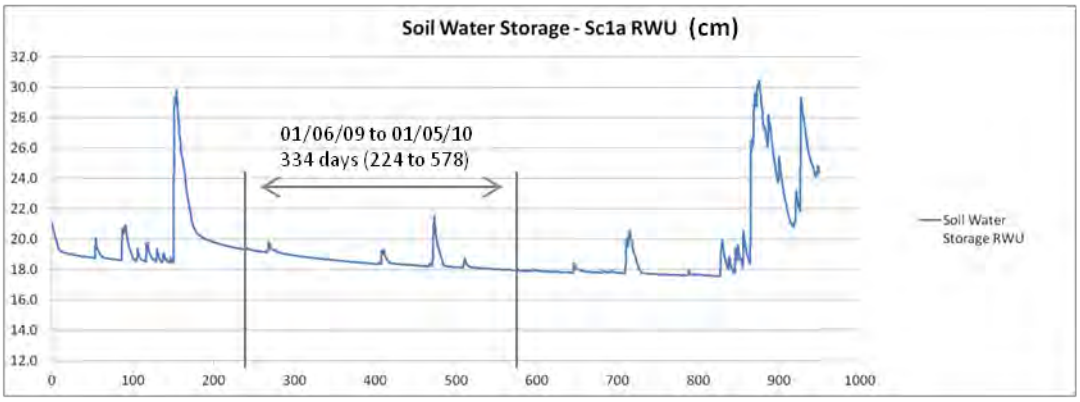
Day	Date	Day	Date	Day	Date
1	1/10/2008	336	1/09/2009	701	1/09/2010
124	1/02/2009	489	1/02/2010	823	1/01/2011
244	1/06/2009	578	1/05/2010	943	1/05/2011

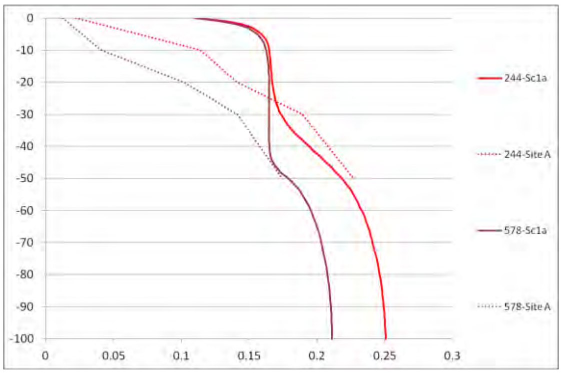
Figure 12: Scenario 1(a) RWU – Soil Moisture and Root Water Uptake (950 days). Water Content (cm^3/cm^3) and Day.

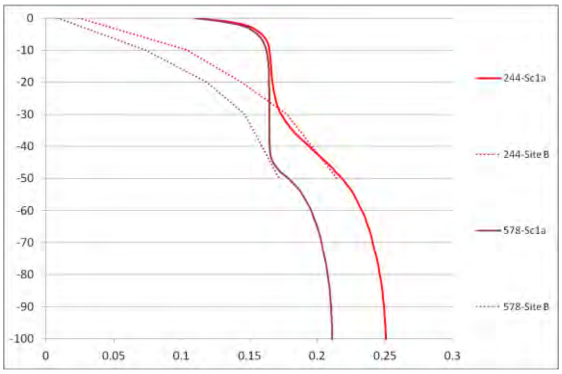
Question: Do the modelled time series soil moisture RWU data for Scenario 1(a) (Clay) compare well with the UWA field results for Site A (T. indica).

Answer: Yes. The model compares well with UWA field data for depths of 25cm-50cm. The UWA field data for the upper 0cm-25cm may be lower due to the reasons detailed in Section 8 (Model Calibration & Validation). The mean, median and maximum Root Water Uptake value (mean= 0.22mm/day, median=0.09mm/day with 36% of values <0.05mm/day, maximum=2.30mm/day) compares well with UWA data (Ave. Sapflow<0.05mm/day, Max Recorded Sapflow = 0.35mm/day)

9.8 Scenario 1(a) RWU – Soil Water Storage (01/06/09 to 01/05/10)







UWA Field Results	Site A	Site B
Δ SWS (cm)	2.59	1.71
Net loss (mm/day) top 50cm	0.08	0.05
Estimated Δ SWS (cm)	2.64	2.13
Net loss (mm/day) bottom 50cm	0.08	0.07
Δ SWS (cm)	5.23	3.84
Net loss (mm/day) in 100cm	0.16	0.12
Hydrus1D Results (RWU)	**Sc1a RWU Site A**	**Sc1a RWU Site B**
Modelled Δ SWS (cm)	2.57	2.57
Net loss (mm/day) in 100cm	0.08	0.08
UWA Results - Hydrus1D (RWU)		
Difference in Δ SWS (cm)	2.66	1.27
Difference in loss (mm/day)	0.08	0.04
Average for Site A and Site B		
Ave. Difference in Δ SWS (cm)		**1.97**
Ave. Difference in loss (mm/day)		**0.06**

Figure 13: Scenario 1(a) RWU – Soil Water Storage (01/06/09 to 01/05/10). Storage (cm); Depth (mbgl) and Water Content (cm^3/cm^3).

Question: Does the Soil Water Storage (SWS) times series data for Scenario 1(a) (Clay Loam) compare well with changes in SWS based on the UWA field results for Site A and site B (T. indica).

Answer: Yes. The model compares well with changes in SWS based on UWA field data, taking into account uncertainties in the upper 25cm of the profile. The modelled SWS and UWA data for SWS agree very well in the 40-50cm interval (refer to graphs).

9.9 Sensitivity and Uncertainty Analysis

The model sensitivity to the following Root Water Uptake Parameters was undertaken:

Evaporation:Transpiration (RWU) ratio. Model used 90%:10% (Ev:Tr). Sensitivity Analysis used a 50%:50% ratio. Both resulted in RWU to as low as 0.16 cm3/cm3 (-7000kPa). The Sensitivity Analysis for Scenario 1(a) still within calibration and insignificant impact to results. This is a Type 1 sensitivity and of no concern (MDBC, 2001. Figure 14).

Feddes' parameters for RWU. Model used -1500kPa to as low as -7000kPa, (Kew 2011). Sensitivity Analysis used -3000kPa to as low as -14000kPa (or 2x model values). The Sensitivity Analysis for Scenario 1(a) show the RWU could transpire to as low as 0.15 cm3/cm3, but still within calibration and insignificant impact to results. This is a Type 1 sensitivity and of no concern (MDBC, 2001. Figure 14).

Other sensitivities were undertaken in Stage 1 Modelling (Appendix 1). These included Soil Type, Access to Groundwater and Rainfall.

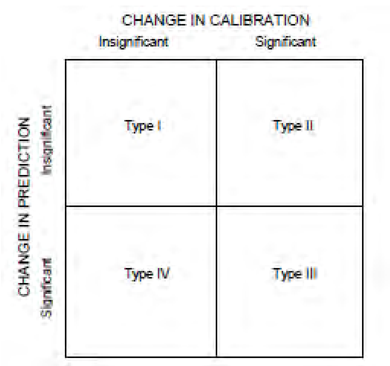


Figure 14: Sensitivity Analysis Decision Matrix (MDBC, 2001)

10 Solute Transport

The Stage 2 modelling follows on from the Stage 1 monitoring by considering solute transport and the precipitation and dissolution of hydrated minerals (such as gypsum).

The ability of HYDRUS1D to accurately model solute transport, precipitation and dissolution of hydrated minerals is dependent on a large number of complex soil, water and chemical parameters, a situation that is further complicated when transient boundary conditions are used (as is the case). Assuring model stability requires that this parameter set is consistent within itself. HYDRUS1D modelling of this sophistication is limited to controlled laboratory experiments where parameters can be accurately determined and well controlled.

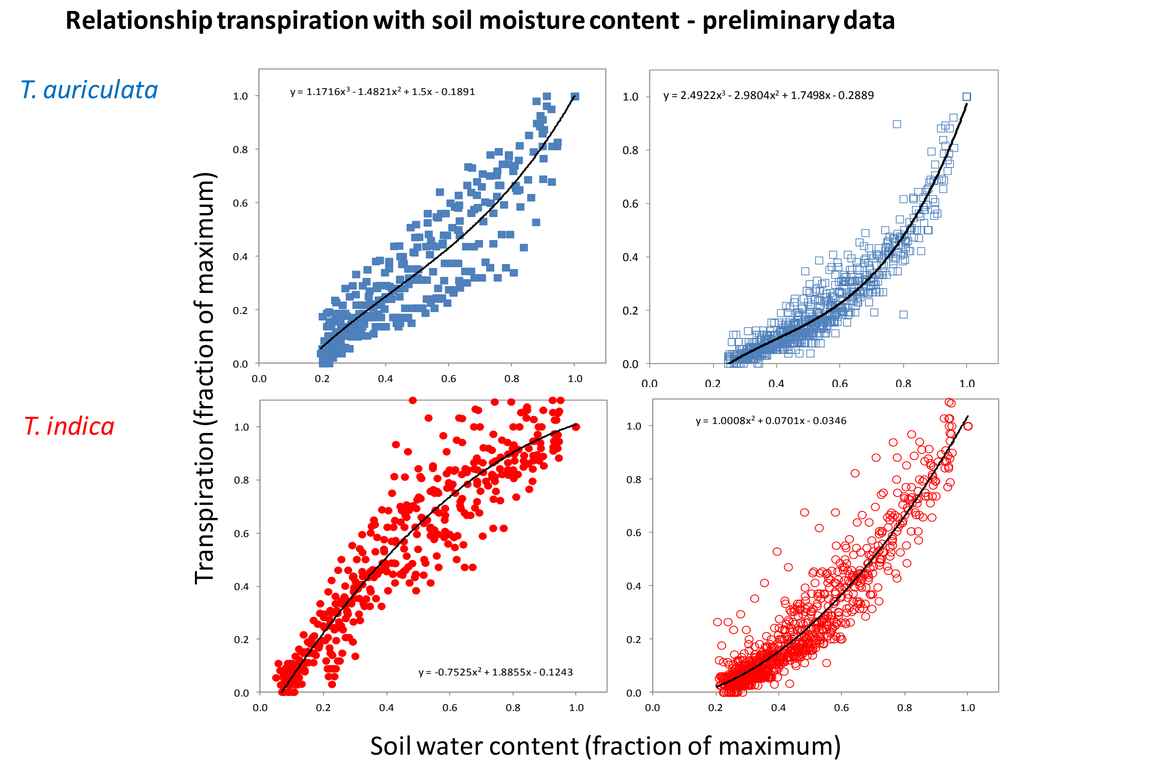
At this stage of the investigation, it should also be brought to the reader's attention that the large number of equations that are the basis of HYDRUS1D (and indeed all modelling software) are generally best applied to parameter values that are in the mid-range of allowable values. That is, model accuracy and stability tends to fall away at the extremes of parameter values. This investigation deals with extremes (highs and lows) of temperature, rainfall, inundation and drying, salinity, precipitation and dissolution etc. As such, there would be little confidence in any results following an update the HYDRUS1D model to include the Main Process of Solute Transport. Adding further complexity to the model at this stage was considered inappropriate in assessing salinity, particularly since reliable data is unavailable and highly impractical to gather through experimentation. Consequently, a more qualitative approach to the effects of salinity on *Tecticornia sp.* will be investigated by making reference to data provided by UWA.

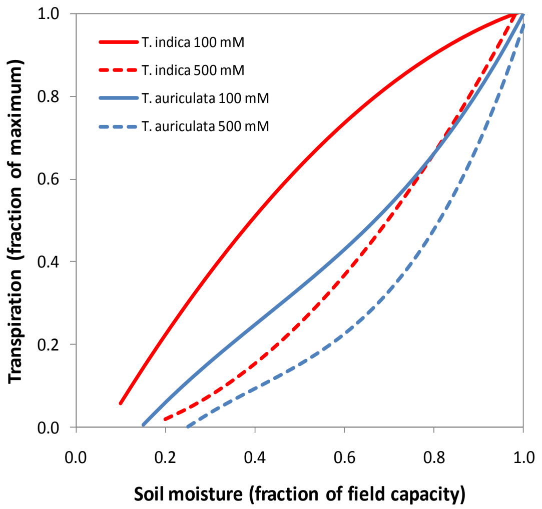
10.1 UWA Investigations – Impacts of Salinity of Transpiration

Figure 15 presents a summary of data from UWA research in to the transpiration rates for *Tecticornia sp.* under different soil water salinity scenarios (100mM and 500mM, units of milli-mole per litre).

For the four scenario graphs:

- Although polynomials have been fitted to each of the graph scenarios, the relationship between Transpiration and Soil Moisture appears to be fairly linear.
- Each of the four graph have data points that lie along the x-axis and all fitted polynomials intersect the x-axis at a value greater than indicating the lowest soil moisture at which transpiration occurs. These values range from about 0.2 (100mM) to 0.3 (500mM) for T. auriculata and from about 0.1 (100mM) to 0.2 (500mM) for T. indica.
- Values for Transpiration and Soil Moisture are represented as a fraction of their maximum. The maximum rate varies with species and salinity level and these results are summarised in the table within Figure 15.



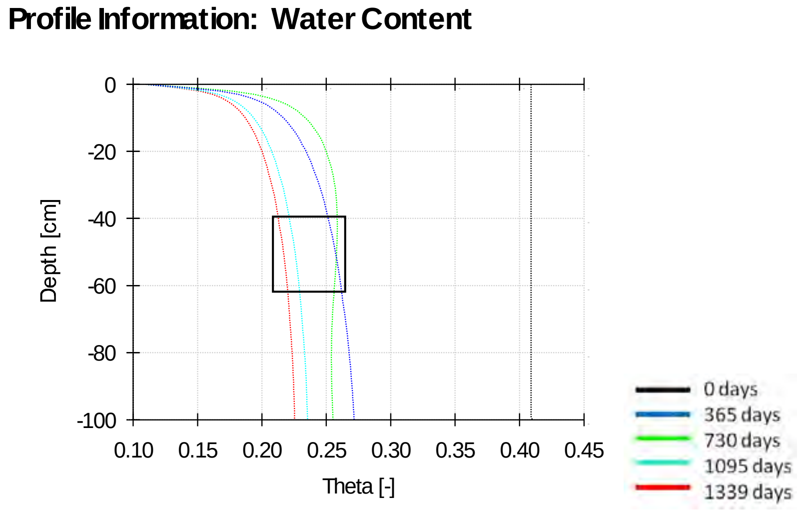


Samphire Species	Salinity mM	Transpiration mL g-1 FW day-1
T. indica	100	1.01
	500	0.43
T. auriculata	100	1.84
	500	0.98

Figure 15: The Transpiration (fraction of maximum) versus Soil Moisture (fraction of field capacity) for the ongoing UWA investigation into Samphire water use.

Under high salinity scenarios (500mM), *T. indica* still transpires at soil moisture values of 10%-20% of field capacity. Figure 16 shows the water content associated with the rooting zone (40cm-60cm) for the Stage 1 Scenario 1(a) (Clay Loam) modelling, the likely scenario for *T. indica.* These water content values range from 0.22 to 0.27, and are associated in the second graph with Hydraulic Capacity values that range from about 5%-15% of the maximum Hydraulic Capacity. This agrees well with the ranges presented in the UWA graphs in Figure 16 (10%-20%).

(a) CLAY LOAM



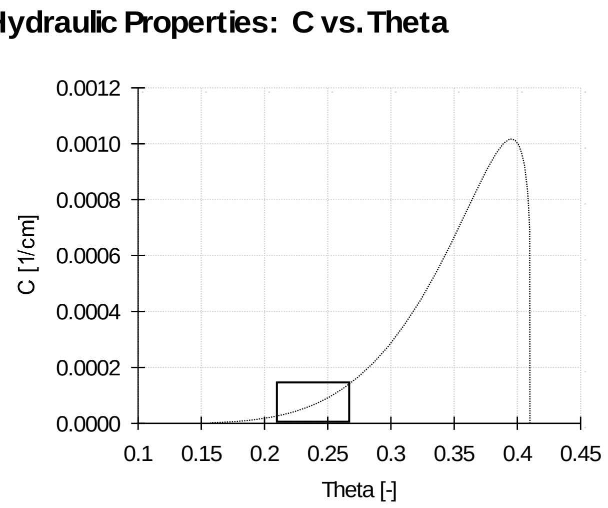


Figure 16: The Stage 1 (Appendix B) model results for Scenario 1(a) (*T. indica*) graph for Depth versus Water Content compared with Hydraulic Capacity versus Water Content. The Water Content (theta) range associated with the estimated Rooting Zone (40cm-60cm) is projected onto the curve for Hydraulic Capacity.

11 Stage 2 – Conclusions

The primary aim of the modelling assessment was to:

> ***"Determine whether surface water and groundwater interactions are vital to the sustainability of the marshes and evaluate the dynamics of stored soil water replenishment and water table fluctuations on water availability for samphire."***

And to test the hypothesis:

> ***"The water requirements of the Fortescue Marsh vegetation can be met by surface water inputs under most climatic regimes, including areas potentially exposed to modified groundwater depth."***

Stage 2 modelling results indicated that surface water and groundwater interactions may not be vital to the sustainability of the marshes. The results also suggest that the hypothesis above is true. That is, water requirements of the Fortescue Marsh vegetation can be met by surface water inputs under most climatic regimes, including areas potentially exposed to modified groundwater depth.

These conclusions are supported by the following results:

- All soil moisture profiles from the HYDRUS1D modelling indicate soil moisture levels that are comparable to field recorded values. Modelled results generally exceeded field results.
- Importantly, this is the case for Scenario 1(a) (not connected to GW), the most likely hydrogeological profile modelled with worst reasonable case scenario inputs.
- Scenario 1(a) Root Water Uptake modelling results for plant water use compared well with calculations based on UWA data.
- For the predictive scenario, a 2m reduction in groundwater levels has a minimal effect on the water content in the upper 100cm of the soil profile. This was performed using the less likely scenario, Scenario 2(a), which assumes connectivity to the watertable (3mbgl and 5mbgl during dewatering).
- The conclusions that can be made from comparing the HYDRUS1D results with salinity and transpiration results provided by UWA are that Samphire species have the ability to continue transpiration at very low water content levels (~10% of Field Capacity) with high salinity (500mM); and that these values are consistent with HYDRUS1D results for Scenario 1(a) and 1(b). These Scenarios represent the profile for T. indica at the fringe of the marsh (i.e. 1m to hardpan, no access to groundwater).
- The model would be further refined by describing the profiles as having an A and B horizon.

The modelling suggests that there is sufficient moisture in the upper soil profile to sustain the samphire vegetation communities even under very dry conditions and with no access to groundwater.

12 References

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Appendix 1 – UNSATURATED ZONE MODELLING

Fortescue Marsh

Stage 1 Investigations

UNSATURATED ZONE MODELLING – Fortescue Marsh Stage 1 Investigations

June 2012

Prepared for
Fortescue Metals Group

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Foreword to Appendix 1

This Appendix forms a preliminary report presenting results from the early stages of the investigation into the unsaturated zone modelling of the Fortescue Marsh. The investigation that began in 2010 was limited to a general assessment of soil moisture levels under various scenarios considered likely at the marsh using HYDRUS1D-4.14 software (Šimůnek et al, 2009). Inputs to the model were based on literature values and atmospheric data from the Newman Aero weather station (BoM site ID 7176). In addition, the preliminary modelling, being general in nature, investigated extremes such as the watertable levels at a constant level of 1 metre below ground level (mbgl) as well extended periods of drought.

Over the course of the investigation, The University of western Australia (UWA) provided Astron Soil and Water Pty Ltd (ASW) with a variety of site-specific datasets as they became available. Importantly, data from the on-site UWA weather station became available as well as comprehensive time-series data of field measured soil moisture levels. The series of time aligned input data and observation data allowed for better calibration and so a better understanding of the water balance for the likely soil profile known to exist at sensitive areas of the site. These site-specific time series results are presented in the main report (6021-10SR001W1_FMG Unsat Zone Model Report, ASW, 2012).

All modelled scenarios and their results that appear in this Appendix will be referred to as “preliminary modelling” or “Stage 1 modelling”.

1 Introduction

Fortescue Metals Group (Fortescue) is proposing to expand its iron ore mining operations at Christmas Creek and Cloudbreak, located approximately 120 kilometres north of Newman. These mining areas are collectively referred to as the Chichester Operations.

The mine expansions will require large scale dewatering to provide access to below watertable ore reserves. Mine pit dewatering creates zones of lowered watertables (drawdown zones) that extend beyond the mine pit boundaries. Groundwater injection can create zones of elevated watertables (mounding zones) centred around the injection bores. Collectively these effects can impact vegetation due to interactions between groundwater levels and vegetation water uptake.

The effects of dewatering have the potential to extend to the fringes of the Fortescue Marsh, an episodically inundated wetland with important conservation values. The Marsh includes a variety of plant communities dominated by samphire (*Tecticornia*) species. Fortescue has initiated a research program to improve understanding of the eco-hydrology of the Marsh vegetation.

Fortescue has contracted Astron Environmental Services Pty Ltd (AES), in its capacity as ASW, to provide unsaturated zone water balance modelling for the Fortescue Marsh for the purposes of:

- Improving understanding of soil moisture dynamics in the unsaturated zone profile, under different soil profile and climate scenarios.
- Identifying the potential contribution of groundwater to meeting vegetation water use requirements.
- Evaluating the potential impacts of modified watertable depth on plant available soil moisture.

Groundwater modelling of the proposed dewatering for the expansion of the Cloudbreak mine identified some areas along the fringe of the marsh that are likely to be within the zone of modelled groundwater drawdown. The extent to which samphire rely on groundwater must be understood to assess the impact that the proposed dewatering could have on the marsh ecology.

Tecticornia indica (*T. indica*) has been identified as the predominant samphire vegetation on the fringe of the marshes that may be affected by mine site dewatering activities and is the primary focus of this investigation. Model simulations of groundwater/surface water interactions with other vegetation in the marshes (*T. auriculata* and *T. medusa*) have also been undertaken to assess water availability under differing scenarios.

The primary aim of the modelling assessment is to:

> ***"Determine whether surface water and groundwater interactions are vital to the sustainability of the marshes and evaluate the dynamics of stored soil water replenishment and water table fluctuations on water availability for samphire."***

And to test the hypothesis:

> ***"The water requirements of the Fortescue Marsh vegetation can be met by surface water inputs under most climatic regimes, including areas potentially exposed to modified groundwater depth."***

The unsaturated zone modelling simulations are run using HYDRUS1D-4.14 software (Šimůnek *et al*, 2009).

Stage 1 of the preliminary modelling is limited to an assessment of soil moisture content based on the current seasonal regime of rainfall and evapotranspiration from October 2008 to May 2011 (Newman Aero), with the simulation period extended to include a worst case scenario "dry season" from June 2011 to May 2012 (modelled using 2009-2010 evaporation data with no rainfall). A qualitative assessment of salinity follows.

2 Stage 1 Scope of Work

Astron Soil and Water have completed Stage 1 of groundwater and unsaturated zone modelling to test the following hypothesis:

> _"The water requirements of the Fortescue Marsh vegetation can be met by surface water inputs under most climatic regimes, including areas potentially exposed to modified groundwater depth."_

The tasks identified in the Stage 1 scope of works are as follows:

1. **Select and obtain the preferred unsaturated zone modelling software (SWAP or HYDRUS-1D).**

A detailed assessment of modelling software was undertaken to determine the most appropriate platform for which to compile a suitable unsaturated zone model to predict water availability within the soil profile underlying the Fortescue Marsh.

2. **Determine how to effectively use the model and assess its suitability to achieve the desired objective of the study.**

Unsaturated zone modelling software estimates water flow in the unsaturated zone above the watertable by finding a numerical solution to the Richards's Equation for specified parameters. A parameter set that is representative of the vertical profile (plant/root/soil/groundwater) of the samphire marshes (and possibly other vegetation units) will be used as input to the simulations.

Based on the software assessment it was determined that adequate modelling resources and capabilities were available to meet the objectives of the study and could be used to simulate a variety of scenarios which may affect the sustainability of the Fortescue Marshes.

3. **Develop an initial parameter set to use in the model (utilising generic parameters for soil and water available in the HYDRUS1D-4.14 interface). This should also include a time series climate data set (developed in conjunction with Fortescue).**

An extensive parameter set was developed based on a range of common and generic model parameters with inputs for site specific parameters (where available) to obtain a realistic output result. Further site investigations were undertaken in April 2011 and the additional soil profile data was incorporated into the modelling.

Parameter list development is discussed in more detail in Section 3.2.

4. **Run the initial parameter set through the model to confirm that it delivers realistic and understandable outputs.**

Various scenarios were developed for evaluation using the HYDRUS1D-4.14 model, to obtain outputs for differing situations based on water input to the system and the interactions of groundwater and different soil profile characteristics.

A detailed discussion of the inputs to the model and the related outputs are described in Section 5 and Section 6 below.

The target outputs from Stage 1 were:

- a working model that produces understandable outputs and is capable of being used for testing parameter sensitivities and scenarios; and
- an initial parameter set (in tabular form) for review by the Fortescue hydrogeology team and subsequent development of this parameter set as new data comes to light
- A simulation using recent rainfall and evapotranspiration data recorded since October 2008 (BoM)
- A model based on recent soil profile descriptions and analysis (Kew Wetherby Soil Survey Pty/Ltd)
- Assess the model calibration and validity based on field measured soil moisture data (UWA) for the modelling period from the ARC Linkage project "Ecophysiology of stem succulent halophytes subject to changes in salinity and water availability: distinguishing natural dynamics from potential mine related impacts" being managed by the University of Western Australia (UWA) with funding support from Fortescue (ARC Linkage project LP0882350).
- Assessment of additional simulations and of Long Term Rain data for Sensitivity/Uncertainty Analysis
- A qualitative assessment of salinity based on UWA experimental data.

3 Methodology

3.1 Model Selection

Two models were evaluated for their suitability of unsaturated zone modelling of the Fortescue Marsh. These were:

1. **Hydrus-1D**: a Windows-based modelling environment for analysis of water flow and solute transport in variably saturated porous media. The software package includes the one-dimensional finite element model HYDRUS for simulating the movement of water, heat, and multiple solutes in variably saturated media. The model is supported by an interactive graphics-based interface for data-preprocessing, discretisation of the soil profile, and graphic presentation of the results. Further information about this model is available at: www.pc-progress.com/en/Default.aspx?hydrus-1d

2. **SWAP (Soil Water Atmosphere Plant)**: SWAP simulates transport of water, solutes and heat in unsaturated/saturated soils. The model is designed to simulate flow and transport processes at field scale level, during growing seasons and for long term time series. It offers a wide range of possibilities to address both research and practical questions in the field of agriculture, water management and environmental protection. Further information about this model is available at: www.swap.alterra.nl

Both models have been widely applied internationally for a variety of applications including ecological assessments.

HYDRUS1D (version 4.14) was selected as the preferred model to be used to assess the water requirements of the Fortescue Marsh vegetation. HYDRUS1D was chosen based on the following features:

- HYDRUS1D has a user friendly Graphical User Interface (GUI), HYDRUS1D vs 4.14.
- HYDRUS1D provides report ready graphs, tables and data via the GUI.
- HYDRUS1D has an option to “save as input to MODFLOW”.

HYDRUS1D has the following Main Processes, allowing the simulation of:

- Water Flow
    - Vapour Transport
    - Snow Accumulation at the Soil Surface
- Multiple Solute Transport
    - General Solute Transport
    - Transport of Major Ions
    - HP1 (HYDRUS-1D with PHREEQC)
- Heat Transport

- Root Water Uptake
- Root Growth
- Carbon Dioxide Transport

3.2 Parameter List Development

A parameter list was developed based on a simulation involving all the Main Processes available in HYDRUS1D. The list was provided to the relevant personnel at UWA and Fortescue who are involved in the Fortescue Marsh research program to identify site specific data that may be available for key parameter input.

Within the HYDRUS1D-4.14 interface, default values are available for many of the parameter inputs that are required and can be used where other data is unavailable. Default values considered most appropriate for the current understanding of the Marsh soil profile were used in the assessment. Additional field investigations have been undertaken by Fortescue that have enabled the suitability of some of these default values to be tested and validated.

A detailed parameter list defining key inputs used in the preliminary modelling is included in Appendix 2.

4 Assumptions and Limitations

4.1 Mathematical Modelling and Parsimony

The preliminary modelling was undertaken with the intention of providing estimates of the soil moisture in the profile under a simplified and conservative set of conditions. While there are assumptions and limitations in all modelling, the results from the simulations provide a suitable starting point for further investigations.

It is common for investigations like this one to undertake modelling of various likely scenarios, as well as some level of Sensitivity and Uncertainty Analysis, so as to provide a range of modelled scenarios (e.g. best case scenario, worst case scenario, extreme worst case scenario etc.) that will "capture" the range of scenarios that are likely in nature. The manipulation of model input parameters to precisely replicate actual recorded data is considered to be less than ideal as this approach is not "parsimonious" and can produce erroneous results when the model is used as a predictive tool. This is at odds with one of the fundamental tenets of mathematical modelling; i.e. the notion of "parsimony" (Fowkes and Mahony, 1996). It is considered better to have a range of simulations from a more generalised model with the intention of "capturing" the natural scenarios (the approach used in this investigation). This idea is represented conceptually in Figure 1.

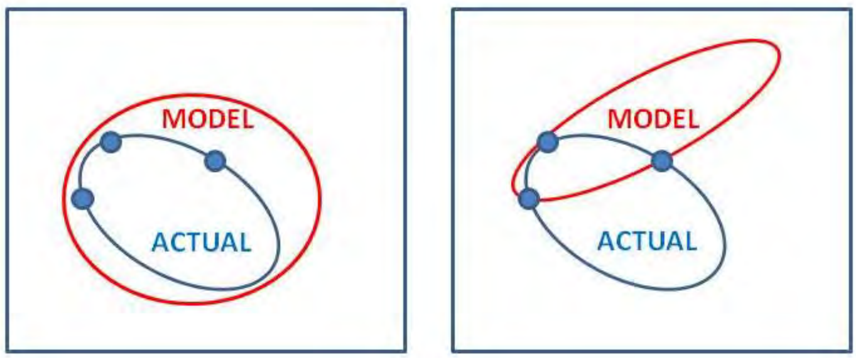


Figure 1: Model Parsimony.

The schematic on the left represent the range of results using a more generalised model approach (i.e. parsimonious) with reasonable calibration (3 blue dots) and capturing all "actual" results. The schematic on the right represents the range of results using a highly manipulated model with more precise calibration but with possible erroneous results and failing to capture all "actual" results.

4.2 Conceptual Model

The Conceptual Model for the Scenarios is presented in Figure 2. The three main samphire communities *T. indica, T. auriculata and T. medusa* have been identified in the marsh. As a general rule, these communities extend from the fringe of the marsh (chiefly *T. indica*), to inside the fringe (chiefly *T. auriculata*) and toward the centre (chiefly *T. medusa*). For Stage 1 modelling, only data from the *T. indica* and *T. medusa* communities are used since these represent the extremes of the marsh.

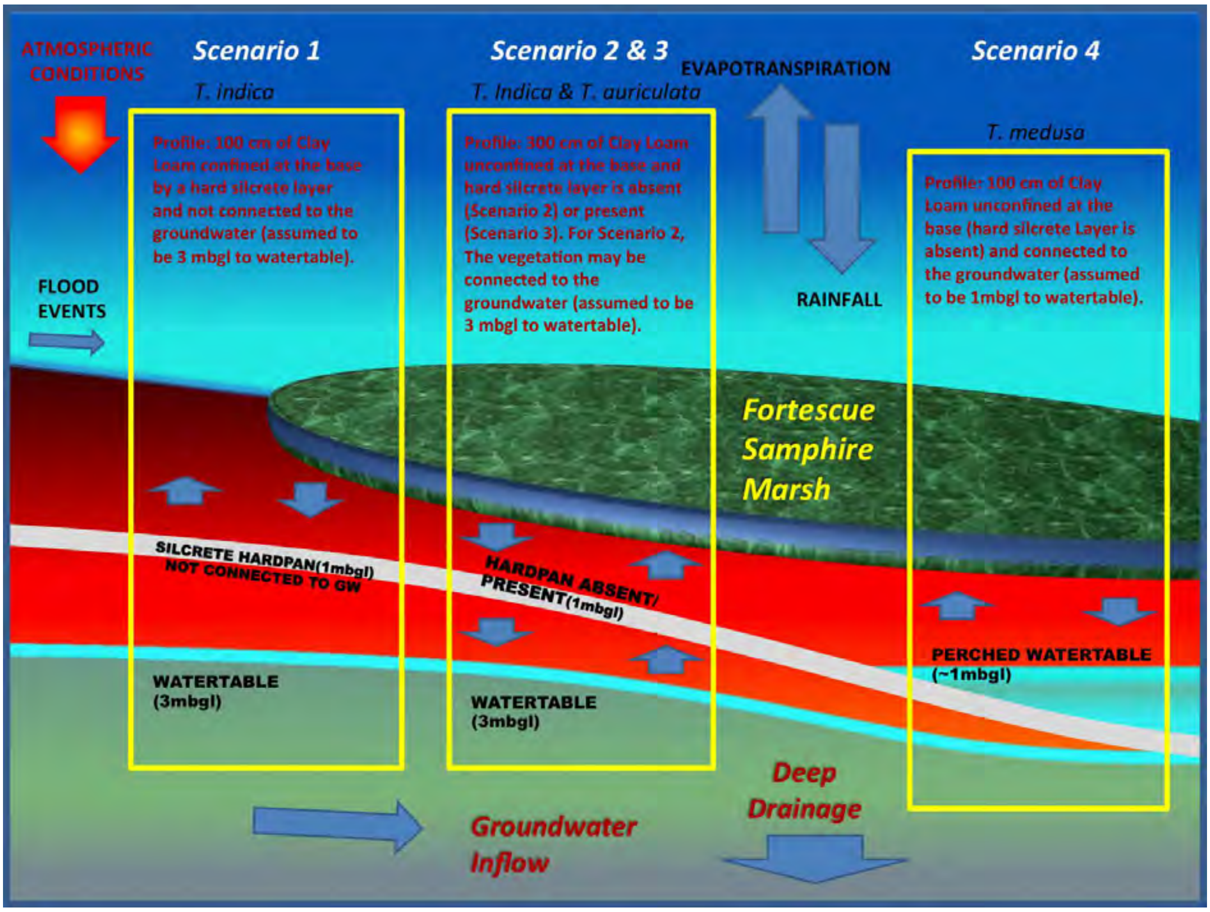


Figure 2: Conceptual Site Model

4.3 HYDRUS1D Main Processes -Assumptions

The modelling investigation for Stage 1 was limited to an assessment of the moisture content within the assumed Clay Loam and Clay soil profile. The assessment of moisture content was performed by selecting "Water Flow" in the Main Processes menu in HYDRUS1D-4.14. All the other Main Processes were not selected.

4.4 Hydro-geological Scenarios - Assumptions

The HYDRUS1D model was used to estimate the water content in either a Clay Loam or Clay soil profile under four different groundwater scenarios. In the model, moisture in the soil profile depends on the geometry of the profile, soil hydraulic properties, and the time variable atmospheric boundary conditions of rainfall and evapotranspiration. The following assumptions were made:

- The soil type for the upper soil profile (approximately top 1m) in all four Scenarios is the assumed to be Clay Loam or Clay. This is consistent with the findings of the UWA research project and more recent field results from test pits reported in the *Fortescue Marsh – preliminary soil investigation –Final report* (Kew, 2011). A hardpan including gypsum minerals has been recorded below this depth and is known to be extensive.

- Based on the US Soil Texture Triangle, the bulk density of the Clay Loam soil type ranges from about 1.27 g/cm^3 to 1.35 g/cm^3 (Saxton *et al*., 1986). An upper limit value of 1.35 g/cm^3

was used to convert gravimetric water content values from field measurements (units in g/g) to volumetric moisture content values (units in cm^3/cm^3) for comparison with the model outputs.

- The bulk density for Clay soil types are generally lower, however the methods used to calculate bulk density are unsuitable for well compacted soils high in clay (Saxton *et al*., 1986). In addition, precipitates of leached minerals (such as gypsum) are likely to occupy some of the pore spaces in the soil due to the cycle of inundation and drying. Clay soils of this nature may have bulk density values that are at the upper end of the range given for clay soils of 1.1 g/cm^3 to 1.6 g/cm^3 (ANRA, 2000-2002)

- The soil hydraulic properties for the single porosity van Genuchten – Mualem model for Clay Loam and Clay soils are based on parameters from Carsel and Parrish (1988) and are provided in HYDRUS1D-4.14. An “air entry” value of -2cm was used (recommended for clay soils).

- The saturated hydraulic conductivity for the silcrete is given as being between $1x10^{-7}$ m/day to $1x10^{-4}$ m/day (Domenico and Schwartz, 1990). The saturated hydraulic conductivity of the silcrete was set at Ks = 0.0001 m/day and represents the upper value (and most conservative) for the likely range of values for Ks.

- The modelled period is 1339 days (1st October 2008 to 31st May 2012) starting with a saturated soil profile. Rainfall and evapotranspiration (ET) inputs were based on daily values recorded from the Bureau of Meteorology (BOM) Newman Aero Weather Station (Station ID 007176) from October 2008 to May 2012. The period from 1st June 2011 to 31st May 2012 was assumed to have no rainfall (0mm) and ET based on the preceding year’s values (June 2010 to May 2011). This provides a “worst reasonable case scenario” with respect to rainfall by modelling a 1 year period of drought.

5 Modelled Scenarios

5.1 Approach

The approach will be based on the concepts represented in Figure 1 and the Conceptual Site Model (Figure 2):

- Model parsimony.
- Conservative parameters.
- Model based on available soil profile data, atmospheric conditions and lower boundary conditions.
- The modelled scenarios provide results that range from a "worst reasonable case scenario" to a "best reasonable case scenario" (with respect to soil type). The soil type is most critical to water retention/loss (for any given atmospheric/ boundary conditions). As such, the simulations based on (a), Clay Loam soils, represent the worst reasonable case for each Scenario 1 to 4, and the simulations based on (b), Clay soils, represent best reasonable case for each Scenario 1 to 4.
- The model results can be compared with field recorded soil moisture data to test whether the model is sufficiently calibrated and that the range of outputs successfully captures the range of field measured data (as in the left hand side schematic in Figure 1.)
- An uncertainty analysis to assess the "worst case scenario" of extended (but unlikely) periods of drought (10 years of no rain). These results can be compared with field data to assess whether this scenario results in soil moisture levels below field measured data and to what degree. Other uncertainties will also be investigated in this way.

5.2 Scenarios

The preliminary assessment included 4 groundwater scenarios as follows:

1. A shallow (100 cm) soil profile available to plant roots, confined by a hard silcrete (impeding) layer which functions as an aquitard.
2. A deep (300 cm) soil profile available to plant roots, with potential capillary connection to the underlying groundwater.
3. A deep (300cm) soil profile confined by a hard silcrete (impeding) layer of very low hydraulic conductivity present between 100cm and 150cm.
4. A shallow (100 cm) soil profile available to plant roots, overlying and in connection with groundwater at 100cm.

These scenarios were considered adequate to broadly represent potential conditions near the fringes of the Marsh (Scenarios 1, 2 and 3) and further towards the centre of the Marsh (Scenario 4).

The assessment continued by investigating these four scenarios based on soil types identified at the site following recent field results:

(a) Clay Loam soils (comparatively free draining soils)
(b) Clay soils (comparatively high water retaining soils)

There are therefore eight model scenarios in total:

- Scenario 1(a) and (b), Scenario 2(a) and (b), Scenario 3(a) and (b), and Scenario 4(a) and (b).

5.3 Predictive Scenarios – Impacts from Dewatering

Finally, the model can be used as a predictive tool for the assessment of the response of the model following the (unlikely) reduction of the (connected) water table from 3mbgl to 5mbgl (i.e. Scenario 2, Scenario 1 and 3 are not connected to watertable). This 2m reduction in groundwater levels is the worst case scenario impact from the proposed dewatering activities. The response of the modelled soil moisture levels in the profile following this reduction of groundwater levels can be assessed and an inference can be made as to how it may affect Samphire communities, particularly for the upper 0.5m where the majority of the Samphire's roots occur.

6 Model Inputs

6.1 Parameters

The following parameter values were used for the four (4) scenarios. Parameters relating to some of the more technical aspects of the numerical model development have been intentionally left out of this report.

6.1.1 Soil Type

The predominant soil types were identified as Clay Loam and Clay to provide the suitable range of scenarios. The soil descriptions are based on the US Soil Texture Triangle (Figure 3):

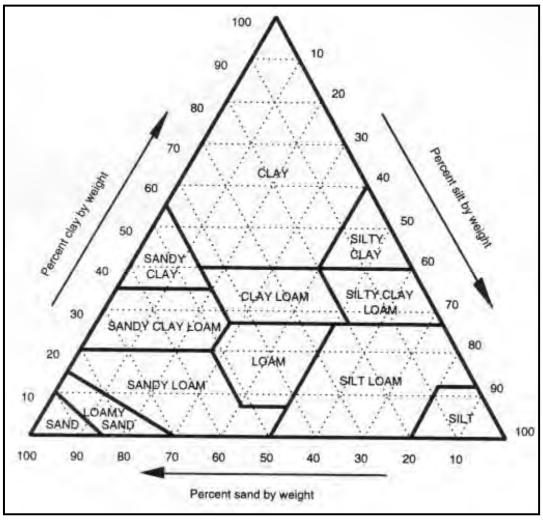


Figure 3: US Soil Texture Triangle

6.1.2 Bulk Density

Based on this classification, the upper limit value for bulk density of Clay Loam soil type was 1.35 g/cm^3 (Saxton *et al.*, 1986 in Šimůnek *et al.*, 2009). Saxon et al (1986) stresses that the methods described for assessing bulk density by are not valid for soils with a high clay content. Soils high in clay were identified in the test pits and as such, an estimate for the bulk density must be made. Clay soils that are compacted have bulk density values that are at the upper end the range given for this soil type of 1.1 g/cm^3 to 1.6 g/cm^3(ANRA, 2002). For simulations involving Clay soils, a value of 1.6 g/cm^3 was used. The values used for Clay Loam and Clay soils represent a conservative approach with respect to the effective porosity since a higher bulk density value results in reduced pore water availability.

The different measures of water content are related by the equation:

ϴ(Volumetric) = Bulk Density x ϴ(Gravimetric)

The higher values used for Bulk Density will result in a higher estimation for ϴ(Volumetric) for field measured moisture (undertaken by UWA).

6.1.3 Soil Hydraulic Properties

The soil hydraulic properties for Clay loam and Clay are presented in Table 1.

Table A: **Soil Hydraulic Properties for the single porosity van Genuchten-Mualem model**

Param.	Description	Clay Loam	Clay
Qr	Residual soil water content, θ_r	0.095	0.068
Qs	Saturated soil water content, θ_s	0.41	0.38
Alpha	Parameter α in the soil water retention function [L^{-1}]	0.019	0.008
n	Parameter *n* in the soil water retention function	1.31	1.09
Ks	Saturated hydraulic conductivity, K_s [LT^{-1}]	6.24	4.8
l	Tortuosity parameter in the conductivity function [-]	0.5	0.5

Source: Values provided in HYDRUS1D-4.14 from Carsel and Parrish (1988)

6.1.4 Upper Boundary Conditions

Atmospheric Boundary Conditions with Surface Layer was chosen to represent the fluxes at the surface of the profile. This allows ponding during heavy rainfall periods. In the model, ponding will be significantly less and for much shorter periods since the model does not include runoff from upper reaches of the river to the Marsh.

This makes the model a conservative representation of the Marsh hydrogeology with respect to water inputs into the soil profile, and therefore appropriate for investigating the potential exposure of vegetation to dry soil conditions.

6.1.5 Rainfall

The transient model period is 1339 days (1st October 2008 to 31st May 2012).

Rainfall inputs were based on daily values recorded for Newman Aero Weather Station (ID 007176) from October 2008 to May 2012. The period from 1st June 2011 to 31st May 2012 was assumed to have no rainfall (0mm). This provides a worst case scenario when investigating moisture content at the end of each simulation.

The three graphs presented in Figure 4 indicate that:

- Rainfall conditions for the modelled period (and the period immediately preceding) are marginally drier than the medium to longer term rainfall patterns.
- Longer term rainfall conditions are currently stable following a steady increase overall since 1998 (exemplified by the Residual Rainfall Mass Curve which shows the moving average for 1972-2010).

The model is therefore conservative with regard to rainfall inputs since the 1339 day simulation period begins with a 2 year period of relatively dry conditions and ends with a year of no rainfall. In addition, the longer term pattern shows conditions are currently fairly stable, and that there is little evidence of an overall drying trend.

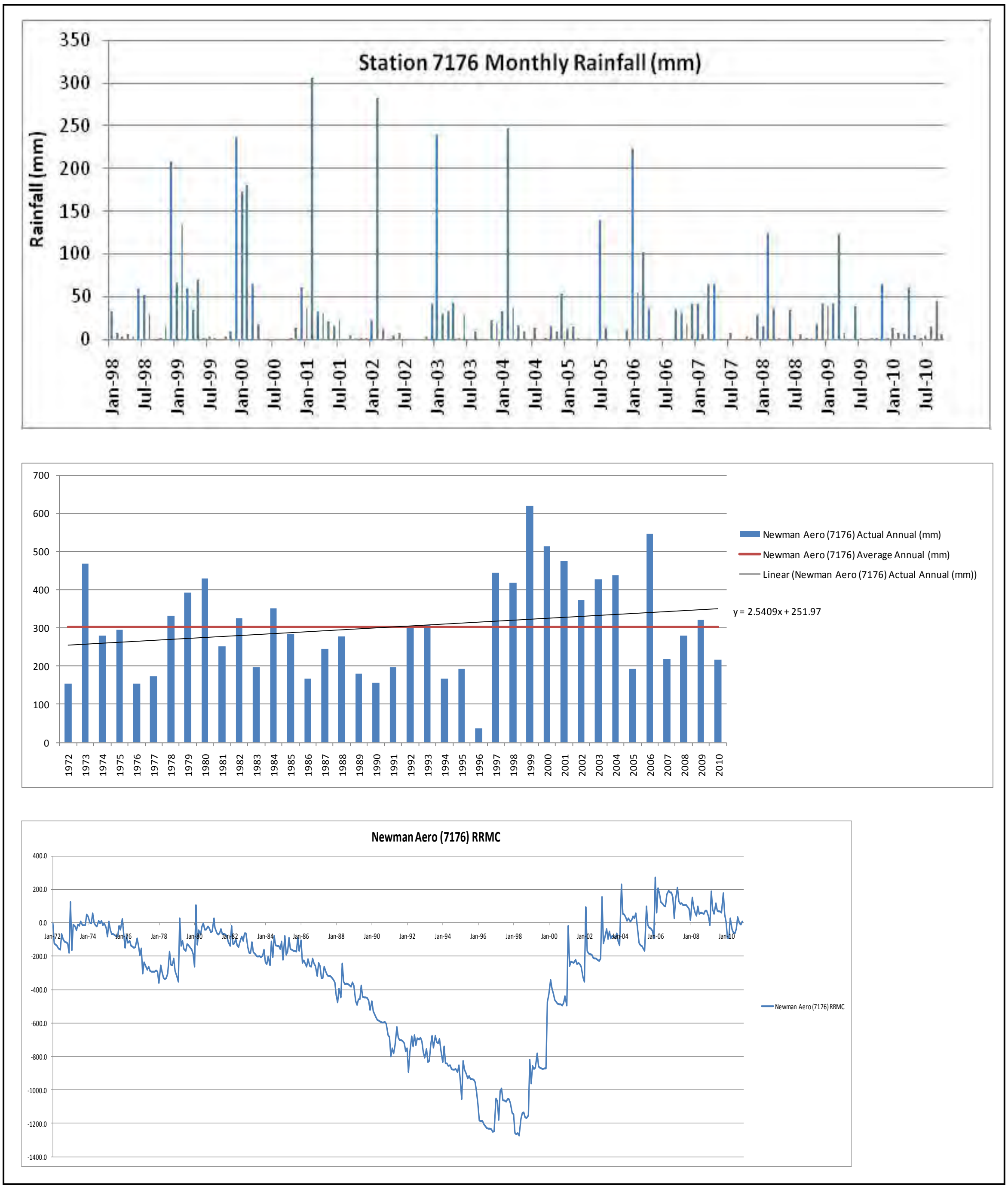


Figure 4: **Station 7176 Monthly Rainfall (BoM, 1998 to 2010), Annual Rainfall (1972 to 2010) and Long Term Residual Rainfall Mass Curve (1972 to 2010)**

6.1.6 Evapotranspiration (ET)

ET values were based on daily values recorded for Newman Aero Weather Station (ID 007176) from October 2008 to May 2012. The period from June 2011 to May 2012 repeated the ET values for May 2010 to May 2011. The values for ET represent a standardised "reference evapotranspiration" used by BoM and described in *Bureau of Meteorology Reference Evapotranspiration Calculations (C.P. Webb, 2010).* The abstract from this document is reprinted below:

> Reference evapotranspiration (ET_o) data is valuable for a range of users, including farmers, hydrologists, agronomists, meteorologists, irrigation engineers, project managers,

consultants and students. Daily ETo data for 399 locations in Australia will become publicly available on the Bureau of Meteorology's (BoM's) website (www.bom.gov.au) in 2010. A computer program developed in the South Australian Climate Services Centre of the BoM (SACSC) is used to calculate these figures daily. Calculations are made using the adapted Penman-Monteith equation recommended by the United Nations Food and Agriculture Organisation (FAO56-PM equation). Inputs to the equation include temperature, relative humidity and wind speed data from BoM weather stations and satellite derived daily solar radiation data. In the proposed ET_o tables for each weather station, daily evaporation pan (E_{pan}) data are presented alongside ET_o data. E_{pan} data are often used to estimate ET_o and the methods and limitations of doing so are discussed, as is the issue of missing data.

Crop water need, potential evapotranspiration and actual evapotranspiration are related as follows:

crop water need = potential evapotranspiration - actual evapotranspiration

Potential ET represents the (maximum) water demand of the atmosphere and therefore is appropriate for worst case scenario modelling. ET values were based on daily values recorded for Newman Aero Weather Station (BoM ID 007176)

Figure 5 shows the cumulative infiltration and Figure 6 shows the cumulative evaporation for the modelled period.

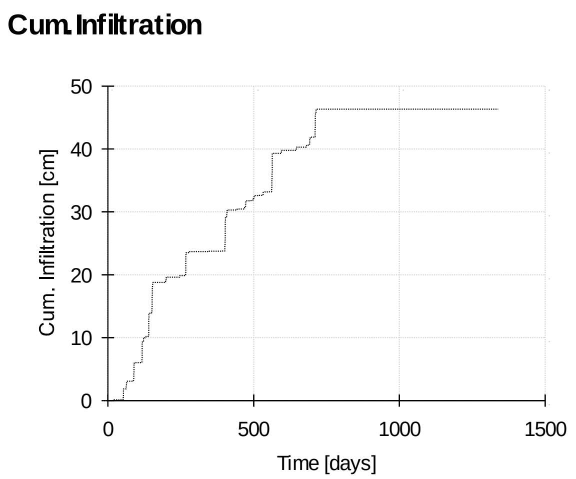


Figure 5: Cumulative Infiltration (Oct 2008 – May 2012)

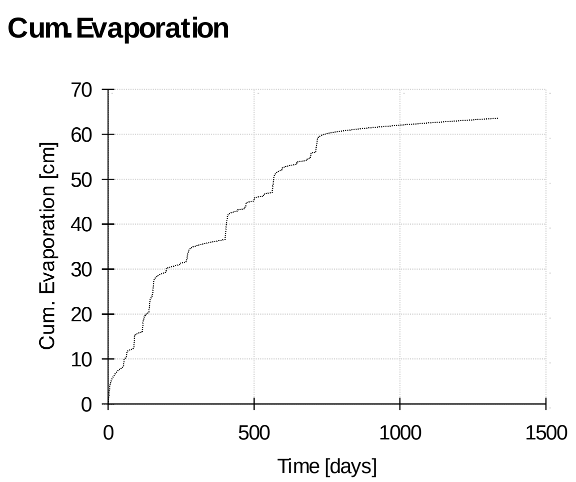


Figure 6: Cumulative Evaporation (Oct 2008 – May 2012)

6.1.7 Lower Boundary Conditions

Either a *constant flux* or *constant water content* lower boundary condition was used in the model. The values assigned to the lower boundary conditions are described for each scenario.

6.2 Modelled Scenarios

6.2.1 Scenario 1 (a) and (b)

Scenario 1 represented the vegetation community along the fringe of the Fortescue Marsh (primarily *T. indica*) and is considered to be the vegetation community most susceptible to alterations to the hydrogeology/hydrology in the region (i.e. watertable is influenced by dewatering). The profile is described in the model as follows:

- Profile: 100 cm of (a) Clay-Loam soils or (b) Clay soils confined at the base by a hard silcrete layer and not connected to the Groundwater (assumed to be 3mbgl to watertable).

- Lower Boundary Condition: Constant Flux = 0 cm/day for (a) and (b)

6.2.2 Scenario 2 (a) and (b)

Scenario 2 represented the same vegetation community as Scenario 1 (*T. indica*), however the profile is described in the model as follows:

- Profile: 300 cm of (a) Clay-Loam soils or (b) Clay soils unconfined at the base (hard silcrete layer is absent). The vegetation is possibly connected to the groundwater (assumed to be 3mbgl to watertable).

- Lower Boundary Condition: Constant Water Content ($\theta_{SATURATED}$) = (a) 0.41 or (b) 0.38

6.2.3 Scenario 3 (a) and (b)

Scenario 3 represented a similar vegetation community as Scenario 1 and 2 (*T. indica*). The profile is described in the model as follows:

- Profile: 300 cm of (a) Clay-Loam soils or (b) Clay soils and Silcrete. The hard silcrete layer is present between -100 cm and -150 cm. The vegetation is possibly connected to the groundwater (assumed to be 3mbgl to watertable), albeit through the hard silcrete layer of very low hydraulic conductivity.

- Lower Boundary Condition: Constant Water Content ($\theta_{SATURATED}$) = (a) 0.41 or (b) 0.38

- The saturated hydraulic conductivity of the silcrete was set at Ks = 0.0001 m/day and represents the upper value (and most conservative) for the likely range of values for Ks (Domenico and Schwartz, 1990).

6.2.4 Scenario 4 (a) and (b)

Scenario 4 represented the vegetation community in the middle of the Fortescue Marsh (*T. medusa*) and is considered to be the vegetation community least susceptible to alterations to the hydrogeology/hydrology in the region (i.e. watertable is not influenced by dewatering). The profile is described in the model as follows:

- Profile: 100 cm of (a) Clay-Loam soils or (b) Clay soils unconfined at the base (hard silcrete layer is absent) and connected to the groundwater (assumed to be 1 mbgl to watertable).

- Lower Boundary Condition: Constant Water Content ($\theta_{SATURATED}$) = (a) 0.41 or (b) 0.38

7 Model Outputs & Results – Stage 1

7.1 Modelled Scenarios – HYDRUS1D Results

7.1.1 Scenario 1 (a) and (b) (*T. indica*).

- Profile: 100 cm of (a) Clay-Loam soils or (b) Clay soils confined at the base by a hard silcrete layer and not connected to the groundwater (assumed to be 3 mbgl to watertable).
- Lower Boundary Condition: Constant Flux = 0 cm/day for (a) and (b).

(a) CLAY LOAM

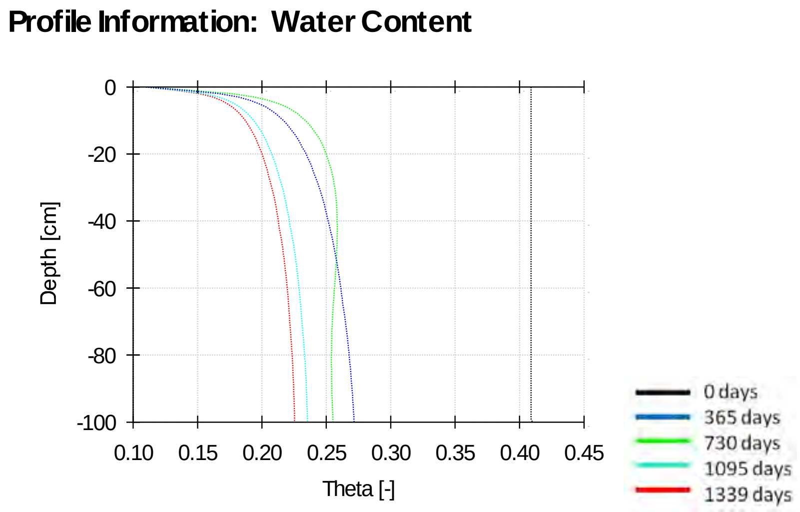


Figure 7: **Water Content (1 Oct 2008 – 31 May 2012) - Scenario 1a**

(b) CLAY

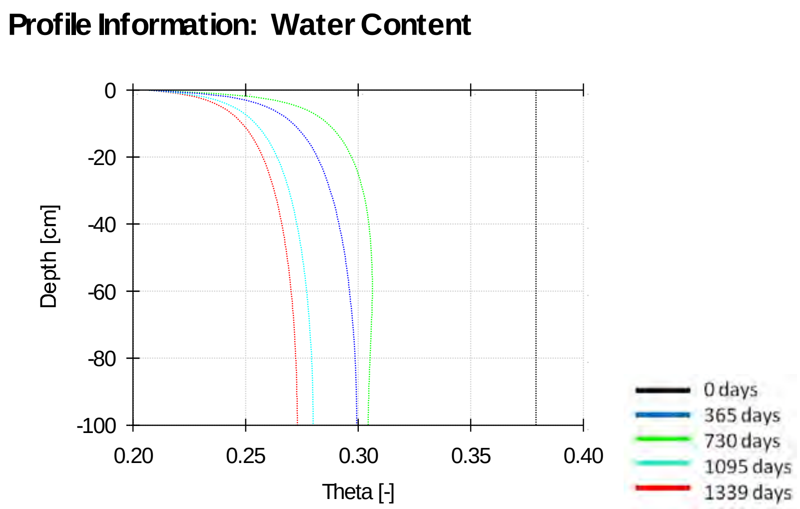


Figure 8: **Water Content (1 Oct 2008 – 31 May 2012) - Scenario 1b**

7.1.2 Scenario 2 (a) and (b) (*T. indica*).

- Profile: 300 cm of (a) Clay-Loam soils or (b) Clay soils unconfined at the base (hard silcrete layer is absent). The vegetation is possibly connected to the groundwater (assumed to be 3 mbgl to watertable).

- Lower Boundary Condition: Constant Water Content ($\Theta_{SATURATED}$) = (a) 0.41 or (b) 0.38.

(a) CLAY LOAM

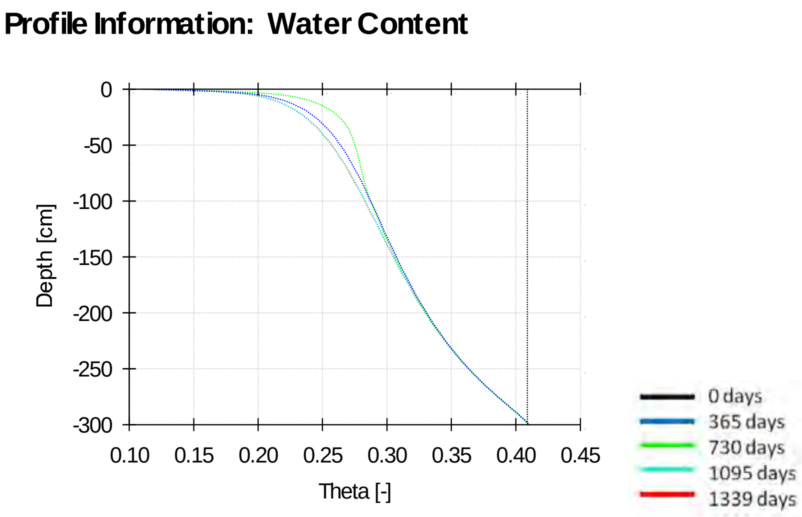


Figure 9: **Water Content (1 Oct 2008 – 31 May 2012) - Scenario 2a**

(b) CLAY

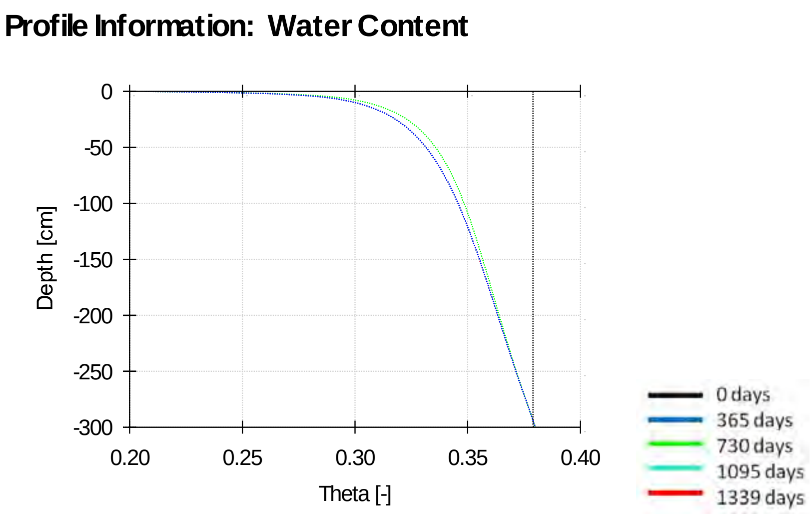


Figure 10: **Water Content (1 Oct 2008 – 31 May 2012) - Scenario 2b**

7.1.3 Scenario 3 (a) and (b) (*T. indica*).

- Profile: 300 cm of (a) Clay-Loam soils and Silcrete or (b) Clay soils and Silcrete. The hard silcrete layer is present between -100 cm and -150 cm. The vegetation is possibly connected to the groundwater (assumed to be 3mbgl to watertable), albeit through the hard silcrete layer of low hydraulic conductivity.

- Lower Boundary Condition: Constant Water Content ($\theta_{SATURATED}$) = (a) 0.41 or (b) 0.38.

- The saturated hydraulic conductivity of the silcrete was set at K_s = 0.0001 m/day and represents the upper value (and most conservative) for the likely range of values for K_s (Domenico and Schwartz 1990).

(a) CLAY LOAM

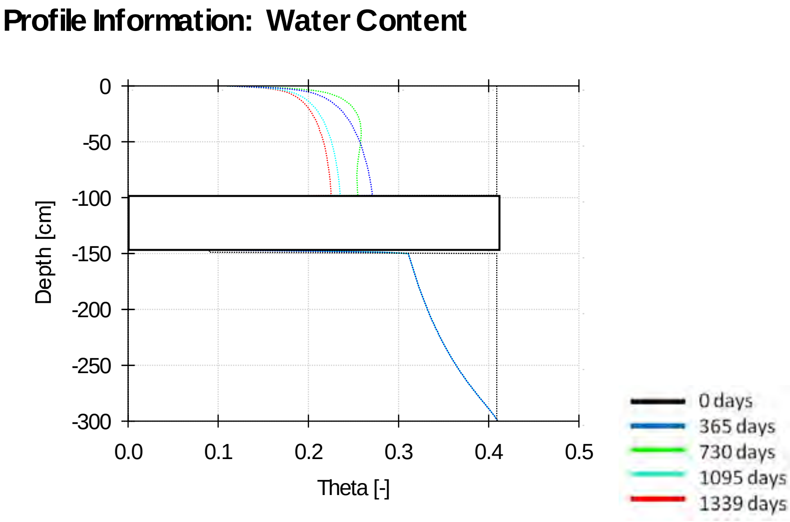


Figure 11: Water Content (1 Oct 2008 – 31 May 2011) - Scenario 3a

(b) CLAY

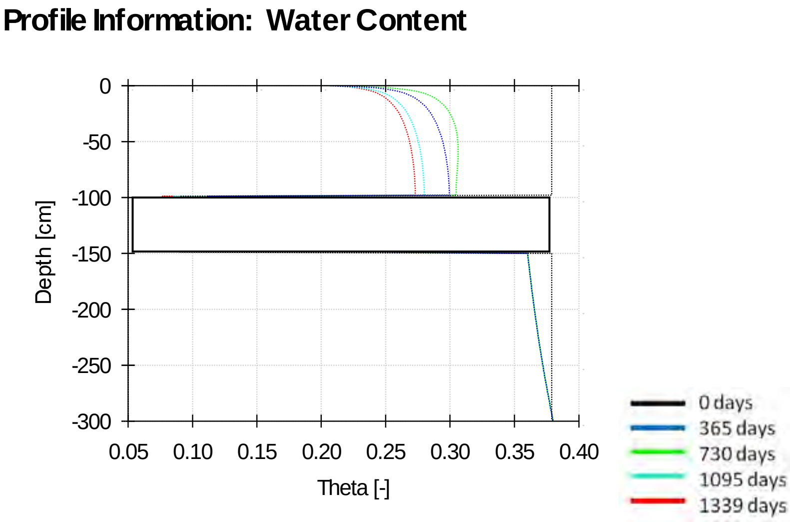


Figure 12: Water Content (1 Oct 2008 – 31 May 2011) - Scenario 3b

7.1.4 Scenario 4 (a) and (b) (*T. medusa*)

- Profile: 100 cm of (a) Clay-Loam soils or (b) Clay soils unconfined at the base (hard silcrete layer is absent) and connected to the groundwater (assumed to be 1mbgl to watertable).
- Lower Boundary Condition: Constant Water Content ($\theta_{SATURATED}$) = (a) 0.41 or (b) 0.38.

(a) CLAY LOAM

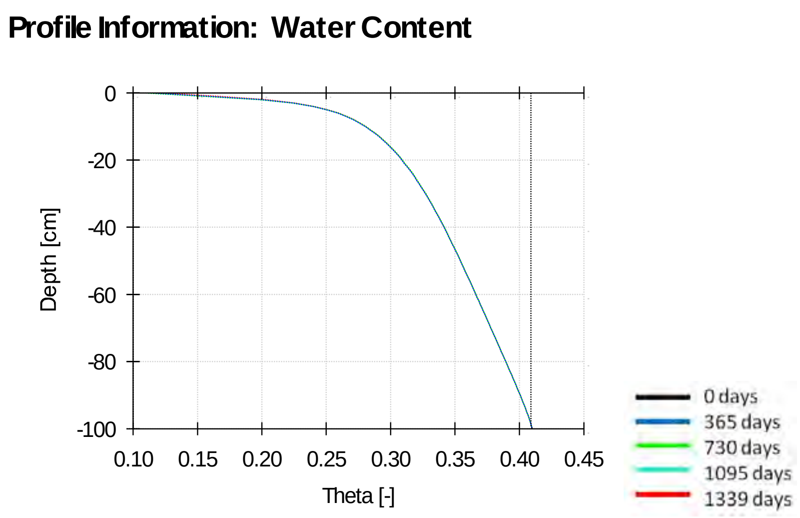


Figure 13: **Water Content (1 Oct 2008 – 31 May 2011) - Scenario 4a. Soil Moisture is maintained, due to capillary action from the shallow watertable is in relative equilibrium**

(b) CLAY

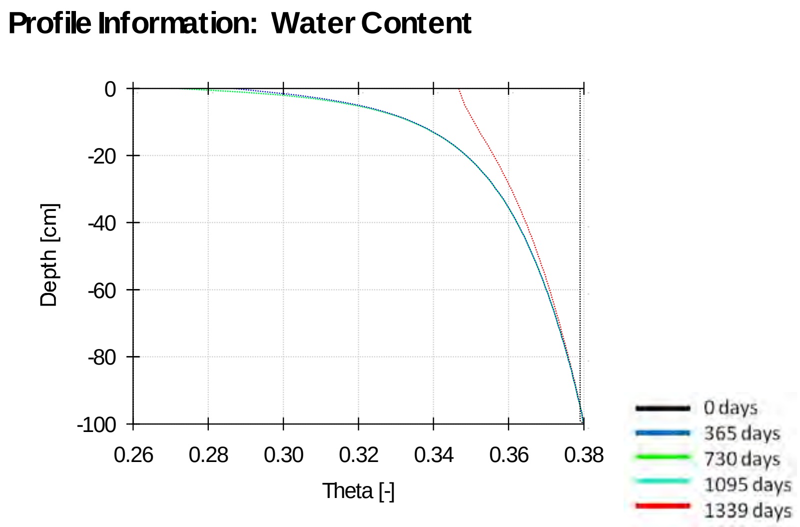


Figure 14: **Water Content (1 Oct 2008 – 31 May 2011) - Scenario 4b.**

Note that heavy rainfall period from late 2010 through to April 2011 (resulting in temporary ponding) followed by year of no rainfall is represented by the red line, and demonstrates significant water retention for Clay soils. The profiles show that soil moisture equilibrium is established (Clay Loam) or exceeded (Clay) since all four of the colour line graphs representing the yearly model results coincide.

7.2 Model Calibration and Validation

The model calibration and validation was undertaken by comparing modelled results to observed field data. The field data was gravimetric soil moisture readings from research conducted by UWA. Gravimetric soil moisture values were provided for three locations along two transects A and B.

These results provide gravimetric water content (in g/g) for soil depths to 40 cm (the midpoint of a 30cm-50cm interval). The readings are from sampling events that took place between October 2008 and May 2011.

Calibration and validation of the HYDRUS1D model consisted of the comparison between the modelled soil water content and the observed soil water content (minimum, mean and maximum over time). This was necessary since a time-series comparison approach could not be warranted due to the non site-specific atmospheric data.

The model output from initial saturation to the end of the 1339 day simulation was used for all scenarios, as this represents the simulated soil water content range up to and including the extensive period of drying (0 mm of rainfall for June 2011 to May 2012).

For a comparison of the field data with the model output, the following scenarios were investigated:

- Scenarios 1, 2 moisture profiles for both soil types were compared against the field data for *T. Indica* A (marsh fringe vegetation) but not for *T. auriculata* (inside fringe vegetation, this may be included in future stages of modelling). Inspection of Scenario 3 moisture profiles and data (hardpan at 1mbgl, 3m to GW) shows that the moisture content for the upper 1m is within 3 decimal places of Scenario 1 moisture content values and need not be included in the comparison.

- Scenario 4 moisture profiles were compared against the field data for *T. Medusa* A (central vegetation).

- The minimum, mean and maximum gravimetric water content values (over time) were converted to volumetric water content by multiplying the values by the estimated (worst reasonable case) bulk density values of BD=1.35 g/cm^3 for (a) Clay Loam soils, and BD=1.6 g/cm^3 for (b) Clay soils.

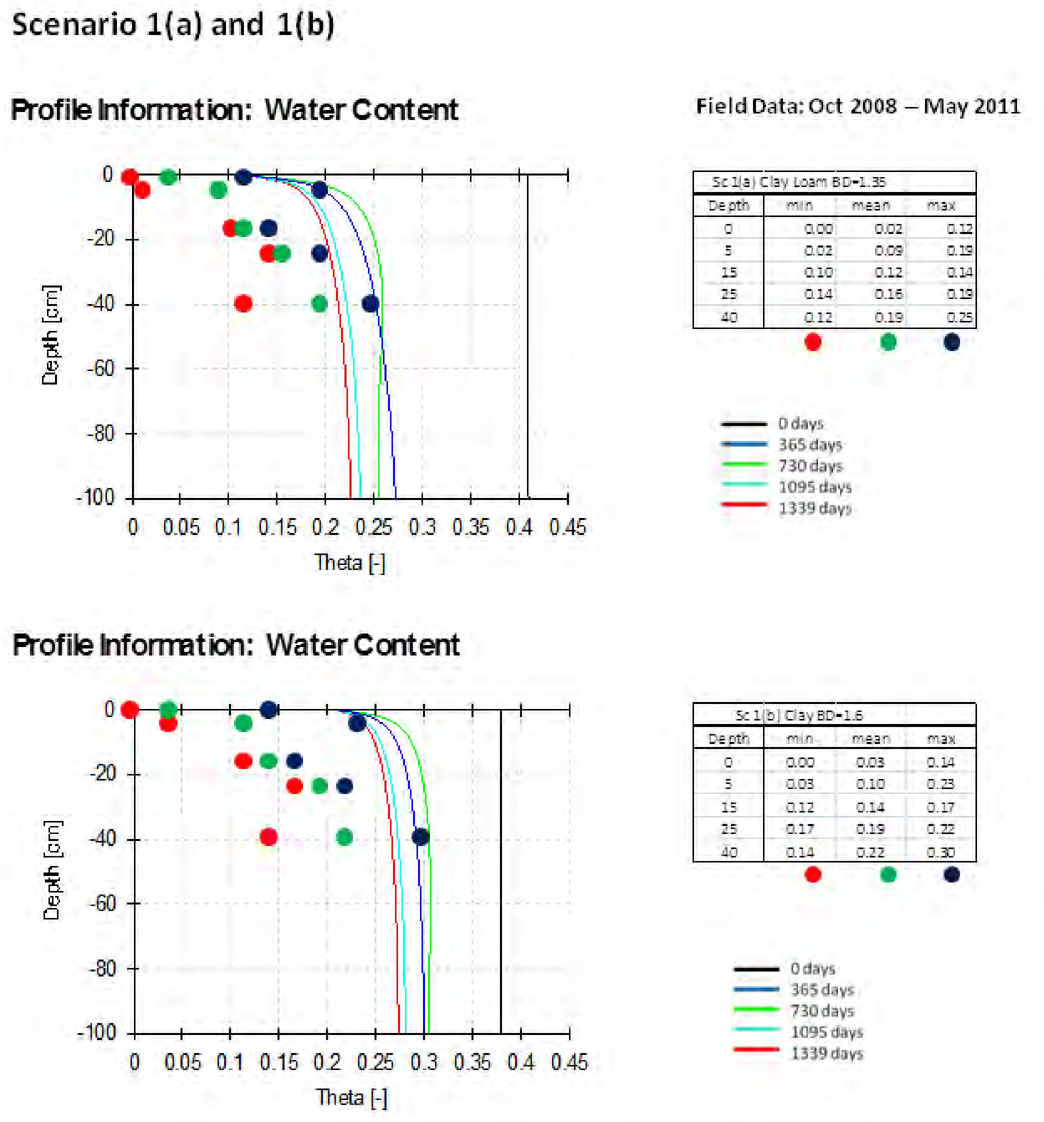
The figures that follow (Figures 15, 16 and 17) show the converted field data (min, mean and max) with the modelled profiles. It should be noted that:

- The maximum recorded field data for T. indica (rather that the mean of these values) is generally well correlated with the range of soil moisture profiles generated for the modelled period. This suggests a possible excess of moisture in the model, moisture that may be available for root uptake.

- The mean recorded field data for T. indica is generally well correlated with the (consistent) range of soil moisture profiles generated for the modelled period. The increase of moisture with depth and the beyond saturation values (inundation) is consistent with the modelled scenario that has a shallow, constant watertable.

- The field data for T. indica (shown within model Scenarios 1 and 2) indicates that at minimum moisture levels (red dots), moisture levels near rooting depth (40cm) are clearly less than for immediately higher in the profile (25cm), and this may be indicative of active moisture uptake at this lower depth

- The field data T. medusa (shown with model Scenario 4) shows an increase of moisture with depth, regular inundation and no apparent root uptake zone at 40cm since there is sufficient water throughout the profile (including just below ground level at 5cm) to support the samphire's root water uptake requirements.



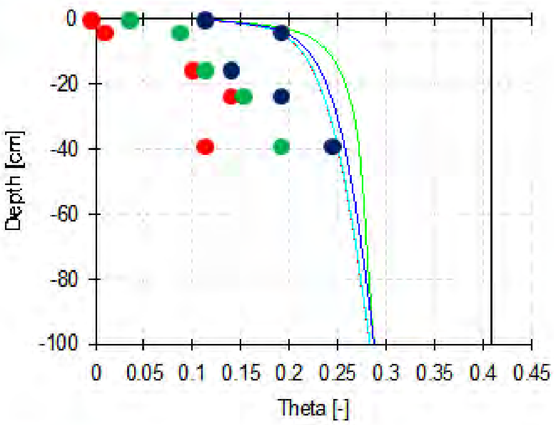
Sc 1(a) Clay Loam BD=1.35			
Depth	min	mean	max
0	0.00	0.02	0.12
5	0.02	0.09	0.19
15	0.10	0.12	0.14
25	0.14	0.16	0.19
40	0.12	0.19	0.25

Sc 1(b) Clay BD=1.6			
Depth	min	mean	max
0	0.00	0.03	0.14
5	0.03	0.10	0.23
15	0.12	0.14	0.17
25	0.17	0.19	0.22
40	0.14	0.22	0.30

Figure 15: Modelled and Observed water content for Scenario 1 (Clay Loam and Clay)

Scenario 2(a) and 2(b)

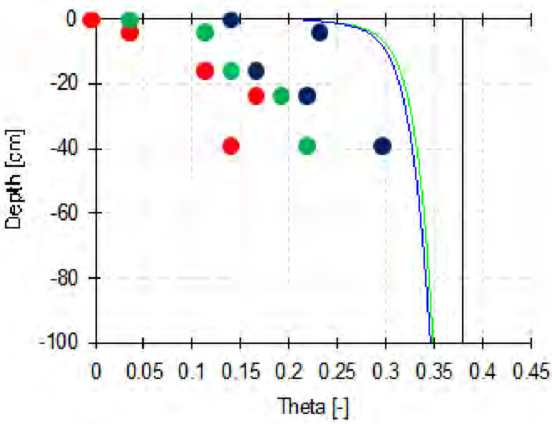
Profile Information: Water Content



Field Data: Oct 2008 – May 2011

Sc 2(a) Clay Loam BD=1.35			
Depth	min	mean	max
0	0.00	0.02	0.12
5	0.02	0.09	0.19
15	0.10	0.12	0.14
25	0.14	0.16	0.19
40	0.12	0.19	0.25

Profile Information: Water Content



Sc 2(b) Clay BD=1.6			
Depth	min	mean	max
0	0.00	0.03	0.14
5	0.03	0.10	0.23
15	0.12	0.14	0.17
25	0.17	0.19	0.22
40	0.14	0.22	0.30

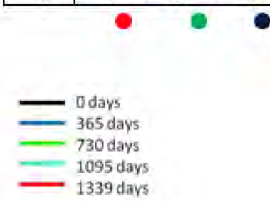


Figure 16: Modelled and Observed water content for Scenario 2 (Clay Loam and Clay)

Scenario 4(a) and 4(b)

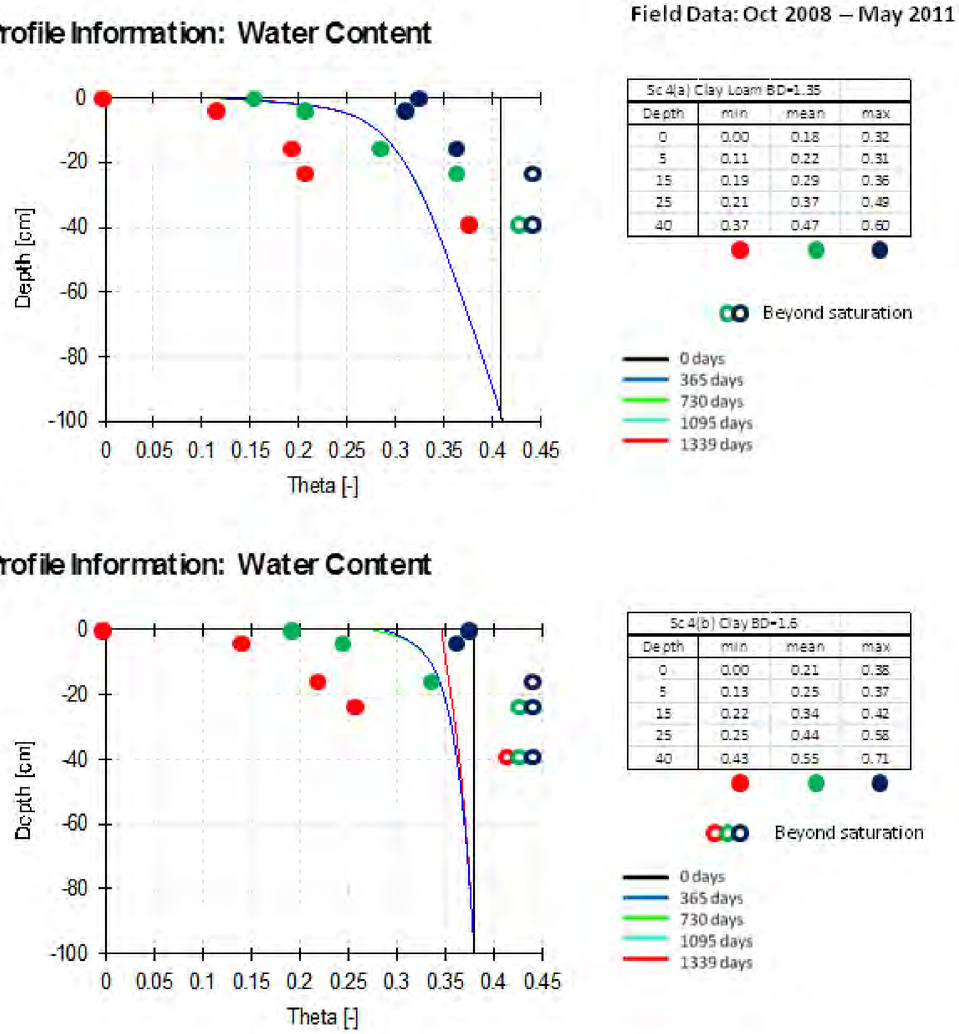


Figure 17: Modelled and Observed water content for Scenario 4 (Clay Loam and Clay)

7.3 Model Water Mass Balance

The model water mass balance for two of the investigation's scenarios (Scenario 1a and 1b) is presented in Appendix A to demonstrate the robustness of the numerical model.

The water mass balance provides data for five time periods (0, 365, 730, 1095 and 1339 days). The data can be used to assess the water fluxes throughout the simulation period.

Importantly, the output provides the relative error in the water mass balance of the entire flow domain (WatBalR as %). The maximum values for WatBalR are 0.001% (to 3 decimal places) for Scenario 1(a) and 0.000% for Scenario 1(b) indicating that the HYDRUS1D model is numerically robust. These results are typical for all eight simulations.

HYDRUS1D model output is presented in Appendix 2.

7.4 Sensitivity and Uncertainty Analysis

In many instances hydrogeological/hydrological modelling endeavours to model real world scenarios as closely as possible with a singular parameter set based on available and reliable data, and then provide parameter sensitivity estimates and uncertainty estimates based on this singular result.

For the Samphire Marsh modelling, the complexity of the processes, the high degree of "unknowns" and the lack of reliable data means that any modelling results based on a singular parameter set are necessarily highly uncertain. The approach used in this modelling report endeavours to capture real world values by using conservative modelling across a range of soil types and groundwater scenarios to determine the boundaries of the "feasible region" of likely soil moisture values. In doing so, much of the sensitivity and uncertainty analysis is inherent in the model since these boundaries are determined based on worst case/best case scenarios and a range of conservative parameter values.

7.4.1 Soil Type

The sensitivity of the model to "soil type" was qualitatively assessed by running simulations with a range of soil types and their default parameter sets found in HYDRUS1D. The differences in the profiles for Clay Loam and Clay soils (as used in this report) are indicative of the model sensitivity to soil types under a set of extreme atmospheric conditions typical of the Pilbara. Clay Loam soil moisture levels at a depth of ~40cm were about 80%-85% of the Clay soil moisture levels for each of the scenarios. The simulation of all scenarios using both a Clay Loam profile and a Clay profile provide the likely range of values for water content.

A detailed quantitative sensitivity analysis is difficult since a "soil type" is actually a combination of many parameters interacting in different and complex ways. In addition, estimates of bulk density required to compare modelled to measured soil moisture values adds another level of complexity. To further complicate things, BD values vary with inundation and drying.

The approach used in the preliminary modelling is to use a range of soil parameters in an attempt to capture the range of likely moisture level values (i.e. range of uncertainty). The response of the model to variation in each of the various key soil parameters is assessed during the uncertainty analysis, and indeed, helps to determine its range.

7.4.2 Access to Groundwater

Scenario 2 and Scenario 3 distinguish between a profile with groundwater accessible at 3mbgl (hardpan absent) and a profile where this access is retarded by a hardpan layer between 100cm and 150cm. Not surprisingly, results for the upper 100cm in Scenario 3 match the results for Scenario 1 to within 4 decimal places. This analysis shows that the profiles without access to groundwater (represented by Scenario 1(a)) had a final soil moisture value of 0.21 at a depth of 40cm. With access to groundwater (Scenario 2(a)), the final soil moisture at 40cm was 0.25. Recorded values for the fringe vegetation area at 40cm depth ranged from 0.12 to 0.25 with a mean value of 0.19. Both profiles had moisture values exceeding the mean field recorded value for water content. The uncertainty in the presence or absence of the hardpan is therefore of little concern and is an important result in the overall context of this investigation.

7.4.3 Rainfall

The uncertainty associated with Rainfall is taken into account by including a 1 year dry period for all simulations. To more fully assess the effects of extended dry period, a simulation was performed with a saturated profile subjected to 10 years of drought (Figure 18). A comparison on soil moisture at a depth of ~40cm indicates that the 10 year drought will reduce moisture to about 0.18, whereas the simulation of Oct08-May11 followed by 1 year of dry indicates moisture levels at the end of the period of about 0.21. More importantly, inspection of Figure 18 shows that subsequent dry years yield less and less reduction in soil moisture as the profile approaches “residual” soil moisture. The field recorded moisture content values for this scenario at 40cm depth were estimated to range from 0.12 to 0.25 (mean 0.19). Even after a 10 year drought, the model shows there is still moisture retained in the upper profile and these values are very near to the field recorded values.

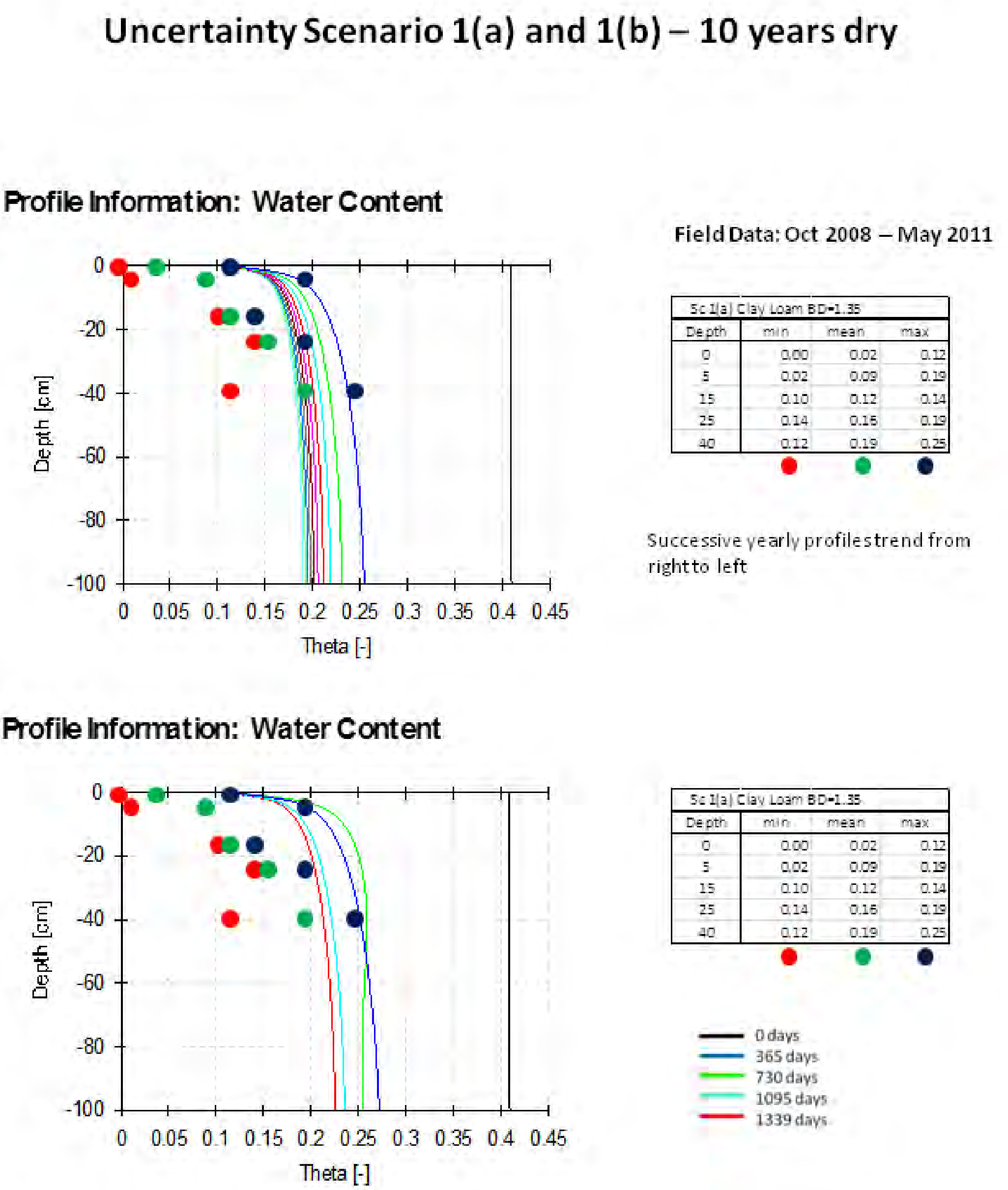


Figure 18: Scenario 1(a) with simulated drying of the saturated profile following a 10 year drought. The profile curves, going from right to left, represent water content at each successive year.

7.4.4 Bulk Density

Conservative bulk density values were chosen from the available literature values. The natural cycle of wetting/dissolution/drying/precipitation/rewetting continually alters the bulk density of the soils throughout the measurement period and lead to uncertainty in results when converting from gravimetric to volumetric moisture content.

7.4.5 UWA Field Data

The modelled results seem to compare well (in general) to maximum (T. indica) and mean (T. medusa) values from the field data (Figures 15, 16 and 17). It is possible that samples from the field assessment are prone to some level of drying due to the harsh climatic conditions in the Pilbara. This may account for the higher modelled values (as well as root uptake). It is also evident that some of the field values exceed the likely saturation water content for these soil types. This may be a consequence of excessive free draining water in the already saturated soil sample.

7.4.6 Other Uncertainty

As in all modelling of this nature, there is uncertainty at every level of the assessment and a fully quantifiable measure of error is impossible. The methodology used in this assessment seeks to adequately quantify uncertainty sufficient to capture the range of actual soil moisture at the marsh and therefore provide useful preliminary results to help understand the transient water balance in the simulated profiles.

8 Predictive Scenario – Impact from Dewatering

The proposed dewatering near the marsh at Cloudbreak is expected to marginally reduce the natural watertable (by about 1m) in the area along the fringes of the Fortescue Samphire Marsh. On site test pits indicate that the hardpan layer (at ~1mbgl) is present and the samphire species (chiefly *T. indica*) is not connected to the watertable (~3mbgl), a profile represented in this assessment as Scenario 1. The absence of the hardpan layer (modelled as Scenario 2) is nonetheless a possibility. In reality, the profile at the fringes of the marsh (and therefore the samphire community's access to groundwater) lies somewhere between Scenario 1 and Scenario 2, but closer to Scenario 1.

To assess the impact on soil moisture in the upper soil profile (100cm) following a worst case scenario 2m reduction in the watertable from 3mbgl to 5mbgl (groundwater modelling suggests this is unlikely, but it is suitable for our purposes). Scenario 2(a) was used since this provides the worst case scenario since the upper Clay Loam soil profile is connected to the watertable. Clearly, a 2m reduction in groundwater levels for Scenario 1 would have no affect on the upper 1m of the soil profile since the hardpan layer (at 1mbgl) separates the upper 1m from watertable (at 3mbgl).

Figure 19 compares the moisture profile for Scenario 2(a) (3m to groundwater, hardpan absent and Clay Loam soil, the worst case scenario soil type) and Scenario 2(a) with the groundwater at 5mblg (note: y-axis only extends to 300cm to make visual comparisons easier).

The moisture content for the upper 100cm can be compared using these moisture profiles at the end of the simulation period (1339 days).

- Scenario 2(a) with 3m to GW: Water Content ranges from about 0.15 to 0.28
- Scenario 2(a) with 5m to GW: Water Content ranges from about 0.13 to 0.24

The conclusion that can made from this comparison is that the soil moisture in the upper 100cm of the soil profile will only be marginally impacted by a 2m reduction in the watertable (from 3mbgl to 5mbgl). Both water content profiles exceed average soil moisture recorded values (Figure 16).

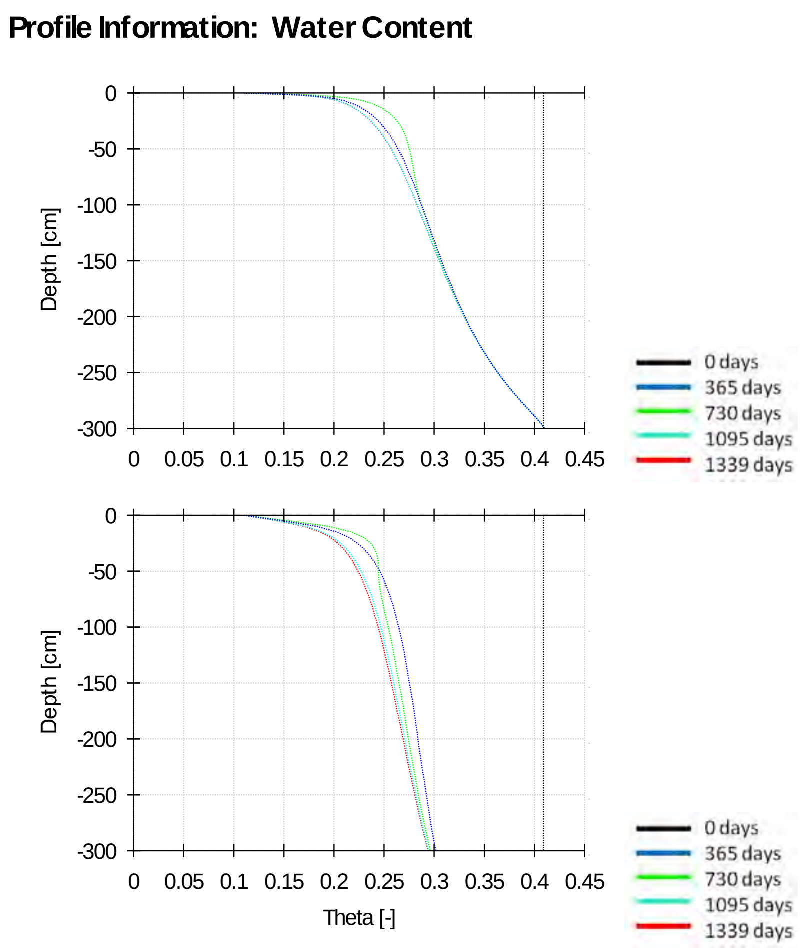


Figure 19: Scenario 2(a) with 3m to GW and Scenario 2(a) with 5m to GW. Note that both graphs extend to 300cm for easy visual comparison.

9 Solute Transport

9.1 Solute Transport – HYDRUS1D Modelling

The preliminary investigations included a qualitative analysis of solute transport and the precipitation and dissolution of hydrated minerals.

The ability of HYDRUS1D to accurately model solute transport, precipitation and dissolution of hydrated minerals is dependent on a large number of complex soil, water and chemical parameters, a situation that is further complicated when transient boundary conditions are used (as is the case). Importantly, the soil salinity and moisture varies from fresh to hypersaline and from saturated to residual moisture at highly irregular intervals. Assuring model stability requires that the parameter set is consistent within itself. HYDRUS1D modelling of this sophistication is generally limited to controlled laboratory experiments where parameters can be accurately determined and well controlled.

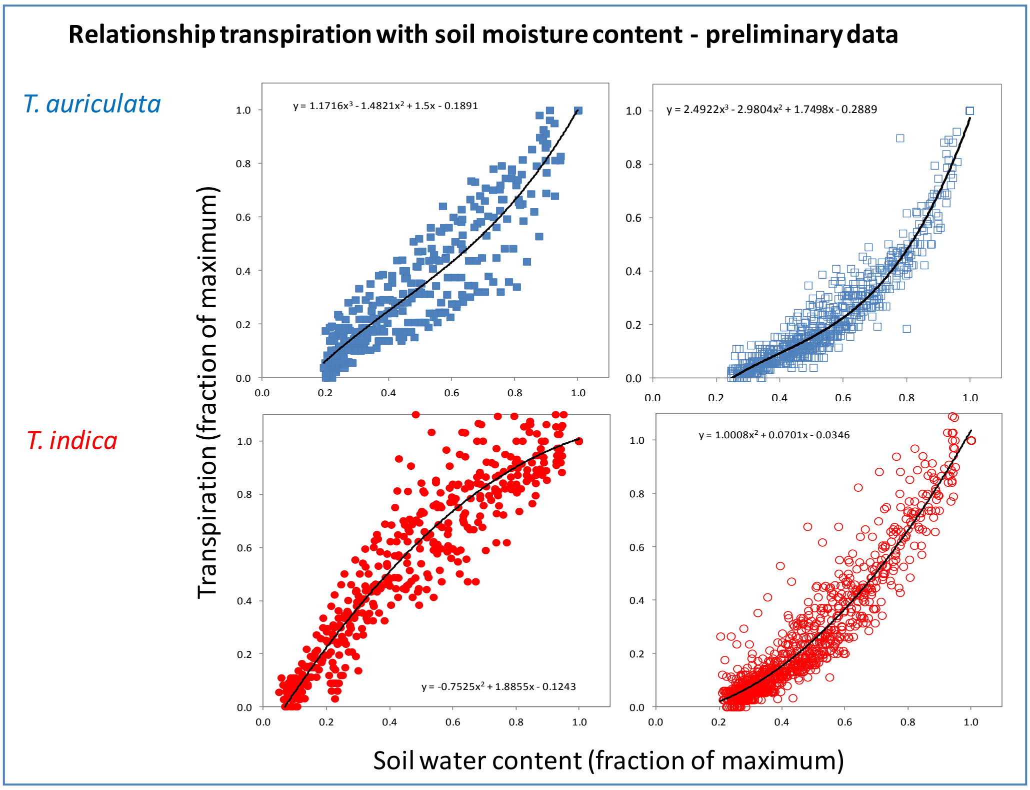
At this stage of the investigation, it should also be brought to the reader's attention that the large number of equations that are the basis of HYDRUS1D (and many modelling programs) are generally best applied to parameter values that are in the mid-range of allowable values. That is, model accuracy and stability tends to fall away at the extremes of parameter values. This investigation deals with extremes (highs and lows) of temperature, rainfall, inundation and drying, salinity, precipitation and dissolution etc. As such, there would be little to be gained in updating the HYDRUS1D model to include the Main Process of Solute Transport. Adding further complexity to the model at this stage was considered inappropriate in assessing salinity, particularly since reliable data is unavailable and highly impractical to gather through experimentation. Consequently, a more qualitative approach in determining the possible effects of salinity on *Tecticornia sp.* will be undertaken with reference to UWA experimental data.

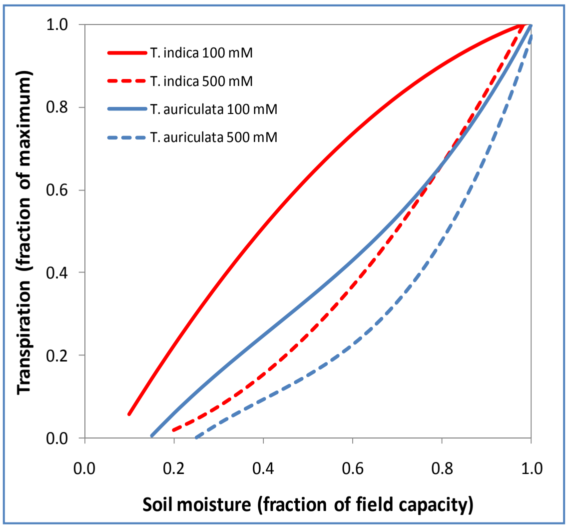
9.2 UWA Investigations – Impacts of Salinity of Transpiration

Figure 16 presents a summary of data from UWA research in to the transpiration rates for *Tecticornia sp.* under different soil water salinity scenarios (100mM and 500mM, units of milli-mole per litre).

For the four scenario graphs:

- Although polynomials have been fitted to each of the graph scenarios, the relationship between Transpiration and Soil Moisture appears to be fairly linear.
- Each of the four graphs have data points that lie along the x-axis and all fitted polynomials intersect the x-axis at a value greater, indicating the lowest soil moisture at which transpiration occurs. These values range from about 0.2 (100mM) to 0.3 (500mM) for T. auriculata and from about 0.1 (100mM) to 0.2 (500mM) for T. indica.
- Values for Transpiration and Soil Moisture are represented as a fraction of their maximum. The maximum rate varies with species and salinity level and these results are summarised in the table within Figure 20.



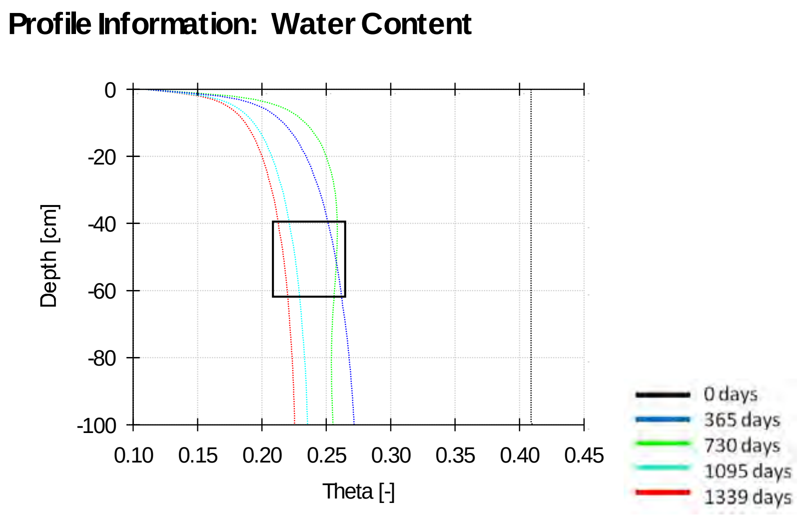


Samphire Species	Salinity mM	Transpiration mL g-1 FW day-1
T. indica	100	1.01
	500	0.43
T. auriculata	100	1.84
	500	0.98

Figure 20: The Transpiration (fraction of maximum) versus Soil moisture (fraction of field capacity) for the ongoing UWA investigation into Samphire water use.

Under high salinity scenarios (500mM), *T. indica* still transpires at soil moisture values of 10%-20% of field capacity. Figure 21 shows the water content associated with the rooting zone (40cm-60cm). For Scenario 1(a) (Clay Loam), the likely scenario for *T. indica.* These water content values range from 0.22 to 0.27, and are associated in the second graph with Hydraulic Capacity values that range from about 5%-15% of the maximum Hydraulic Capacity. This agrees well with the ranges presented in the UWA graphs in Figure 16 (10%-20%). A similar relationship is apparent for Scenario 1(b) (Clay), although the results are not presented here.

(a) CLAY LOAM



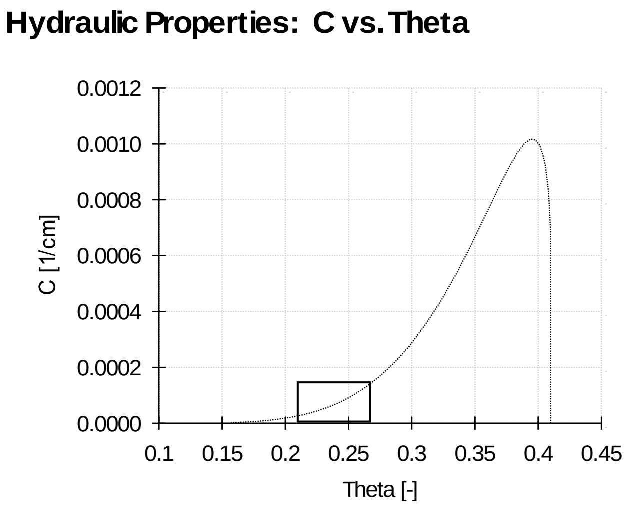


Figure 21: The Scenario 1(a) (*T. indica*) graph for Depth versus Water Content compared with Hydraulic Capacity versus Water Content. The Water Content (theta) range associated with the estimated Rooting Zone (40cm-60cm) is projected onto the curve for Hydraulic Capacity.

10 Stage 1 Preliminary Modelling - Conclusions

The primary aim of the modelling assessment is to:

> ***"Determine whether surface water and groundwater interactions are vital to the sustainability of the marshes and evaluate the dynamics of stored soil water replenishment and water table fluctuations on water availability for samphire."***

And to test the hypothesis:

> ***"The water requirements of the Fortescue Marsh vegetation can be met by surface water inputs under most climatic regimes, including areas potentially exposed to modified groundwater depth."***

Stage 1 modelling results indicate that surface water and groundwater interactions may not be vital to the sustainability of the marshes. The results also suggest that the hypothesis above is true. That is, water requirements of the Fortescue Marsh vegetation can be met by surface water inputs under most climatic regimes, including areas potentially exposed to modified groundwater depth.

These conclusions are supported by the following results:

- All soil moisture profiles from the HYDRUS1D modelling indicate soil moisture levels that are comparable to field recorded values. Modelled results generally exceed field results.
- Importantly, this is the case for Scenario 1(a) (not connected to GW), the most likely hydrogeological profile modelled with worst reasonable case scenario inputs.
- The assessment of longer term rainfall trends suggests that a 10 year drought is highly unlikely. As a worst case scenario (Scenario 1(a), not connected to watertable), the simulation of a 10 year drought indicates that water content in the upper 100cm of the profile approaches residual soil moisture levels that are comparable to field recorded values and exceed the minimum field recorded values.
- For the predictive scenario, a 2m reduction in groundwater levels has a minimal effect on the water content in the upper 100cm of the soil profile. This was performed using the less likely scenario, Scenario 2(a), which assumes connectivity to the watertable (3mbgl and 5mbgl during dewatering).

Put simply, the modelling suggests that there is sufficient moisture in the upper soil profile to provide moisture for root water uptake (so far not included in any of the simulations).

The conclusions that can be made from comparing the HYDRUS1D results (from Stage 1) with salinity and transpiration results provided by UWA are that Samphire species have the ability to continue transpiration at very low water content levels (~10% of Field Capacity) with high salinity (500mM); and that these values are consistent with the range of HYDRUS1D results for Scenario 1(a) and 1(b) representing the profile for *T. indica* at the fringe of the marsh (i.e. 1m to hardpan, no access to groundwater).

Finally, it is evident that the samphire species survive despite a high likelihood of extended drought and inundation periods

11 References

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Appendix 1 – HYDRUS1D Parameter List

Fortescue Marsh Unsaturated Zone Model HYDRUS1D Parameter List

The following tables show many of the required input parameters for a Hydrus1D simulation. The list is based on a simulation involving all the Main Processes available in Hydrus1D. Model complexity will depend on data availability. For example, if there was an insufficient data set for Root Growth, then this Main Process will not be selected. Also, some unknown parameters can be estimated or ignored. Input Parameters relating specifically to set-up and run time of the Numerical Model are not included.

If data unavailable, model can use Hydrus defaults or literature values based on general soil and solute types
Data Required - Data is site specific or species specific.

Main Processess

Geometry Information (cm)	Nmat	No. of Soil Materials
	DSP	Depth of the Soil Profile

Water Flow

Soil Hydraulic Properties
For Each Soil Material
Hydrus1D has a selection based on Soil Type

Qr	Residual soil water content, θ_r
Qs	Saturated soil water content, θ_s
Alpha	Parameter α in the soil water retention function [L^{-1}]
n	Parameter n in the soil water retention function
Ks	Saturated hydraulic conductivity, K_s [LT^{-1}]
l	Tortuosity parameter in the conductivity function [-]
Hysteresis	No Hysteresis or Hysteresis (drying or wetting)

Solute Transport

General Solute

Soil Specific Parameters:
For Each Soil Material

Bulk.d.	Bulk density, ρ [ML^{-3}]
Disp	Longitudinal dispersivity, D_L [L]
Frac	Dimensionless fraction of adsorption sites classified as type-1, i.e., sites with instantaneous sorption when the **chemical nonequilibrium** option is considered [-]. Set equal to 1 if equilibrium transport is considered. Dimensionless fraction of adsorption sites in contact with mobile water when **physical nonequilibrium** is considered [-]. Set equal to 1 if all sorption sites are in contact with mobile water.
ThImob	Immobile water content. Set equal to 0 when **physical nonequilibrium** is not considered.
Diffus.W	Molecular diffusion coefficient in free water, D_w [L^2T^{-1}]
Diffus.G	Molecular diffusion coefficient in soil air, D_a [L^2T^{-1}]

Solute Specific Parameters:
For Each Soil Material

Kd	Adsorption isotherm coefficient, k_s [$M^{-1}L^3$]
Nu	Adsorption isotherm coefficient, ν [$M^{-1}L^3$] (referred to as η in the manual)
Beta	Adsorption isotherm coefficient, β []
Henry	Equilibrium distribution constant between liquid and gaseous phases, k_g []
SinkWater1	First-order rate constant for dissolved phase, μ_w [T^{-1}]
SinkSolid1	First-order rate constant for solid phase, μ_s [T^{-1}]
SinkGas1	First-order rate constant for gas phase, μ_g [T^{-1}]
SinkWater1'	First-order rate constant for dissolved phase, μ_w' [T^{-1}], representing the chain reaction
SinkSolid1'	First-order rate constant for solid phase, μ_s' [T^{-1}], representing the chain reaction
SinkGas1'	First-order rate constant for gas phase, μ_g' [T^{-1}], representing the chain reaction
SinkWater0	Zero-order rate constant for dissolved phase, γ_w [$ML^{-3}T^{-1}$]
SinkSolid0	Zero-order rate constant for solid phase, γ_w [T^{-1}]
SinkGas0	Zero-order rate constant for solid phase, γ_s [$ML^{-3}T^{-1}$]
Alpha	First order rate coefficient for one site or two site nonequilibrium adsorption, mass transfer coefficient for solute exchange between mobile and immobile liquid regions, ω [T^{-1}]

Heat Transport

Heat Transport Parameters
For Each Soil Material
Hydrus1D has a selection based on Soil Type

Solid	Volume fraction of solid phase [-]
Org	Volume fraction of organic matter [-]
Dl	Longitudinal thermal dispersivity [L]
b1	Coefficient b1 in the expression for the thermal conductivity function [W/L/K]
b2	Coefficient b2 in the expression for the thermal conductivity function [W/L/K]
b3	Coefficient b3 in the expression for the thermal conductivity function [W/L/K]
Cn	Volumetric heat capacity of the solid phase [J/L3/K]
Co	Volumetric heat capacity of organic matter [J/L3/K]
Cw	Volumetric heat capacity of the liquid phase [J/L3/K]

Root Water Uptake

Water Stress Parameters

Feddes (1978) Parameters

P0	Value of the pressure head below which roots start to extract water from the soil.
POpt	Value of the pressure head below which roots extract water at the maximum possible rate.
P2H	Value of the limiting pressure head, below which roots cannot longer extract water at the maximum rate (assuming a potential transpiration rate of *r2H*).
P2L	As above, but for a potential transpiration rate of *r2L* .
P3	Value of the pressure head, below which root water uptake ceases (usually taken at the wilting point).
r2H	Potential transpiration rate [LT^{-1}] (currently set at 0.5 cm/day).
r2L	Potential transpiration rate [LT^{-1}] (currently set at 0.1 cm/day).

OR

Water Stress Parameters

S-shaped function of van Genuchten [1985]

P0	The exponent, *p* , in the root water uptake response function associated with water stress [-]; its recommended value is 3.
P50	The coefficient, *h50* , in the root water uptake response function associated with water stress [L]. Root water uptake at this pressure head is reduced by 50%

Salinity Stress Parameters

Stress Model	**No Solute Stress, Additive, or Multiplicative, Passive or Active**

If Multiplicative

The S-shaped root water uptake salinity stress response function:

Pphi0	The exponent, *p* , in the root water uptake response function associated with salinity stress [-]. The recommended value is 3.
Pphi50	The coefficient, *h50* , in the root water uptake response function associated with salinity stress [L]. Root water uptake at this osmotic head is reduced by 50%.
Osm.Coeff.	Coefficients to transform concentrations into equivalent osmotic pressure heads. The osmotic coefficients should be negative for the additive model (to be added to negative pressure heads) and positive for the multiplicative model.

OR

Threshold-slope function according to Maas [1990]:

Threshold	Value of the minimum osmotic head (the salinity threshold) above which root water uptake occurs without a reduction.
Slope	Slope of the curve determining the fractional root water uptake decline per unit increase in salinity below the threshold.

Root Growth

IRT	Initial root growth time
HT	Harvest time
IRD	Initial rooting depth
MRD	Maximum rooting depth
RTP	Time period (e.g., when the same root depths is to be used each year; then the time period is 365 days).

Variable Boundary Conditions

Time	Time for which a data record is provided [T]. Boundary condition values are specified for the time interval preceding time given at the same line. Thus BC values specified in the first row are for the time interval between the initial time and time specified on the same line.
Precip	Precipitation rate [LT^{-1}] (in absolute value).
Evap	Potential evaporation rate [LT^{-1}] (in absolute value).
Trans	Potential transpiration rate [LT^{-1}] (in absolute value).
hCritA	Absolute value of the minimum allowed pressure head at the soil surface [L].
rGWL	Drainage flux [LT^{-1}] across the bottom boundary (positive when water enters the flow region); set to zero when no time-dependent flux boundary condition is specified.
GWL	Groundwater level [L], or other time-dependent prescribed head boundary condition; set equal to zero when no time-dependent head boundary condition is specified.
FluxTop	Time-dependent flux at the soil surface boundary.
hTop	Time-dependent pressure head at the soil surface boundary.
KodTop	Set equal to -1 (+1) when flux (pressure head) is specified as the soil surface boundary condition.
tTop	Time-dependent temperature of the soil surface boundary. When the heat boundary flux is specified as the upper boundary condition, then **tTop** is the temperature of the incoming water.
tBot	Time-dependent temperature of the lower boundary. When the heat boundary flux is specified as the lower boundary condition, then **tBot** is the temperature of the incoming water.
Ampl	Amplitude of the temperature cycle at the soil surface.
cTop	Time-dependent concentration at the soil surface boundary. When the solute flux is used as the boundary condition, then cTop is the solute concentration of the incoming water (do not specify if solute transport is not considered or when no time variable boundary conditions are used).
cBot **(cRoot)**	Time-dependent concentration at the lower boundary. When the solute flux is used as the

Meteorological Conditions	Time	Time [Day]
	Radiation	Net radiation flux at the surface [MJ/m2]
	TMax	Maximum air temperature [oC]
	TMin	Minimum air temperature [oC]
	Humidity	Relative humidity or vapor pressure [%]
	Wind	Average daily wind speed at the measurement height specified [km/d]
	SunHours	Bright sunshine hours per day [hr] or cloudiness or transmission coefficient (based on selection in the Meteorological Parameters window)
	Crop Height	Crop height [L]
	Albedo	Albedo [-]
	LAI/SCF	Leaf area index or soil cover fraction (based on selection in the Meteorological Parameters window)
	Root Depth	Rooting depth [L]

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Appendix 2 – HYDRUS1D Water Mass Balance

The maximum values for WatBalR are 0.001% (to 3 decimal places) for Scenario 1(a) and 0.000% for Scenario 1(b) indicating that the HYDRUS1D model is numerically robust. These results are typical for all eight simulations.

```
******* Program HYDRUS

 ******* Scenario 1a Clay-Loam 1m to hardpan

Date:  27. 5.    Time:  22:41:17

 Units: L = cm   , T = days , M = mmol



----------------------------------------------------------

 Time       [T]       0.0000

----------------------------------------------------------

 Sub-region num.                   1

----------------------------------------------------------

 Area     [L]       0.10000E+03  0.10000E+03

 W-volume [L]       0.40900E+02  0.40900E+02

 In-flow  [L/T]     0.00000E+00  0.00000E+00

 h Mean   [L]      -0.33809E+01 -0.33809E+01

 Top Flux [L/T]    -0.50772E+01

 Bot Flux [L/T]     0.21946E+01

----------------------------------------------------------



----------------------------------------------------------

 Time       [T]     365.0000

----------------------------------------------------------

 Sub-region num.                   1

----------------------------------------------------------

 Area     [L]       0.10000E+03  0.10000E+03

 W-volume [L]       0.24845E+02  0.24845E+02

 In-flow  [L/T]    -0.14446E-01 -0.14446E-01

 h Mean   [L]      -0.58966E+04 -0.58966E+04

 Top Flux [L/T]     0.14447E-01
```

Bot Flux [L/T] 0.79769E-04

WatBalT [L] -0.27466E-03

WatBalR [%] 0.001

Time [T] 730.0000

Sub-region num. 1

Area [L] 0.10000E+03 0.10000E+03

W-volume [L] 0.24894E+02 0.24894E+02

In-flow [L/T] -0.34512E-01 -0.34512E-01

h Mean [L] -0.57398E+04 -0.57398E+04

Top Flux [L/T] 0.34512E-01

Bot Flux [L/T] -0.28238E-04

WatBalT [L] -0.29564E-03

WatBalR [%] 0.000

Time [T] 1095.0000

Sub-region num. 1

Area [L] 0.10000E+03 0.10000E+03

W-volume [L] 0.21852E+02 0.21852E+02

In-flow [L/T] -0.42552E-02 -0.42552E-02

h Mean [L] -0.66802E+04 -0.66802E+04

Top Flux [L/T] 0.42548E-02

Bot Flux [L/T] 0.24418E-04

WatBalT [L] -0.30327E-03

WatBalR [%] 0.000

Time [T] 1339.0000

Sub-region num. 1

Area [L] 0.10000E+03 0.10000E+03

W-volume [L] 0.21005E+02 0.21005E+02

In-flow [L/T] -0.28425E-02 -0.28425E-02

h Mean [L] -0.70673E+04 -0.70673E+04

Top Flux [L/T] 0.28421E-02

Bot Flux [L/T] 0.16368E-04

WatBalT [L] -0.31281E-03

WatBalR [%] 0.000

Calculation time [sec] 2.50000000000000

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Report

Modelling Analysis of the Impact of Mine Dewatering on Soil Water Availability to the Samphire Vegetation on the Fringe of Fortescue Marsh

Water Management

April 2014
CH-16018-SY-WM-0001

Fortescue
The New Force in Iron Ore

<table>
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EXECUTIVE SUMMARY

The Christmas Creek Life of Mine (LoM) Project will increase dewatering and water disposal activities over the extended life of the mine. Hydrogeological modelling indicates that drawdown associated with orebody dewatering may extend to the northern fringe of the Fortescue Marsh, which contains samphire vegetation communities of conservation significance.

A vertical two-dimensional (2-D) numerical model was employed to assess the potential impact of drawdown on the soil water availability to the samphire community in and adjacent to the Fortescue Marsh. HYDRUS software by PC-Progress, Prague, Czech Republic, was used to construct the numerical model. Field transpiration data derived from upscaled University of Western Australia (UWA) samphire sap flow measurements were used for calibrating transpiration parameters of the model. Field-measured saturated hydraulic conductivities and saturated water contents for the top loam-textured layer and parameters extracted from the HYDRUS soil database were employed in the simulations. The numerical model was validated by comparing simulated soil moisture content against sampled soil water content profiles at a single point in time.

The CRC's Stochastic Climate Library (SCL) was used to generate 2000 replicates of long-term daily weather sequences using historical observation data at Newman Weather Station. Daily rainfall sequences of 3-year wet weather and 3-year dry weather spells were selected from the SCL-generated data based on cumulative probability distribution of 3-year rainfalls. The selected 3-year daily rainfall sequences were applied to the numerical soil water model to analyse the impact of mining dewatering on plant root water uptake or plant transpiration.

Four groundwater levels (404, 403, 402 and 401 mAHD) were selected to set the lower boundary conditions of different scenarios of numerical simulations. The groundwater level of 404 mAHD represents the average groundwater level in the Fortescue Marsh near Christmas Creek prior to mining dewatering, while the GWLs of 403, 402 and 401 mAHD represent Marsh groundwater levels with 1-, 2- and 3-m drawdowns, respectively, introduced by mine dewatering . Sensitivity analysis was conducted by manipulating key model parameters.

The simulation results show that the root water uptake under repeated 3-year dry weather spells is little affected by up to 3 m groundwater drawdowns, and soil water content remains above the samphire permanent wilting point at all times even under conditions of prolonged drought and with a 3-m groundwater drawdown. Applying the 5%-probability-level 3-year rainfalls over the whole LoM is a very conservative practice. The average annual rainfall of the 3-year dry weather spells is 204.6 mm, about 63% of the long-term mean of annual rainfall of 325.9 mm.

The overall findings suggest that groundwater drawdown of up to 3 m would not introduce any significant adverse impact on the samphire communities near the northern fringes of the Fortescue Marsh. Surface water inputs (i.e. rainfall and flood waters) are likely to maintain soil moisture levels sufficient to meet samphire water use requirements under all but extreme climate regimes.

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1. INTRODUCTION

Fortescue Metals Group's (Fortescue's) Christmas Creek iron ore mine is located approximately 110 km north of Newman and 35 kilometres east of Fortescue's Cloudbreak mine in the Pilbara region of Western Australia. Fortescue is proposing to redefine the Life of Mine (LoM) plan at the Christmas Creek iron ore mine, which will involve:

- increasing ore production;
- developing new mine infrastructure; and
- increasing dewatering and water disposal activities over the extended life of the mine (approximately 15 years of operational mining).

This proposal is referred to as the Christmas Creek LoM Project,

Fortescue has undertaken a hydrogeological assessment of the Christmas Creek LoM Project using a 3D numerical model (Fortescue 2012). The modelling indicates that drawdown associated with dewatering the orebody may extend to the northern fringe of the Fortescue Marsh, which contains samphire vegetation communities of conservation significance. This report is concerned with predicting the potential impact of drawdown on the samphire communities.

The HYDRUS software package was used to construct a vertical 2-dimensional variably-saturated model to simulate soil water dynamics and plant water uptake by samphire vegetation on the fringe of the Fortescue Marsh. The model was used to investigate the effect of groundwater drawdown on samphire vegetation root water uptake and transpiration.

HYDRUS is a general software package for simulating water, heat, and solute movement in two- and three- dimensional variably saturated media. The software package consists of the interactive graphics-based user interface, and a set of computational programs. The numerical computational programs in the HYDRUS package solve the Richards equation for variably-saturated water flow and the convection-dispersion equation for heat and solute transport. The water flow equation incorporates a sink term to account for water uptake by plant roots. The computational programs in the HYDRUS package have been developed from the condensed wisdom of many scientists (Neuman, S. P., 1972; Davis, L. A. and Neuman, S. P., 1983; Vogel, T., 1987; Celia, M. A., et al., 1990; and Simunek, J., et al, 1992) and are updated with the cutting-edge advancements of compensated root water uptake in variably-saturated soil water modelling (Simunek & Hopmans 2009). The HYDRUS model has been successfully applied in numerous studies to analyse site-specific problems relating to plant water use and growth, soil moisture dynamics and soil salinization (Simunek *et al.* 2008; Forkutsa *et al.* 2009a,b; Xie *et al.* 2011).

2. BACKGROUND

The Fortescue Marsh is an extensive intermittent wetland, situated in the floor of a broad valley that separates the Hamersley and Chichester ranges. The marsh ecosystem is unique in the Pilbara, and has multiple conservation values of regional and national significance. Some of these include:

- recognised as a wetland of national importance within the Directory of Important Wetlands in Australia
- classified as a priority ecological community (PEC – Priority 1) by the Department of Environmental and Conservation (DEC)
- includes unique and diverse samphire vegetation communities
- supports various rare and endangered flora and fauna species
- has important Aboriginal heritage and cultural values.

The marsh fringing vegetation is dominated by samphire vegetation types, which exhibit zonal species distribution patterns broadly correlated with topographic, edaphic and hydrological factors. South of the Christmas Creek mining area the dominant samphire taxon near the marsh boundary is *Tecticornia indica* subsp. *bidens* (ENV 2012), which grows in heath formations in a zone roughly defined by topographic elevations between 406 and 407.5m AHD. It commonly co-occurs with *T.* sp. Dennys Crossing (K.A. Shepherd & J. English KS 552) in this zone. Both of these samphire taxa are widespread in Western Australia. Other samphire taxa such as *T. auriculata*, *T. medusa* (Priority 3) and *T.* sp. Christmas Creek (K.A. Shepherd & T. Colmer *et al.* KS 1063) (Priority 1) typically occur further into the marsh.

The *T. indica* subsp. *bidens* dominated communities are generally more open or 'sparse' (canopy cover 30-70%) in upgradient locations and closed or 'dense' (canopy cover 70-100%) further downgradient into the marsh (Figures 1 and 2). The edge of the samphire vegetation is typically abrupt, and abuts a low sparse to open shrubland intersected by shallow drainage tracts often lined with Mulga (*Acacia aptaneura*) and *Acacia synchronicia*.

The predicted maximum extent of drawdown (1 m drawdown below baseline water levels) associated with the Christmas Creek LoM Project intersects the margins of the *T.indica* subsp. *bidens* communities at some locations (Figure 3). These areas are the subject of the modelling study described in this report.

3. MODEL DOMAIN AND BOUNDARY CONDITIONS

MODEL DOMAIN

Soil water movement in the root zone of the samphire vegetation on the fringe of the Fortescue Marsh may be characterised by a vertical 2-dimensional flow system in a transect perpendicular to the topographic contour lines across the vegetated strip. A typical transect consisting of two segments of different samphire canopy densities shown in Figure 4 was selected as the simulated domain for the HYDRUS model. This was derived from the growing conditions observed in the area depicted in Figure 2.

BOUNDARY CONDITIONS AT UPSTREAM AND DOWNSTREAN ENDS

Since the dense samphire vegetation extends significantly further downgradient from the downstream end of the simulated domain, and vertical flow usually dominates soil water movement in the vadose zone, a no-flux boundary is applied to the vertical segment of the model domain at the downstream end. Similarly, a no-flux boundary is applied to the vertical segment of the model domain at the upstream end. The HYDRUS 2-D model currently ignores run-on from upgradient areas and/or floodwaters permeating out of the marsh basin, and therefore is a conservative approximation of available water to the samphire vegetation communities. In reality the many drainage tracts entering the marsh deliver water to the fringing vegetation following significant rains. Marsh flooding, although infrequent[1], is also expected to replenish soil water in the fringing areas when it occurs. The vegetation is characteristically denser near the drainage outlets, and the samphire vegetation communities often protrude into these outlets (Figures 2 and 3).

BOUNDARY CONDITIONS AT THE BOTTOM OF MODEL DOMAIN

The lower boundary of the model domain is set as a constant head boundary simulating groundwater levels. With the assumed elevation of 398 mAHD along the bottom of model domain, a 5 mH_2O of prescribed constant head along the lower boundary simulates a groundwater level of 403 mAHD.

BOUNDARY CONDITIONS AT GROUND SURFACE

The upper boundary of the model domain is the ground surface exposed to the atmosphere. Flow conditions on a ground surface exposed to the atmosphere are dependent on the values of the primary variable, matric potential or pressure head, and need to be treated as the so-called system-dependent boundaries in the HYDRUS model setup. Positive and negative fluxes, representing soil surface evaporation and net rainfall or irrigation respectively, are applied to a system-dependent ground surface boundary. The system dependent boundary is simulated as a boundary of specified fluxes, if the simulated matric potential at the ground

[1] ponding on the marsh occurs only after significant rainfall events of greater than 90 mm/month (Fortescue 2012)

surface is between the prescribed maximum and minimum matric potential values. If the simulated matric potential at the ground surface exceeds the prescribed maximum value or falls below the prescribed minimum value, the system-dependent boundary switches to constant head boundary conditions with the constant head value set at the prescribed maximum or minimum pressure head accordingly. The maximum constant head is set at 0, while the minimum constant head is set at a value 1 mH_2O less than the 'wilting point[2]' (e.g., -1001 mH_2O with a matric potential of -1000 mH_2O at permanent wilting point) in our simulations. The minimum constant head is set slightly lower than wilting point to avoid numerical inflow on an evaporation boundary.

For a ground surface with plant canopy cover, the boundary flux, q_{Surf}, in mm/day, may be calculated with

$$q_{Surf} = (1 - f_c) * ET_0 - P_n \qquad [1]$$

where $(1\text{-}f_c)*ET_0$ is the potential evaporation from soil surface (mm/day); f_c is the fraction of canopy cover on a projected area basis; ET_0 is reference daily evapotranspiration (mm/day) calculated using FAO56-PM equation (Webb, C. P. 2010); and P_n is net daily precipitation or irrigation (mm/day).

Three year (01/01/2009 to 31/12/2011) reference daily evapotranspiration data from the University of Western Australia (UWA) Weather Station located south of the Cloudbreak mine (740645E; 7525000N) was used in the simulations. To account for days when the ET_0 data are missing from the UWA Weather Station data set, ET_0 data from Newman Aero Weather Station was used to estimate the missing ET_0s using the correlation in Figure 5.

Net precipitation associated with rainfall events is calculated from observed gross precipitation, P_g, and the potential/maximum canopy interception loss, P_c. For a given rainfall event, if the portion of gross precipitation falling on the plant canopy is greater than P_c, the difference between gross precipitation and the maximum canopy interception loss is the net precipitation. Otherwise, the net precipitation of a rainfall event only includes the non-intercepted portion falling between the plant canopies, where f_c <1. Assuming the amount of precipitation falling on the canopy is proportional to fraction of canopy cover, f_c, we have

$$P_n = \begin{cases} P_g - P_c, f_c * P_g \geq P_c \\ (1 - f_c) * P_g, f_c * P_g < P_c \end{cases} \qquad [2]$$

The potential/maximum canopy interception of a rainfall event, P_c, is estimated with the following dynamic canopy interception model (Dunkerley, 2008; Wang et al., 2012)

$$P_c = S_c + In_c \qquad [3]$$

[2] the effective pressure head below which plant roots cease to absorb water due to the lack of driving gradient.

where S_c is the potential/maximum loss of precipitation to static canopy storage; In_c is the potential loss due to intra-storm evaporation of canopy-intercepted rainfalls from plant surfaces. Using 1 mm over canopy area to estimate S_c of a daily rainfall event, and applying the canopy portion of the reference ET, ET_0, we have

$$P_c = (1 + ET_0) f_c \quad [4]$$

Note that a S_c value of 1 mm is conservative, and was selected based on upper values reported in the literature for xerophytic shrubs with various morphological forms (Garcia- Estringana *et al.* 2010; Wang *et al.* 2005; Wang *et al.* 2012). The vegetative articles of *T. indica* subsp. *bidens* are characteristically hairless and vertically oriented. Furthermore the surfaces of the vegetative articles have been observed to be hydrophobic in glasshouse experiments using this species conducted by UWA (Prof. Erik Veneklaas UWA pers. comm.). These traits suggest that actual S_c values for *T. indica* subsp. *bidens* are more likely to be significantly less than 1 mm.

The current HYDRUS software can simulate two different system-dependent boundaries: one simulated with as so-called atmospheric boundary; and the other simulated as the #1 variable flux boundary, i.e., VarFl1. The standard HYDRUS simulation modules can simulate root water uptake from only one plant system. Hence, the recently-released double vegetation module was used in the simulations for the purposes of this study.

4. SOIL PROFILE AND ROOT WATER UPTAKE DISTRIBUTION

Various investigations undertaken by Fortescue have provided information on soil profiles near the northern fringe of the Fortescue Marsh (UWA 2012; Astron 2012a; Astron 2012b). This has included backhoe pit excavations, soil profile descriptions and vertical sampling for gravimetric water content determinations (20 cm depth intervals). The generalised soil profile at the marsh fringe south of the Christmas Creek mining area can be described as follows:

- Silty loam A horizon, typically 30 to 40 cm deep.
- Clay loam to light clay B horizon with poorly developed sub-angular blocky structure, extending to depths of 100 to 250 cm.
- An underlying layer of nodular calcrete in a clayey matrix, which becomes grittier at depth. Backhoe pit excavations conducted in May 2012 revealed shallow watertables within this calcrete layer at depths of 1 to 2.5 m, as dictated by surface elevation.

SOIL HYDRAULIC PROPERTIES

In the HYDRUS model a 2-layered system with a 40 cm loam-textured top layer overlaying a clay-loam-textured layer was assumed. van Genuchten's closed-form equations are employed in the HYDRUS 2-D model to evaluate volumetric water content and hydraulic conductivity at different matric potential or pressure head of unsaturated soils. Parameters of van Genuchten's closed-form equations are estimated from soil texture class (Carsel, R. F. and R. S. Parrish, 1988) by querying HYDRUS' built-in soil database. Saturated hydraulic conductivity (K_s) of the top layer is derived from K_s measured in mulga grove and inter-grove areas on the north side of Fortescue Marsh, in soils of similar texture (Heyting, M 2011). The mean of K_s values from the intergrove areas was selected, as this was lower than the mean of K_s values from grove areas and therefore may indirectly compensate for salinity effects on K_s in the Marsh surface soil layer. van Genuchten closed-form parameters used in the HYDRUS 2-D model are summarised in Table 1.

Table 1. van Genuchten closed-form hydraulic parameters.

Layer ID	Extent	Texture Class	Θ_r (v/v)	Θ_s (v/v)	α (1/m)	n	K_s (m/day)	l
1	0-40 cm	Loam	0.078	0.43	3.6	1.56	0.3288	0.5
2	40 cm to bottom of simulated domain	Clay Loam	0.095	0.41	1.9	1.31	0.0624	0.5

Figures 6 and 7 show the soil moisture retention curves of the loam- and clay loam-textured soils with small and large ranges of soil matric potentials, while the curves in Figures 8 and 9 depict the variations of unsaturated hydraulic conductivities with soil matric potential. Ten-based logarithm of hydraulic conductivity is used is used in the graphs to demonstrate the high non-linearity and drastic decrease (many orders of magnitude) in unsaturated hydraulic conductivity as the soils dry out. The small range retention and hydraulic conductivity curves are included to reveal the detailed information near saturation, while the large range curves provide more complete overall pictures of the hydraulic characteristics of the soils.

VERTICAL DISTRIBUTION OF ROOT WATER UPTAKE

Tecticornia indica subsp. *bidens* root systems exposed in the backhoe pit excavations did not have pronounced taproots, with the woody root systems predominantly confined to the top 70 cm of the soil profile. Examination of root abundance on pit faces indicated a predominance of fine roots in the top 50 cm of the soil profile, but with a few fine roots penetrating to depths of up to 2.5 m. The vertical root density distribution was quantified at one location (774600E; 7516180N) to inform the parameterisation of HYDRUS, which models root water uptake using a macroscopic approach (i.e. soil water uptake is averaged over a large number of roots in a representative bulk soil volume, with the distribution of root water uptake approximated by the relative root density distribution in the soil profile). The normalised distribution of the density of fine roots was used to define the stepwise normalised root water uptake model presented in Figure 10. The vertical distribution of root water uptake assumes proportionality between the density of fine roots and rate of root water uptake. Note that the current HYDRUS graphic user interface can only accommodate a flat ground surface scenario to automatically set up root water uptake distribution as per Vrugt's (Vrugt et al, 2001) root density distribution model, thus necessitating the development of the stepwise samphire root water uptake function.

5. WATER STRESS REDUCTION MODEL AND COMPENSATED ROOT WATER UPTAKE

WATER STRESS REDUCTION COEFFICIENT

The dependence of plant transpiration on the root zone soil moisture conditions is modelled using Feddes' (1978) water stress response function. In Feddes model, the water stress reduction coefficient, $\alpha(h)$, is introduced to calculate the actual root water uptake from potential root water uptake at any given point in the root zone, i.e.,

$$S(h) = \alpha(h)S_p \qquad [5]$$

where $S(h)$ in T^{-1} is the root water uptake rate from unit volume of bulk soil at a point where the matric potential is h (mH_2O); S_p is the potential water uptake rate (T^{-1}). Figure 11 shows a schematic plot of the water stress reduction coefficient, $\alpha(h)$. h_1 is an anaerobiosis point above which the plant roots cease to absorb water due the lack of aeration. h_2 and h_3 are the pressures at the upper and lower ends of the optimal water uptake range, in which plants transpire at the potential transpiration level. h_4 is the effective pressure head or matric potential at the plant's permanent wilting point below which plant roots cease to absorb water due to the lack of driving gradient and usually lack of water.

The HYDRUS software implements a linear interpolation scheme that simulates a variable lower end pressure of the optimal water uptake range.

$$h_3 = \begin{cases} h_{3,H} - \frac{h_{3,H}-h_{3,L}}{T_{p,H}-T_{p,L}}\left(T_{p,H} - T_p\right), T_{p,L} < T_p < T_{p,H} \\ h_{3,L}, T_p \le T_{p,L} \\ h_{3,H}, T_p \ge T_{p,H} \end{cases} \qquad [6]$$

where $h_{3,L}$ is the pressure head at the lower end of the optimal water uptake range, associated with the lower limit of potential transpiration rate, $T_{p,L}$; $h_{3,H}$ is the pressure head at the lower end of the optimal water uptake range, associated with the higher limit of potential transpiration rate, $T_{p,H}$.

A total of 7 parameters are required to define Feddes (1978) water stress reduction model. Symbols and descriptions of the parameters are shown in Table 2. The permanent wilting point soil matric potential, h_4 and the matric potential at the lower end of the optimal water uptake range $h_{3,L}$, were estimated from glasshouse experiment data (Figure 12a).

EXPERIMENTAL DETERMINATION OF THE WATER STRESS INDICES

The water stress indices in Figure 12a were estimated from measured transpiration rates of draught-stressed samphire plants grown in in the sealed plastic pots designed to achieve gradual depletion of soil moisture (Marchesini et al., 2014). The experimental pots are 20 cm in height and diameter and were packed with 5.6 kg of dry clayey soils with an electrical conductivity of 24.4 dS m^{-1} measured in the saturated soil-paste extracts. The WP4 Dewpoint Potentiameter (Decagon, Pullman, WA, USA) was used to measure total water potentials of soil samples at different soil moisture contents to establish the soil moisture retention curve of the clayey soil used for the pot experiments. The soil moisture retention curve is then used to estimate soil water potentials from pot water contents during the experiments.

Evapotranspiration rates from draught-stressed pots were estimated by weighing the pots every 2 days. Sixteen bare soil pots maintained at 100%, 80%, 60%, and 40% of the field capacity of the clayey soil, respectively, were used to estimate water losses from soil surface evaporations at different soil moisture contents. Soil surface evaporation from a planted pot on a certain day was estimated from the pot soil moisture content on that day using the evaporation-water content relationship established from the measurements of the bare soil pots. Soil moisture contents at different times of the draught-stressed pots were estimated from the observed weight changes. Transpiration rates were determined by subtracting the soil surfaces evaporations from the evapotranspirations.

Planted control pots with their moisture contents maintained at levels slightly below field capacity were used to estimate potential evapotranspirations at different times. Potential transpirations were derived from the measured potential evapotranspirations and the evaporation-water content relationship established from the measurements of the bare soil pots. The water stress indices in Figure 12a are the ratios of the transpiration rates from the draught-stressed pots to the potential transpiration rates from the control pots.

CONVERTING SOIL WATER POTENTIALS TO MATRIC POTENTIALS

The abscissa of the Figure 12a is in water potential, not matric potential. Soil water potentials are the sum of the soil matric potentials and the salinity-induced osmotic potentials across the semipermeable membrane of the cell walls of plant roots. However, the Feddes water stress reduction module in HYDRUS model uses soil water pressure head or matric potential instead of water potential (matric + osmotic) for its input parameters and soil matric potential is the primary dependent variable in the HYDRUS simulations. Hence, the water potentials at permanent wilting point and at the lower end of the optimal water uptake range are converted to soil matric potentials using the osmotic potential of the soil extracts

$$h = \Phi - \frac{\Theta_s}{\Theta(h)}\Psi_0 \qquad [7]$$

where h is the soil water pressure head or soil matric potential; Φ is soil water potential; Θ_s is saturated volumetric soil water content; $\Theta(h)$ is unsaturated soil water content at matric potential h; and Ψ_0 is the osmotic potential. h, Φ, and Ψ_0 are expressed in mH_2O.

Osmotic potential of the soil extracts can be estimated from the electrical conductivity (EC_e) of the saturated soil-paste extracts following standard procedures (Rhoades, 1982; Steppuhn et al., 2005)

$$\Psi_0 = -3.7189EC_e \quad [8]$$

where EC_e is in dS m^{-1}.

The background electrical conductivity of 24.4 dS m^{-1} measured in the saturated soil paste extracts of the highly saline clayey soil for the pot experiments was used to convert the water potentials of the Feddes module parameters in Figure 12a to soil matric potentials in Figure 12b using the Eqns [7] and [8]. Values of the water-stress-reduction parameters used in the HYDRUS model for simulating transpiration by the samphire vegetation on the fringe of the Fortescue Marsh are summarised in Table 2. The anaerobiosis point matric potential is set at 0.5 mH_2O to reflect the fact that some species of samphire grow adventitious roots when in flooded soils and have specialised intercellular gas-filled spaces in their roots, called aerenchyma which acts like a snorkel to provide oxygen to roots under water (UWA Fact Sheet, 2012).

COMPENSATED ROOT WATER UPTAKE

Given a normalized root water uptake distribution function, $b(z)$, the potential water uptake rate, $S_p(z)$, may be expressed as

$$S_p(z) = b(z) * T_p \quad [9]$$

where z represents depth from ground surface.

Combining Eqns [5] and [9] yields

$$S(z,h) = \alpha(h) * b(z) * T_p \quad [10]$$

Integrating the actual root water uptake rate $S(z,h)$ over the depth of root zone gives the actual transpiration, Ta

$$T_a = \int_0^{L_r} S(z,h)dz = T_p \int_0^{L_r} \alpha(h)b(z)\,dz \quad [11]$$

where L_r is the root zone depth.

Moving T_p in Eqn [11] to the left side and defining the ratio of actual to potential transpiration as water stress index, ω, we obtain

$$\omega = T_a/T_p = \int_0^{L_r} \alpha(h)b(z)dz \quad [12]$$

Table 2. Input Values for Feddes Water Stress Reduction Parameters.

Symbols Used in this Report	Symbols Used in HYDRUSS GUI	Pressure Head/ Transpiration Rate	Descriptions
h_1	P0	0.5 mH_2O	Anaerobiosis point matric potential above which roots cease to extract water from the soil due to oxygen deficiency
h_2	POpt	-0.1 mH_2O	Matric potential at the upper end of the of the optimal transpiration range
$h_{3,H}$	P2H	-3.33 mH_2O	Pressure head at the lower end of the optimal water uptake range, associated with the upper limit of potential transpiration rate, $T_{p,H}$
$h_{3,L}$	P2L	-60 mH_2O	Pressure head at the lower end of the optimal water uptake range, associated with the lower limit of potential transpiration rate, $T_{p,L}$
h_4	P3	-1000 mH_2O	Matric potential at permanent wilting point
$T_{p,H}$	r2H	0.005 m/day	the upper limit of potential transpiration rate for estimating the pressure head at the lower end of the optimal water uptake range, h_3
$T_{p,L}$	r2L	0.001 m/day	the lower limit of potential transpiration rate for estimating the pressure head at the lower end of the optimal water uptake range, h_3

Eqn [10] does not consider plant roots' adaptability, i.e., the plant roots' ability to compensate water uptake by absorbing more water from non-stressed or less-stressed portions of the root zone to compensate the reduction in water uptake from severely stress portions. Without water uptake compensation, the water stress index falls below 1 if the pressure head in any part of the root zone goes outside of the optimal water uptake range. However, across a wide range of species, experimental evidence suggests that plants can compensate for water stress in one part of the root zone by taking up water from other parts of the root zone where water is available (Jarvis 1989; Skaggs et al. 2006; Simunek & Hopmans 2009). The current versions of HYDRUS include a compensated root water uptake model, which simulates root water uptake by scaling up the water uptake term by a factor, $1/\omega$, i.e.,

$$S(z,h) = \begin{cases} \alpha(h) * b(z) * \frac{T_p}{\omega}, \omega > \omega_c \\ \alpha(h) * b(z) * \frac{T_p}{\omega_c}, \omega \leq \omega_c \end{cases} \quad [13]$$

The critical water stress index or root adaptability factor, ω_c represents a threshold value, above which the root water uptake reduced in stressed parts of the root zone is fully compensated for by uptake from other, less-stressed parts. Below this critical value, there is a certain reduction of the potential transpiration, although smaller than in uncompensated root water uptake. Hence when $\omega_c = 1$ root water uptake is uncompensated, and when ω_c is near zero root water uptake is fully compensated. Arid zone plants are generally considered to have a low ω_c and correspondingly high ability to compensate for natural stresses (Simunek & Hopmans 2009). The value ω_c used in this study was 0.01, which represents a fully compensated system.

In a fully compensated system, as long as there is enough available water in the root zone to satisfy the transpiration demand of a simulated time step, the simulated actual transpiration using Eqn [13] equals the potential transpiration. The available water in the root zone is the soil water held to the soil matrix with the matric potentials above the effective matric potential at the plant's permanent wilting point and below the anaerobiosis point.

6. MEASURED SAP FLOW AND BASAL PLANT COEFFICIENT

Research undertaken by UWA as part of ARC Linkage project LP0882350[3], a project supported by Fortescue, included field measurements of sap flow in *Tecticornia indica* subsp. *bidens* south of the Cloudbreak mine, conducted over a 3 year period. These data were used to derive plant scale transpiration fluxes, based on measurements of sapwood cross sectional area in the instrumented plants. Transpiration fluxes per unit land area were then estimated using measurements of stem cross sectional area per unit land area in the UWA plots (UWA unpublished data). In accordance with a conservative approach, the maximum measured sap flow rates were used to derive transpiration flux estimates.

Since the availability of measured sap flow data are usually very limited, we analysed the ratio of the measured transpiration flux per unit land area (mm/day) to the reference transpiration T_0 (see Figure 13). The reference transpiration is estimated from reference transpiration ET_0 and the fraction of canopy cover, f_c, i.e., $T_0 = f_c{*}ET_0$. The moving average of the ratio of the measured transpiration flux to the reference transpiration stays about a constant of 0.067 in relatively wet summer seasons and drops to about 0.0267 in the relatively dry winter season. Observations made by UWA over the life of the field experiment suggest that the root zone soil water conditions stayed within the compensable range (i.e. the plants maintained stable water uptake rates and did not become apparently drought stressed) in the summer seasons. Hence, the wet season average of the sap flow-to-reference transpiration ratios is used as the initial estimation of the basal plant coefficient, K_{cb}, of the samphire community on the fringe of Fortescue Marsh (FAO Irrigation and Drainage Papers, Version 56). The basal plant coefficient will be adjusted in the subsequent calibration to minimize the RMSE between the simulated actual daily transpiration and the daily transpiration from sap flow measurements.

The basal plant coefficient, K_{cb}, enables the predictions of daily potential transpiration of a specific plant community ($T_{p,\ Plant}$) from the widely available daily reference evapotranspiration (ET_0) data (Webb, 2010) under different canopy cover conditions.

$$T_{p,\ Plant} = K_{cb} f_c ET_0 \qquad [14]$$

The estimated daily potential transpirations of the samphire community are then used to set up the daily transpiration inputs for the HYDRUS model.

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[3] Project titled '*Ecophysiology of stem succulent halophytes subject to changes in salinity and water availability: distinguishing natural dynamics from potential mine related impacts*'

7. MODEL CALIBRATION AND VALIDATION

CALIBRATION of K_{cb}

Real time simulation from the beginning of 01/01/2009 to the end of 31/12/2011 was conducted to calibrate the basal plant coefficient, K_{cb}. The basal plant coefficient is adjusted in the calibration to minimize the RMSE between the simulated actual daily transpiration and the daily transpiration from sap flow measurements. The lower boundary was set at a constant head of 6.945 mH_2O, which corresponds to the average groundwater level of 404.945 mAHD at the end of 2011. The groundwater levels were observed in the monitoring bore, CCFMM03_S (776980E; 7514850N), located near the focus area targeted for modelling assessment.

Daily rainfall and reference evapotranspiration, ET_0, from UWA Weather Station is used to set up the inputs for the upper boundary. On the days when the ET_0 data are missing from the UWA Weather Station data set, ET_0 data from Newman Aero Weather Station is used to estimate the missing ET_0s using the correlation in Figure 5. Fractional ground cover was estimated from field inspections and photograph reference points. A fractional canopy cover of 0.75 is used in the calibration model. A quasi-steady initial condition is generated by conducting the simulation from an arbitrary initial condition for many years using the same 3-year weather data periodically. The quasi-steady initial condition is employed in the calibration simulation. The available sap flow measurement data start on 06/10/2009, while the calibration simulation starts on 01/01/2009. The 3-month gap is expected to render the effect of initial condition on K_{cb} calibration insignificant.

Figure 14 compares the simulated actual root water uptake/transpiration against the transpiration flux estimated from sapflow measurements. The optimized K_{cb} of 0.0558 results in the minimal RMSE of 0.086 mm/day. The agreement is reasonably good, which confirms the acceptability of the estimated samphire K_{cb} for predictive simulations.

MODEL VALIDATION

Real-time simulation from the end of 31/01/2012 to 2:00 PM of 08/05/2012 was conducted to check the simulated water contents against measured soil water contents in the profiles of UWA backhoe pits #CC1 (774602 E; 7516180N), #CC3 (777253E; 7514797N), and #CC4 (775493E; 7515474N) (see Figures 15, 16, and 17). The starting date for the real time simulation was chosen to avoid the cluster of relatively heavy rainfall events shortly after Tropical Cyclone Heidi. The HYDRUS model experiences convergence problems simulating infiltration into a profile approaching being fully saturated at practically affordable time steps.

The lower boundary for the real time simulation was set at a pressure of 7.68 mH_2O, which simulates the average water table of 405.68 mAHD, observed in the monitoring bore, CCFMM03_S. The initial condition for the segment in Fortescue Marsh was set near saturation (-0.1 mH_2O) in the whole profile, while the initial matric potential for the upgradient segment on the rise was set at -1.5 mH_2O for the top 1-m layer and -0.1 mH_2O for the rest of the profile.

The UWA Pits are mapped to sections of the simulated transect based on ground-surface elevations. CC1 and CC3 are located in the rise segment, while CC4 falls in the segment in Fortescue Marsh. At CC1, the simulated water contents agree reasonably well with the measured data points in the upper and lower parts of the profile. The measured water contents at 120 cm and 140 cm from the ground surface, are significantly lower than simulated results, which may be attributable to the presence of calcrete nodules and weak calcrete cementation observed in this portion of the soil profile at the sampled location. The RMSE for Pit CC1 is 0.073 v/v. At CC3, the simulated water contents match the measured data reasonably well in the lower part of the profile. In the upper part, the model apparently overestimated water content values. The RMSE for CC3 is 0.104 v/v. At CC4, the simulated water contents match the measured data reasonably well. The RMSE for CC4 is 0.046 v/v. Considering the temporal and spatial variability and complexity of the factors influencing soil water movement under field conditions, the match is considered acceptable overall. Hence, the HYDRUS 2-D model is suitable for long-term simulation of soil water regime in samphire root zone and root water uptake under different weather conditions.

Sampled profiles of soil water contents at the UWA Pits are expressed in gravimetric unit (i.e., kg/kg or w/w), while the HYDRUS model uses volumetric unit (i.e., m^3/m^3 or v/v) for soil water content. The measured soil water contents in the sampled profiles are converted into volumetric unit by multiplying the ratio of the bulk densities of soil and water. Measured bulk density of 1310 kg/m^3 (weighted average of samples taken at depths of 0-10 cm, 10-20 cm, 20-30 cm, and 30-50 cm, respectively) is used for both the loam top layer and the clay loam sub-layer in the conversions (Prof. Erik Veneklaas, UWA, pers. Comm.).

8. PREDICTIVE SCENARIO ANALYSIS

SIMULATED SCENARIOS

The HYDRUS 2-D model is used to quantify the effect of groundwater drawdowns caused by mine dewatering on the availability of soil water to the samphire vegetation on the fringe of the Fortescue Marsh. The predictive scenarios simulates root zone soil water movement and root water uptake under different weather conditions and at different drawdowns or groundwater levels (GWLs). A total of 7 scenarios are included in the analysis:

I. 3-year wet weather spells at GWL of 404 mAHD;

II. 3-year wet weather spells at GWL of 403 mAHD;

III. 3-year wet weather spells at GWL of 402 mAHD;

IV. 3-year dry weather spells at GWL of 404 mAHD;

V. 3-year dry weather spells at GWL of 403 mAHD;

VI. 3-year dry weather spells at GWL of 402 mAHD;

VII. 3-year dry weather spells at GWL of 401 mAHD.

The GWL of 404 mAHD simulates groundwater level prior to mine dewatering, while GWLs of 403, 402 and 401 mAHD simulate groundwater levels with 1-, 2- and 3-m drawdowns, respectively.

WET AND DRY WEATHER SPELLS

To generate rainfall sequence in the prediction period, the CRC's Stochastic Climate Library (Srikanthan et al., 2007) was used. Two thousand replicates of 28-year daily rainfall sequences were generated from 28-year consecutive daily rainfall data (01/01/1970 to 31/12/1997) at Newman Aero Weather Station. Figure 18 shows the cumulative probability of the moving sum of 3-year precipitations from the generated rainfall data. The 3-year daily rainfall sequences for both wet and dry weather spells are selected from the generated rainfall data based on proximity of the moving sum 3-year precipitations to the 5 and 95 percentile 3-year cumulative rainfalls in the cumulative probability curve.

RESULTS AND SUMMARY

The simulated actual root water uptake at different GWLs (404, 403, and 402 mAHD) for both wet and dry weather spells (3-Year) are basically the same (see Figures 19 and 20). This indicates that samphire transpiration is not adversely affected by the groundwater drawdowns, which may occur based on the predicted extent of drawdown associated with the Christmas Creek LoM Project.

Figures 21 and 22 show the simulated average root zone water content at different GWLs under 3-year wet and dry weather spells, respectively. Figure 23 shows the simulated root zone water contents at a 3-m drawdown from the pre-mining water levels (GWL 401 mAHD) using the compensated root water uptake module. Average root zone water contents stays above water content at permanent wilting point at all times for all the scenarios simulated. The fully compensated root water uptake mechanism maintains transpiration at the optimal level as long as there is enough water in the root zone to satisfy transpiration demand. The simulated average root zone water content above permanent wilting point indicates that there is still available water left in the root zone after satisfying vegetation transpiration demands, which confirms that samphire transpiration is not adversely affected by up to 3m groundwater drawdowns.

Figure 24 shows the simulated water stress index at a 3-m drawdown from the pre-mining water levels using the uncompensated root water uptake module. There is growing experimental evidence that plants, especially non-cultural plants, can compensate for water stress in one part of the root zone by taking up water from parts of the root zone where water is available (Taylor and Klepper, 1978; Hasegawa and Yoshida, 1982; English and Raja, 1996; Stikic et al., 2003; Leib et al., 2006). The uncompensated root water uptake mode ignores the capability of the plant root system to compensate reduced water uptake from one part of the rhizosphere with increased uptake in another less-stressed region of the rooting zone and, therefore, over-predicts the water stress conditions. The average water stress index for the last 3 years of the LoM (Figure 24) is 0.67, indicating that the plant community is not under severe water stress under repeated 3-year dry weather spells for the whole LoM. Because of the very low transpiration demand of the samphire plants (per UWA sap flow measurements), 3-m drawdowns from the pre-mining groundwater levels will not cause severe water stress to the samphire community along the fringes of the Fortescue Marsh.

Figures 25 and 26 show the cumulative fluxes of different mass balance components in dense and sparse samphire areas, respectively, under 3-year wet weather spells with GWL at 404 mAHD. Figures 27 and 28 show the cumulative fluxes of different mass balance components in dense and sparse samphire areas, respectively, under 3-year dry weather spells with GWL at 402 mAHD. Under prolonged wet weather conditions with a relatively high water table, net recharge to groundwater from percolated rainfall dominates flows at the lower boundary. Under prolonged dry weather conditions with a relatively low water table, phreatic evaporation (negative recharges in Figures 27 and 28) dominates flows at the lower boundary. Cumulative actual transpiration stays at the optimal level in both cases.

9. SENSITIVITY ANALYSIS

Sensitivity analysis is conducted to investigate uncertainties in model input parameters on the simulated cumulative fluxes of the mass balance components. The following scenarios are simulated for sensitivity analysis:

- Increase plant coefficient K_{cb} by 50%;
- Increase static canopy storage for rainfall interception to 1.5 mm;
- Reduce fractional canopy cover in the sparse samphire segment to zero;
- Increase effective wilting point to -700 mH_2O;
- Use the alternative root water uptake distribution in Figure 10;
- Use uncompensated root water uptake.

Figures 29 and 30 show the effect of K_{cb} on simulated cumulative fluxes in the dense and sparse samphire areas, respectively, under 3-year dry weather spells and with a GWL of 402 mAHD. In both areas, increasing K_{cb} by 50% slightly reduces the simulated actual soil surface evaporation. The increase in transpiration is balanced mainly by the increase in phreatic evaporation. Examination of the simulated average root zone water content reveals that the average root zone water content is still above the water content at permanent wilting point after increasing K_{cb} by 50% (see Figure 31), which means the root zone soil water is able to meet the plant's optimal-level transpiration. However, increasing K_{CB} by 50% pushes the average root zone water content to a level very close to water content at permanent wilting point.

Figures 32 and 33 show the effect of static canopy storage on the simulated cumulative fluxes in the dense and sparse samphire areas, respectively, under 3-year dry weather spells, and with a GWL of 402 mAHD. Increasing the static canopy storage by 0.5 mm has a greater effect on the simulated actual soil surface evaporation in the sparse samphire area than in the dense samphire area. The reduction in net precipitation due to the increase in static storage is balanced mainly by the decrease in soil surface evaporation.

Figure 34 shows the effect of ground canopy cover on simulated cumulative fluxes in the sparse samphire area under 3-year dry weather spells with a GWL of 402 mAHD. Reducing canopy cover to zero significantly increases net precipitation received by the ground surface. The increase in net precipitation is mostly lost to increased soil surface evaporation. Reducing ground canopy cover to zero also eliminates the transpiration component, which results in a much reduced phreatic evaporation.

Increasing effective wilting point to -700 mH_2O or switching root water uptake to the alternative distribution in Figure 10 did not cause discernible changes in the simulated cumulative fluxes against the base scenario. Within the ranges investigated, the model is insensitive to effective wilting point and root water uptake distribution.

Figure 35 shows variations of water stress index for uncompensated root water uptake under 3-year dry weather spells. Average root zone water content is included in the graph to demonstrate the synchronized behaviours of the water stress index with water content under 3-year dry weather spells. The water stress indices in the dense samphire area under 3-year dry weather spells stay above the level of 0.8 over about 53% of the time (579 days out of 1096 days) and fall below 0.6 over about 5% of the time (56 days out of 1096 days). The average dense-samphire water stress index under 3-year dry weather spells is about 0.83.

The water stress indices in the sparse samphire area under 3-year dry weather spells stay above the level of 0.8 over 37% of the time (401 days out of 1096 days) and fall below 0.6 over about 6% of the time (66 days out of 1096 days). The average sparse-samphire water stress index under 3-year dry weather spells is about 0.73.

The relatively high water stress indices for both samphire communities under 3-year dry weather spells suggest that the plants are not severely stressed even without compensated root water uptake.

Figure 36 shows variations of water stress index for uncompensated root water uptake under 3-year wet weather spells. Again, the average root zone water content is included in the graph. Under 3-year wet weather spells, water stress indices for both the dense and sparse samphire communities stay above the level of 0.99 over the vast majority of the simulated time (about 98% for both dense and sparse samphire communities). The downward spikes of the water stress index correspond to peaks of average root zone water content, which is opposite to the synchronized behaviours of the water stress index with water content under 3-year dry weather spells. Examination of the pressure head profile on day 44 (corresponding to the first water stress spike) reveals that the sharp decrease in water stress index is caused by reduction in root water uptake due to anaerobiosis in the top soil layer saturated by the clustered rainfall events (see Figure 37). The anaerobiosis effect in the top soil layer vanishes quickly as the infiltrated water redistributes into lower portions of the profile. Sharp decreases and recoveries of water stress index associated with anaerobiosis effect result in the reversed spiky pattern in the water stress indices under 3-year wet weather spells. In a situation with anaerobiosis effect, the root zone usually has more than enough water to satisfy the vegetation's optimal transpiration demand. It is one of the typical scenarios for the plant roots to adopt compensated water uptake mechanism.

10. SUMMARY AND CONCLUSIONS

A vertical 2-dimensional (2-D) numerical model was employed to assess the impact of Christmas Creek LoM Project orebody dewatering on the soil water availability to samphire communities in and adjacent to the Fortescue Marsh. HYDRUS software by PC-Progress, Prague, Czech Republic, was used to construct the numerical model. Time series measurements of samphire transpiration fluxes derived from sap flow measurements were used for calibrating plant transpiration parameters. Field-measured saturated hydraulic conductivities and saturated water contents for the top loam-textured layer and parameters extracted from the HYDRUS database based on soil texture were employed in the simulations. The numerical model was validated by comparing simulated soil moisture content against sampled soil water content profiles at a single point in time.

The CRC's Stochastic Climate Library (SCL) was used to generate 2000 replicates of long-term daily weather sequences using historical observation data at Newman Weather Station. Daily rainfall sequences of 3-year wet weather and 3-year dry weather spells are selected from the SCL-generated data based on cumulative probability distribution of 3-year rainfalls. The selected 3-year daily rainfall sequences were applied to the numerical soil water model to analyse the impact of mine dewatering on plant root water uptake and transpiration.

Four groundwater levels (404, 403, 402 and 401 mAHD) were selected to specify the lower boundary conditions of different scenarios of numerical simulations. The groundwater level of 404 mAHD represents the average groundwater level in the Fortescue Marsh near Christmas Creek prior to mining dewatering, while the GWLs of 403, 402 and 401 mAHD represent Marsh groundwater levels at 1-, 2- and 3-m drawdowns respectively.

The simulation results show that the root water uptake under both wet and dry weather spells (3-year) is little affected by up to 3 m groundwater drawdowns, and soil water content is above the wilting point at all times even under conditions of prolonged drought and groundwater drawdown (i.e. repeated 3-year dry weather spells for the whole LoM and at a 3-m groundwater drawdown). Under wet weather conditions, the water use requirements of the samphire are fully met by rainfall inputs. Under prolonged dry conditions, phreatic evaporation from shallow groundwater contributes to replenishing soil water in the samphire root zone.

The findings of the modelling study suggest that groundwater drawdown of up to 3 m would not introduce any significant adverse impact on the samphire communities near the northern fringes of the Fortescue Marsh. Based on the modelled cumulative fluxes of different mass balance components in dense and sparse samphire areas under the various scenarios tested, it is likely that surface inputs (i.e. rainfall and flood waters) are sufficient to meet samphire water use requirements under all but extreme climate regimes.

11. MODEL LIMITATIONS

The latest, state-of-the-art, double-vegetation version of the HYDRUS program is used to simulate the soil water movement in the root zones of the dense and sparse samphire vegetation communities. Because the model simulates water flow only, the effect of salinity on plant root water uptake is not modelled explicitly in this project.

However, the effect of salinity was indirectly accounted for as follows:

(1) Parameters for Feddes water stress reduction coefficient module (e.g., wilting point matric potential, etc) were derived from UWA experimental data from plants growing in high salinity soils;

(2) the samphire basal plant coefficient, K_{cb}, was estimated from measured sap flows/transpirations fluxes in Fortescue Marsh samphires growing under representative saline conditions south of the Cloudbreak mine site;

Since the current HYDRUS programs do not temporal variation of the soil hydraulic properties, water flow parameters used in the simulations were invariant of soil water salinity levels. Experimental investigations indicate that high salinity levels may cause reductions in soil hydraulic conductivity and soil water retention (Singh & Wallander 2011). Hence, the simulation results may not fully represent the field conditions.

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GLOSSARY

Basal plant coefficient, K_{cb}

Basal plant coefficient, K_{CB} is a coefficient introduced in the dual crop coefficient approach to estimate plant transpiration from reference evapotranspiration. In FAO56 (FAO Irrigation and Drainage Papers, Version 56), the crop coefficient approach is used to estimate crop evapotranspiration, ET_c, from reference evapotranspiration, ET_0, i.e., $ET_c = K_cET_0$, where Kc is the crop coefficient. Most of the effects of the various weather conditions are incorporated into the ET_0, while K_c varies predominately with the specific crop characteristics and only to a limited extent with climate. When values of K_c are needed on a daily basis, the dual crop coefficient approach is used to separate plant transpiration and soil surface evaporation. The basal crop coefficient is used to estimate potential transpiration of a specific plant (i.e., $T_{p,\ Plant} = K_{CB}ET_0$), while the soil water evaporation coefficient is used to estimate evaporation from soil surface. The basal crop coefficient, K_{CB}, as defined in Eqn (57) of the (FAO56) is further modified to include the fraction of canopy cover (f_c) to enable the estimation of plant transpiration from reference evapotranspiration under different canopy cover conditions (i.e., $T_{p,\ Plant} = K_{cb}f_cET_0$).

Compensated root water uptake

Compensated root water uptake is also called root adaptability. It refers to a compensation mechanism to balance reduced water uptake from one part of the rhizosphere by increased uptake in another less-stressed region of the rooting zone.

Critical water stress index, ω_c

Critical water stress index, ω_c is a threshold value of water stress index defined as the ratio of actual to potential transpiration of uncompensated root water uptake. Above the critical value, ω_c, the root water uptake reduced in stressed parts of the root zone is fully compensated for by update from other, less-stressed parts. Below the critical value, ω_c, there is a certain reduction of the potential transpiration, although smaller than in uncompensated root water uptake. For $\omega_c = 1$, root water uptake is uncompensated. For $\omega_c = 0$, root water uptake is fully compensated. Cultural (including agricultural) plants are expected to have relatively high ω_c, while natural plants, especially desert species, are expected to have relatively low ω_c reflecting their ability to compensate for natural stresses.

Intra-storm evaporation loss

Intra-storm evaporation loss refers to the evaporation loss of intercepted precipitation from plant canopies during a rainfall event. In our model it is estimated as the product of fraction of canopy cover, f_c, and reference evapotranspiration, ET_0, i.e., f_cET_0.

Osmotic potential

Osmotic potential is the pressure to which the solution (rather than the pure water) is subjected in order to be at equilibrium through a semipermeable membrane with pure water. Osmotic pressure can be regarded as a solute suction, which arises from the presence of both solutes in the soil water and a semipermeable membrane permeable to pure water but impermeable to the solutes.

Permanent wilting percentage (PWP)

Permanent wilting percentage (PWP) is the soil water content at which plants remain wilted overnight or in a humid chamber unless they are rewatered. Briggs and Shantz (1911) published their concept of the permanent wilting percentage, which was refined by Richards and Wadleigh (1952), Veilhmeyer and Hendrickson (1928, 1950). Slatyer (1957) pointed out that instead of being a soil constant, the permanent wilting percentage really depends on the water potential at which leaves lose their turgor, which depends on their osmotic properties and the meteorological conditions affecting transpiration, and on soil conditions that affect water absorption.

Phreatic evaporation

Phreatic evaporation refers to evaporation from groundwater. It is the upward flux at water table.

Potential/maximum canopy interception loss

Potential/maximum canopy interception loss of a rainfall event includes the static loss due to canopy storage and the dynamic loss due to intra-storm evaporation from canopy surfaces. The static loss is limited by a canopy's storage capacity. Hence, potential/maximum canopy interception loss of a rainfall event equals the storage capacity of a canopy plus the intra-storm evaporation from canopy surfaces during a storm event.

System dependent boundaries

System dependent boundaries refer to the boundaries, along which the numerical conditions cannot be defined a priori due to their dependence on the primary unknown variable, pressure head/matric potential. Ground surface exposed to atmospheric conditions is one of the system-dependent boundaries simulated by HYDRUS. The current HYDRUS package can simulate ground surfaces of two different characteristics (such as fraction canopy cover): with one set to Atmospheric Boundary and the other set to Variable Flux 1 Boundary.

Water stress reduction coefficient

Water stress reduction coefficient is also called water stress response function. It is a prescribed dimensionless function of the soil water pressure head proposed by Feddes (1978) to quantify the ratio of actual to potential water uptake rate at any point in the root zone. There are 4 parameters in Feddes' water stress response function: h1 is the anaerobiosis point, above which the plant roots cease to absorb water due to lack of aeration; h2 and h3 are the upper and lower limits of the soil water pressure head, between them the root water uptake stays at the optimal level; h4 is the wilting point pressure head, below which the plant roots cease to absorb water due to lack of available water. Feddes' model does not simulate the effect of solute in soil water (such as salinity) explicitly. However, the lower limit of the optimal range, h3 and the wilting point h4, can be adjusted to the so-called effective values to implicitly incorporate the effect of salinity on plant transpiration. The implicit approach to simulate the effect of salinity on transpiration is limited by the dynamics of solute components. If concentrations of the component species are significantly affected by the transport process, solute transport needs to be included in the model to adequately simulate the effect of salinity on plant transpiration.

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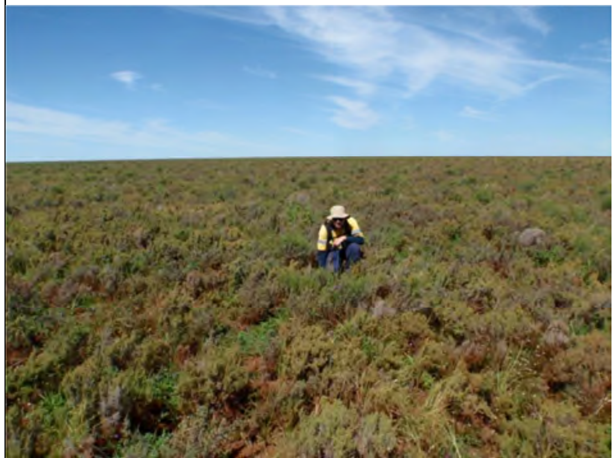
P1 Low open shrubland with more densely vegetated drainage tract in distance (775000E; 7516250N)

P2 Low open (sparse) shrubland with samphire boundary in background (775000E; 7515850N)

P3 Low open shrubland with samphire boundary in far distance (775500E; 7515850N)

P4 Open samphire heath (775000E; 7515600N)



P5 closed samphire heath further down gradient (775000E; 7515200N)

P6 Open samphire heath grading to closed samphire in background (775500E; 7515500N)

Figure 1 Photographic examples of samphire vegetation and adjacent low open shrubland near the edge of the Fortescue Marsh targeted by the modeling study (looking approximately south in all cases)

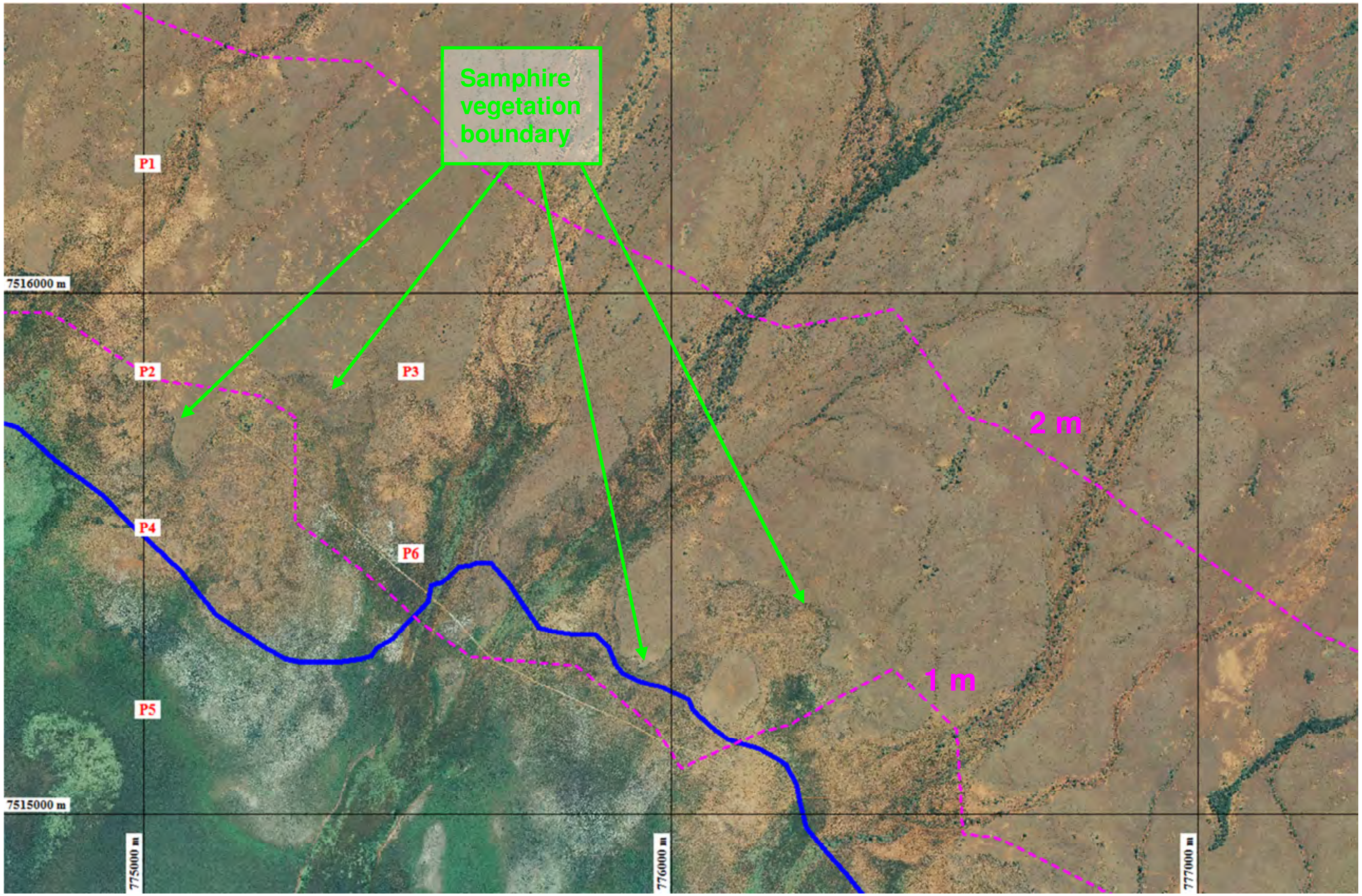


Figure 2 **Aerial image showing Marsh land system boundary (blue), maximum predicted extent of drawdown below baseline water levels (pink dashed) and ground based photograph points (as shown in Figure 2). The samphire vegetation boundary is readily discernible.**

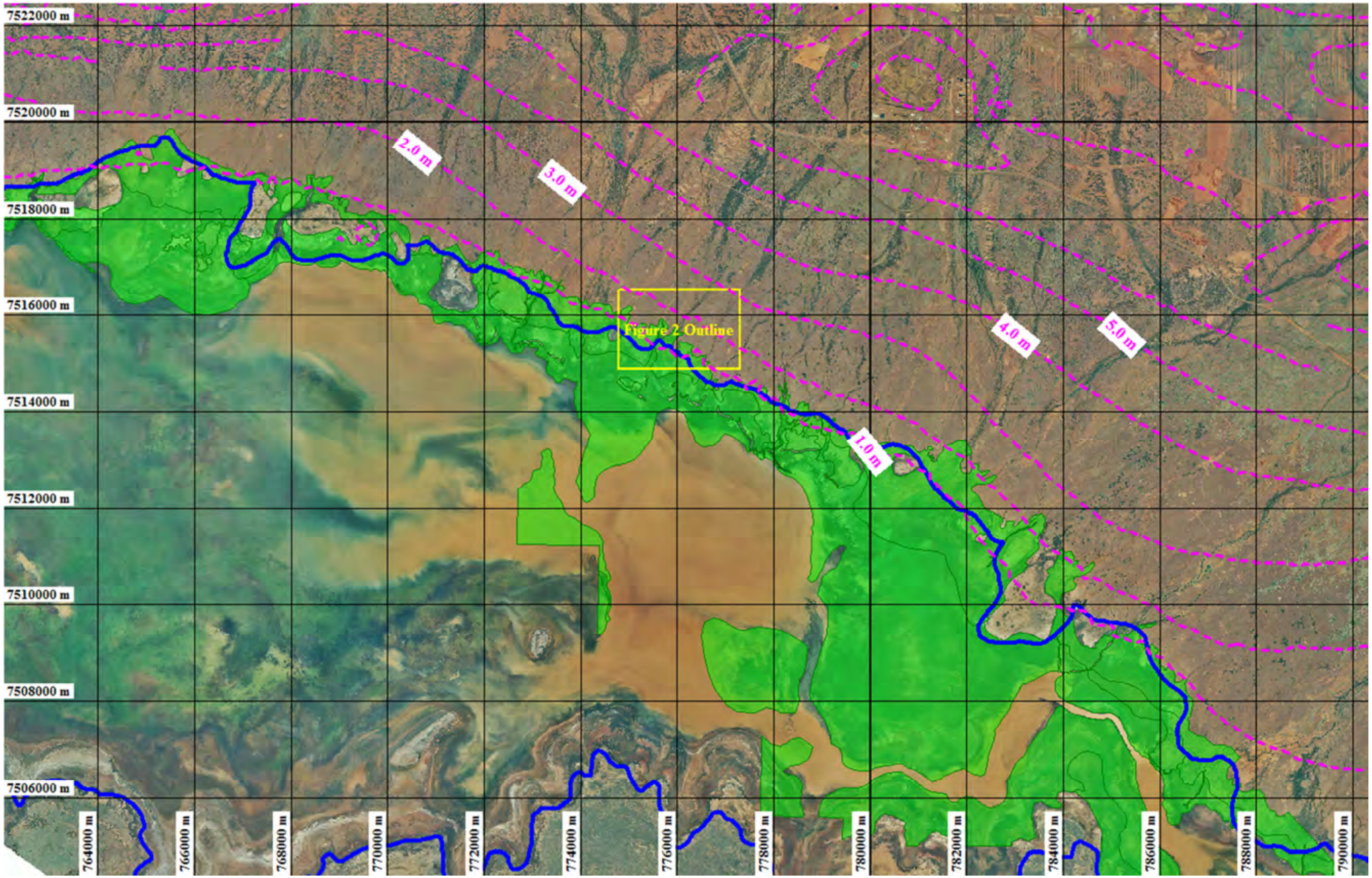


Figure 3 Fortescue Marsh samphire vegetation (green shaded), Marsh land system boundary (blue) and maximum predicted extent of drawdown below baseline water levels (pink dashed) under the Christmas Creek LOM Project

Figure 4. Typical transect and simulated domain of HYDRUS model

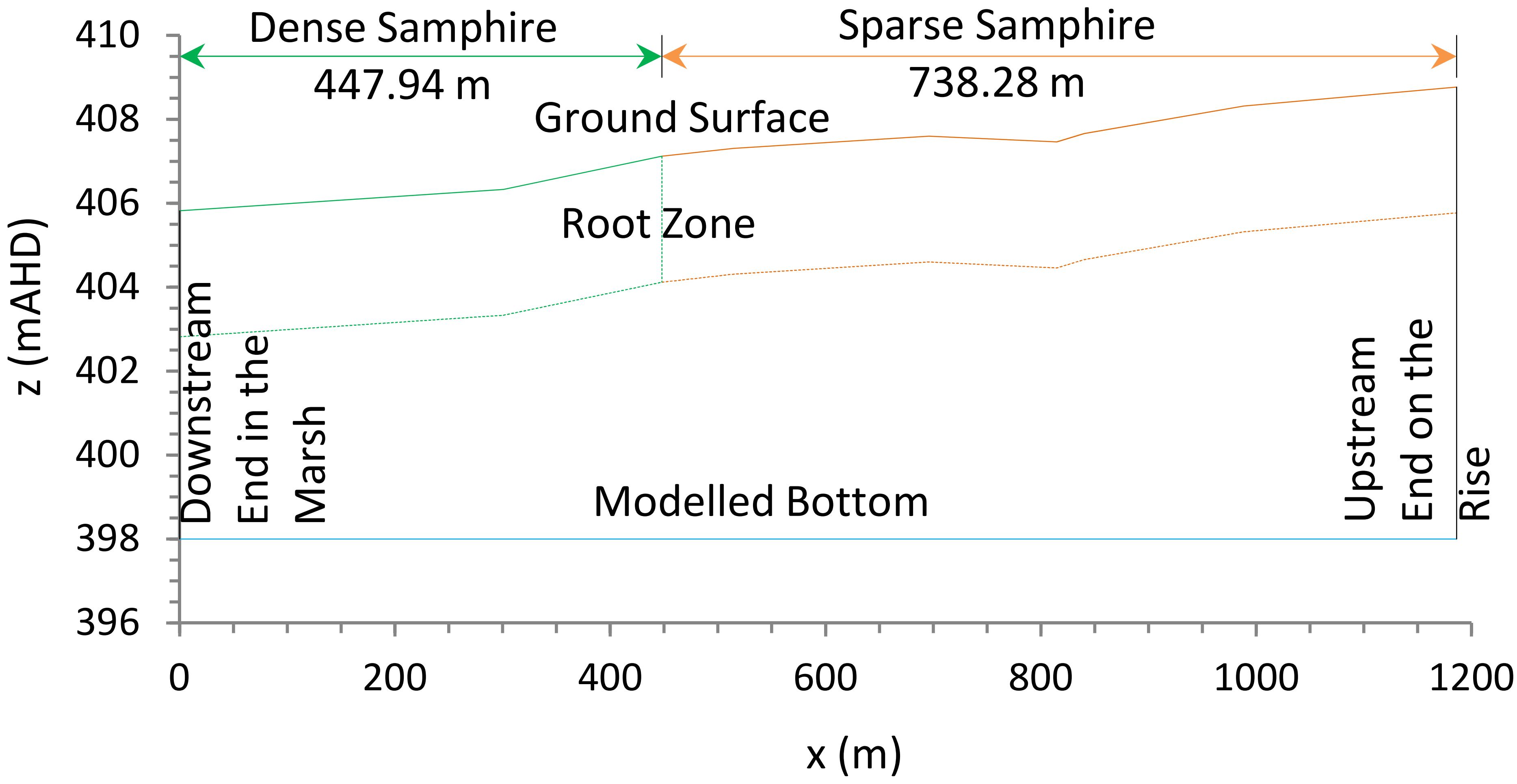


Figure 5. Correlation between ET0 at UWA Weather Station and ET0 at Newman Aero Weather Station.

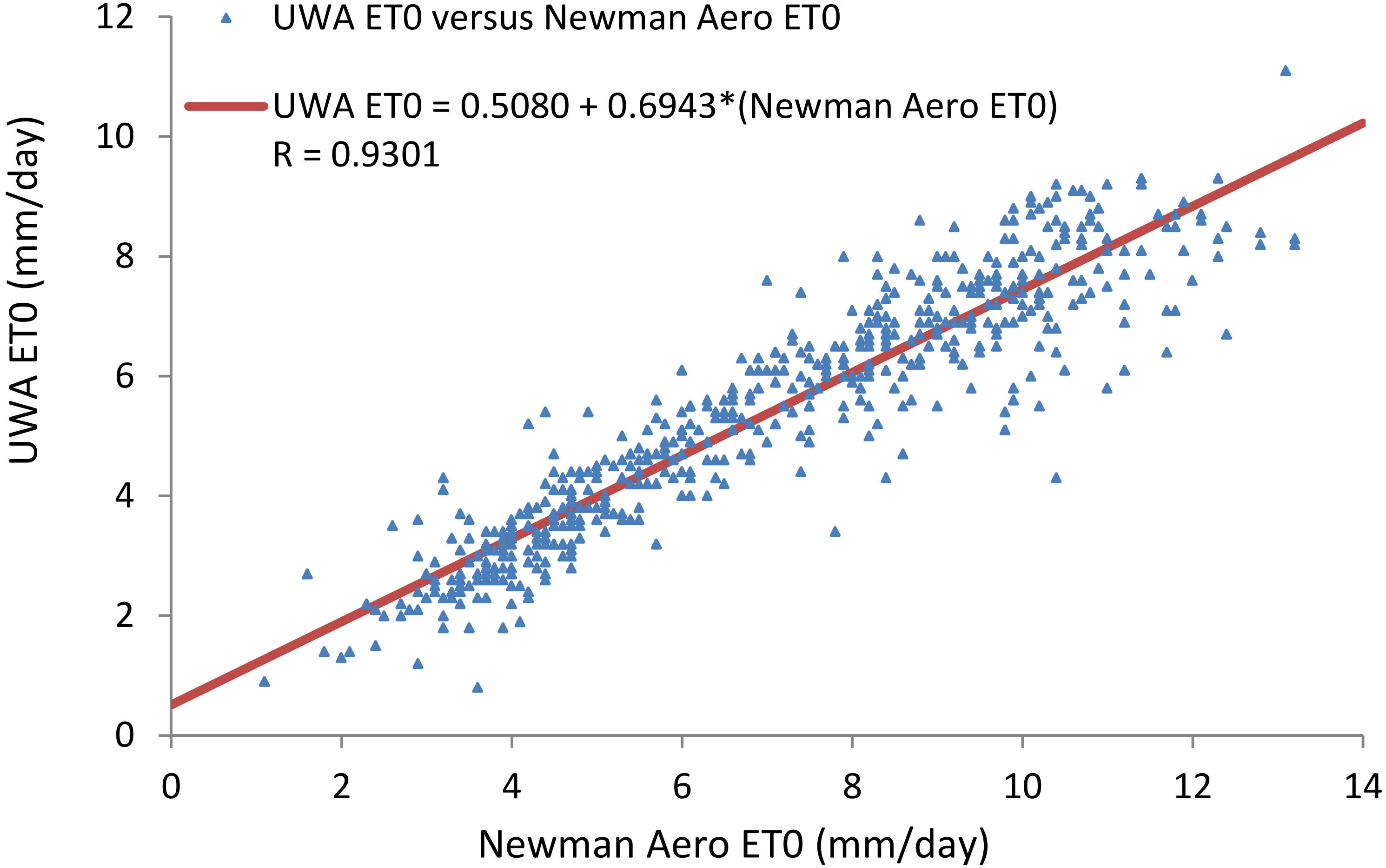
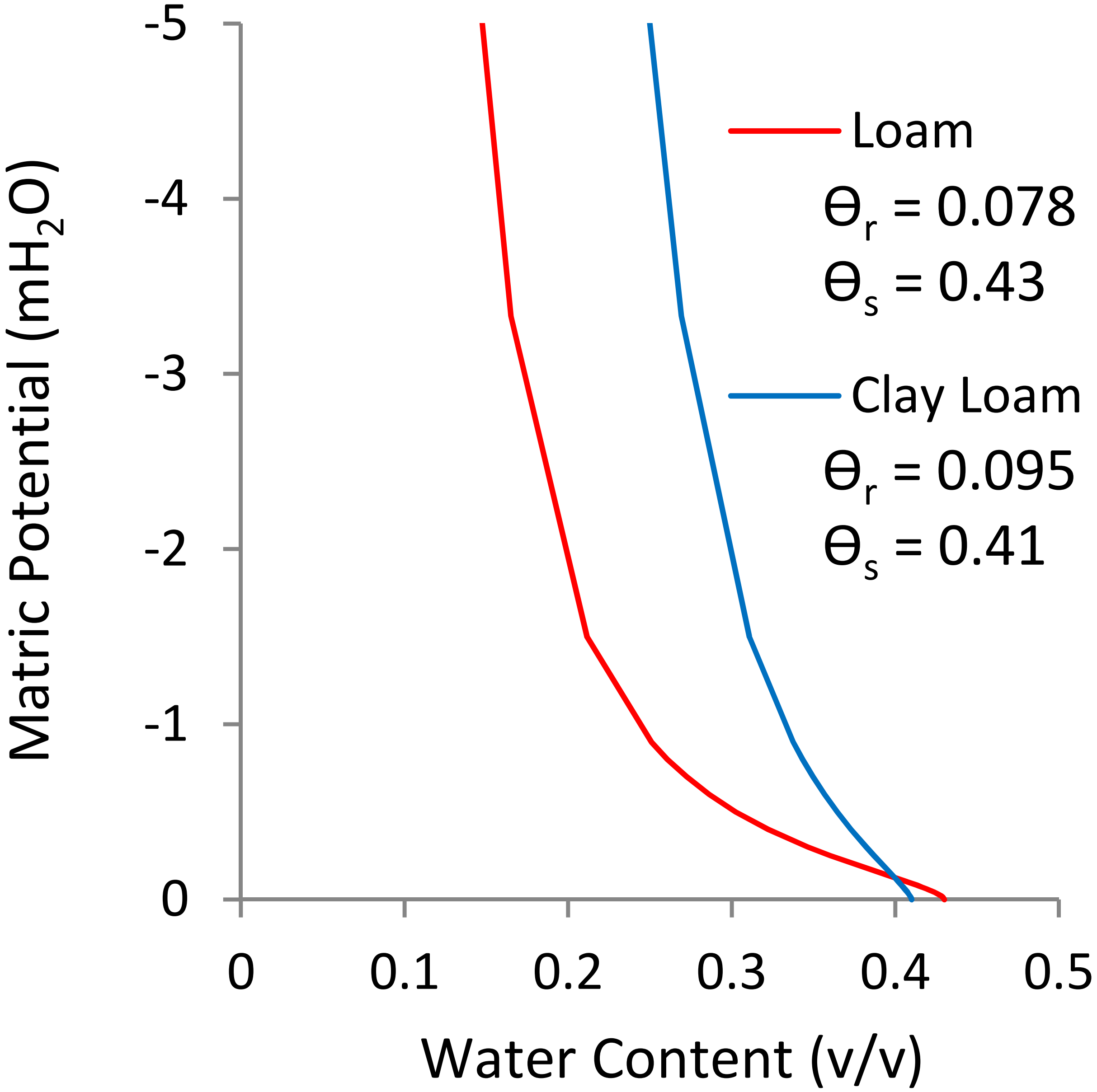


Figure 6. Small Range Soil Moisture Retention Curves



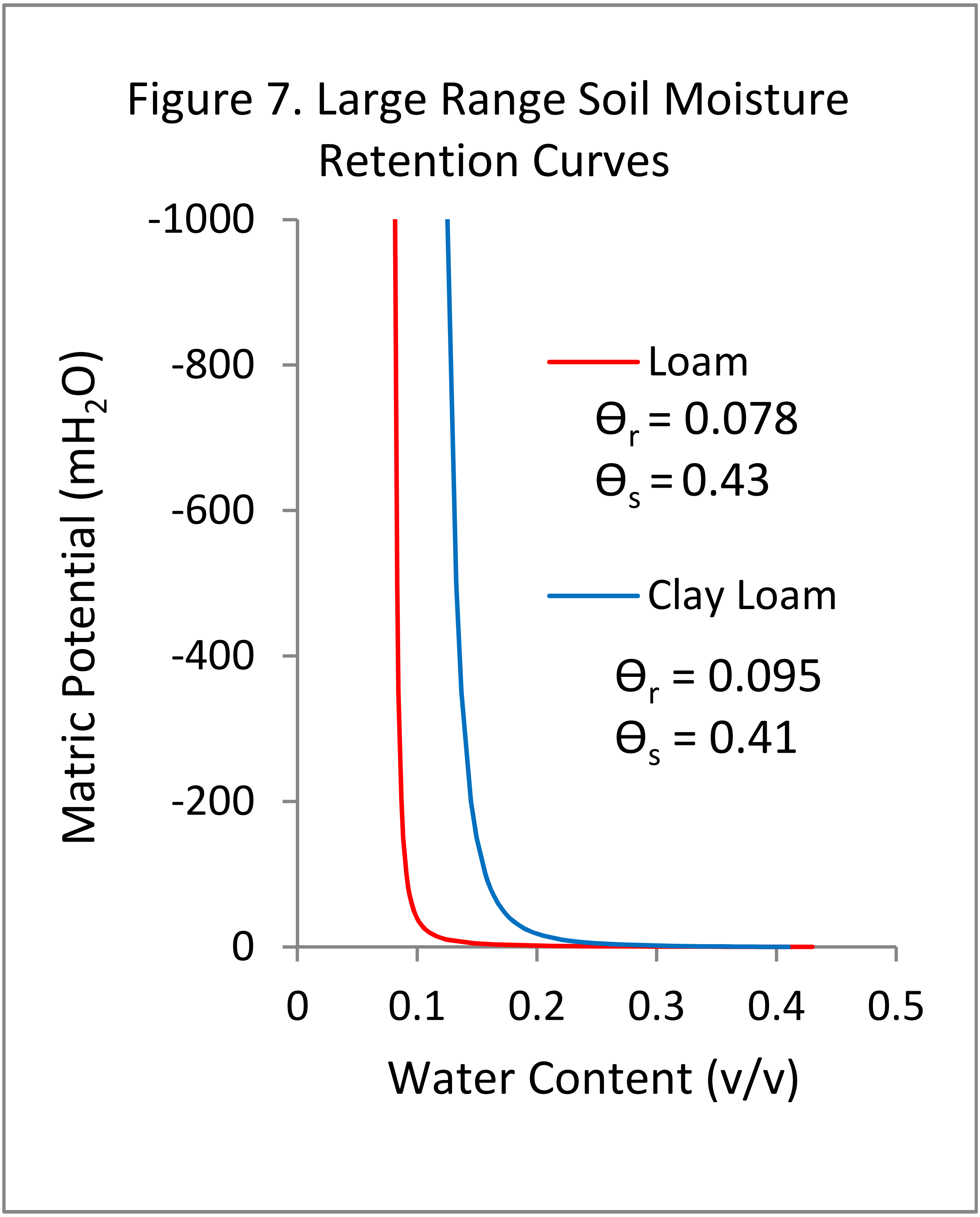


Figure 7. Large Range Soil Moisture Retention Curves
Matric Potential (mH_2O)
-1000
-800
-600
-400
-200
0
0
0.1
0.2
0.3
0.4
0.5
Water Content (v/v)
Loam
$\Theta_r = 0.078$
$\Theta_s = 0.43$
Clay Loam
$\Theta_r = 0.095$
$\Theta_s = 0.41$

Figure 8. Small Range Logarithmic Diagram of Unsaturated Hydraulic Conductivity

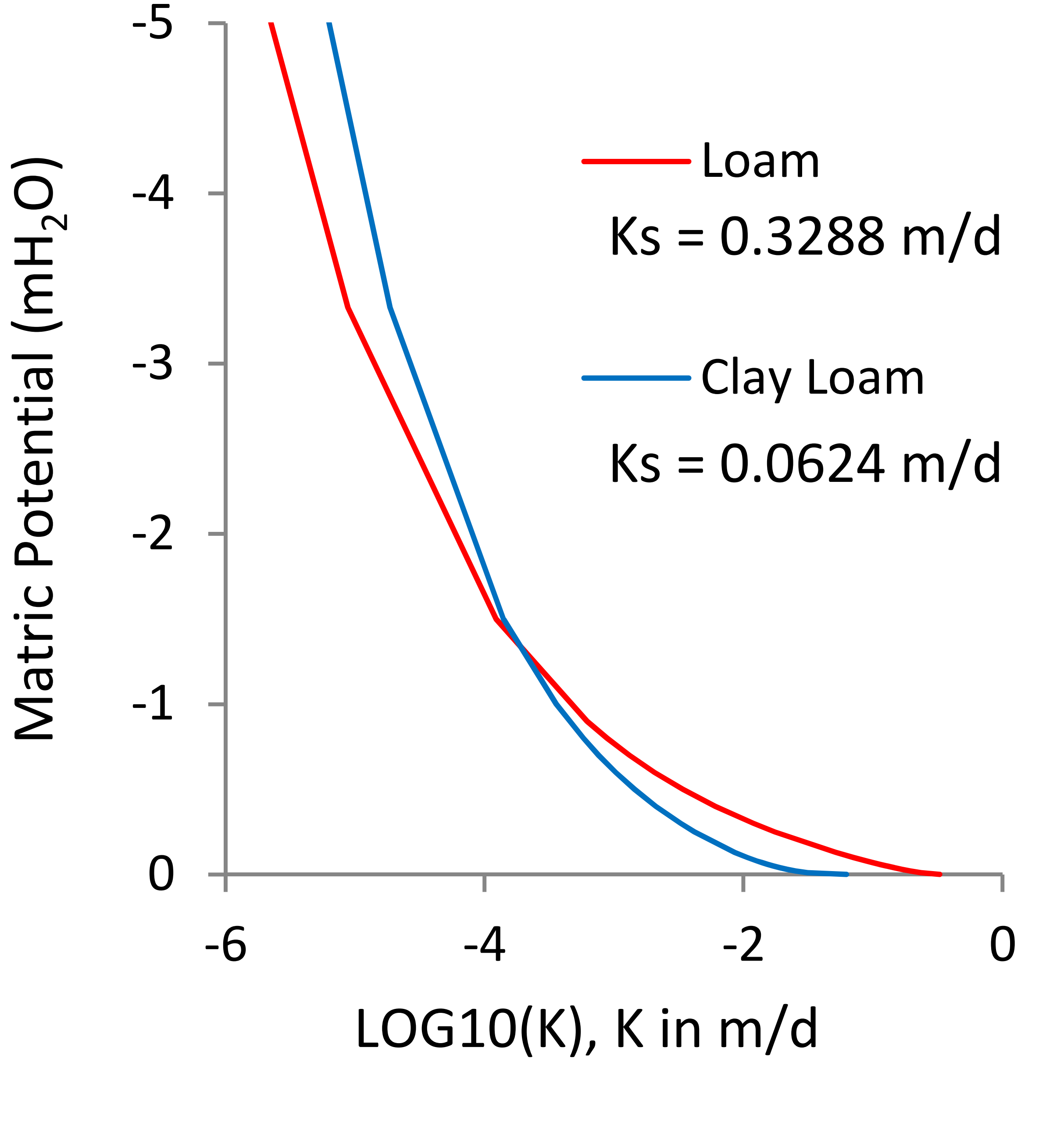


Figure 9. Large Range Logarithmic Diagram of Unsaturated Hydraulic Conductivity

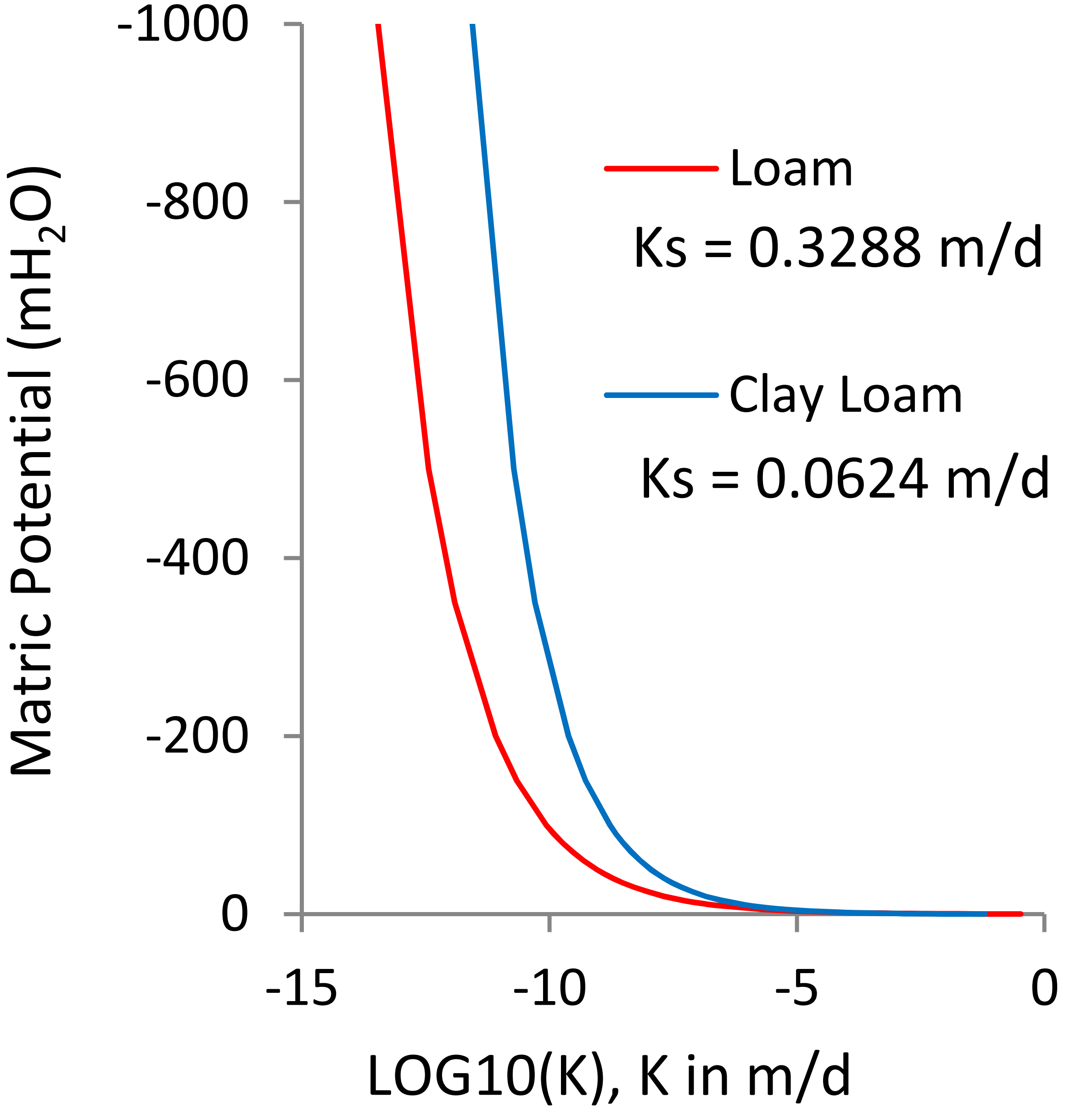


Figure 10. Distribution of Measured Fine Root Density and Normalized Root Water Uptake

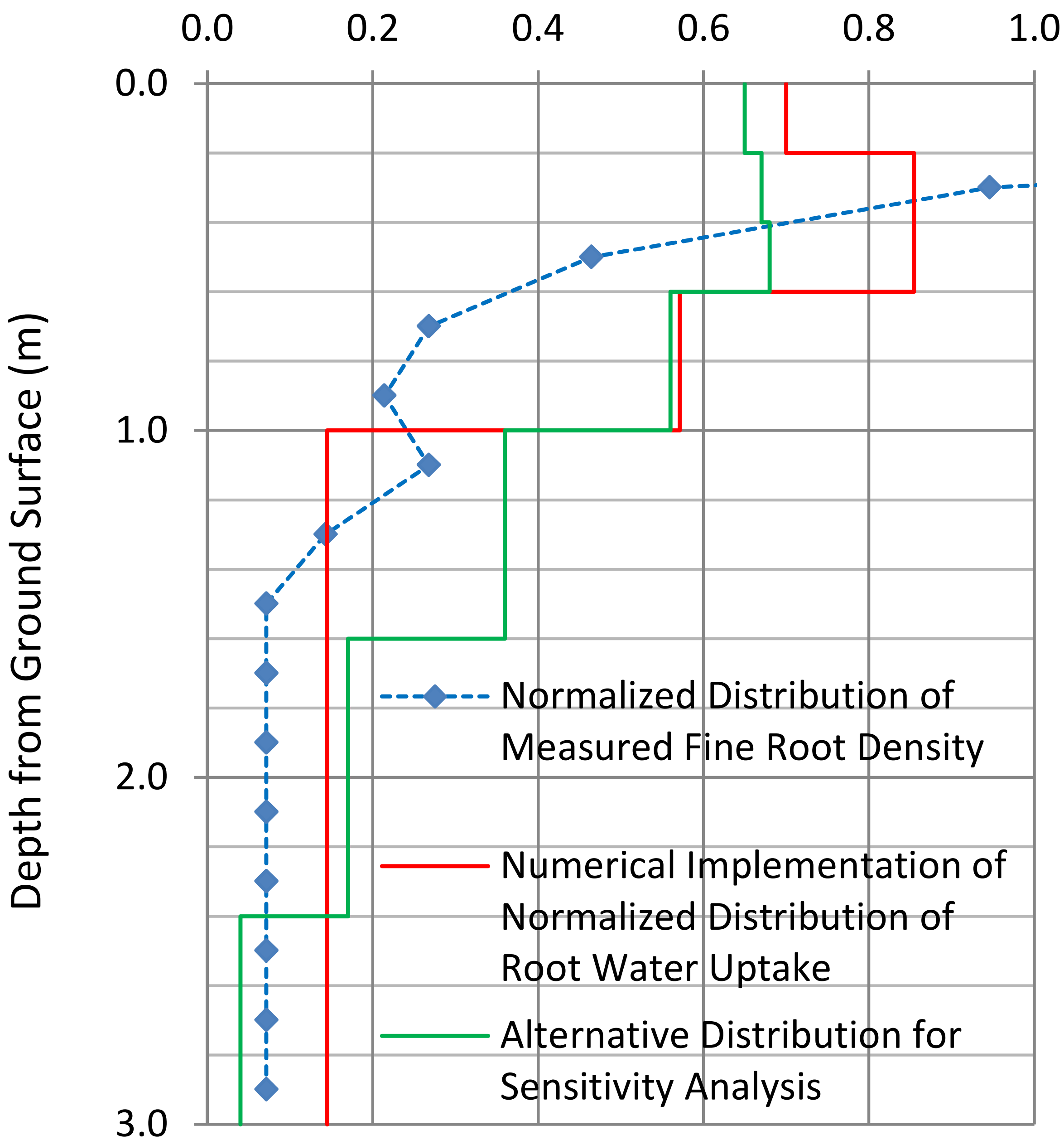
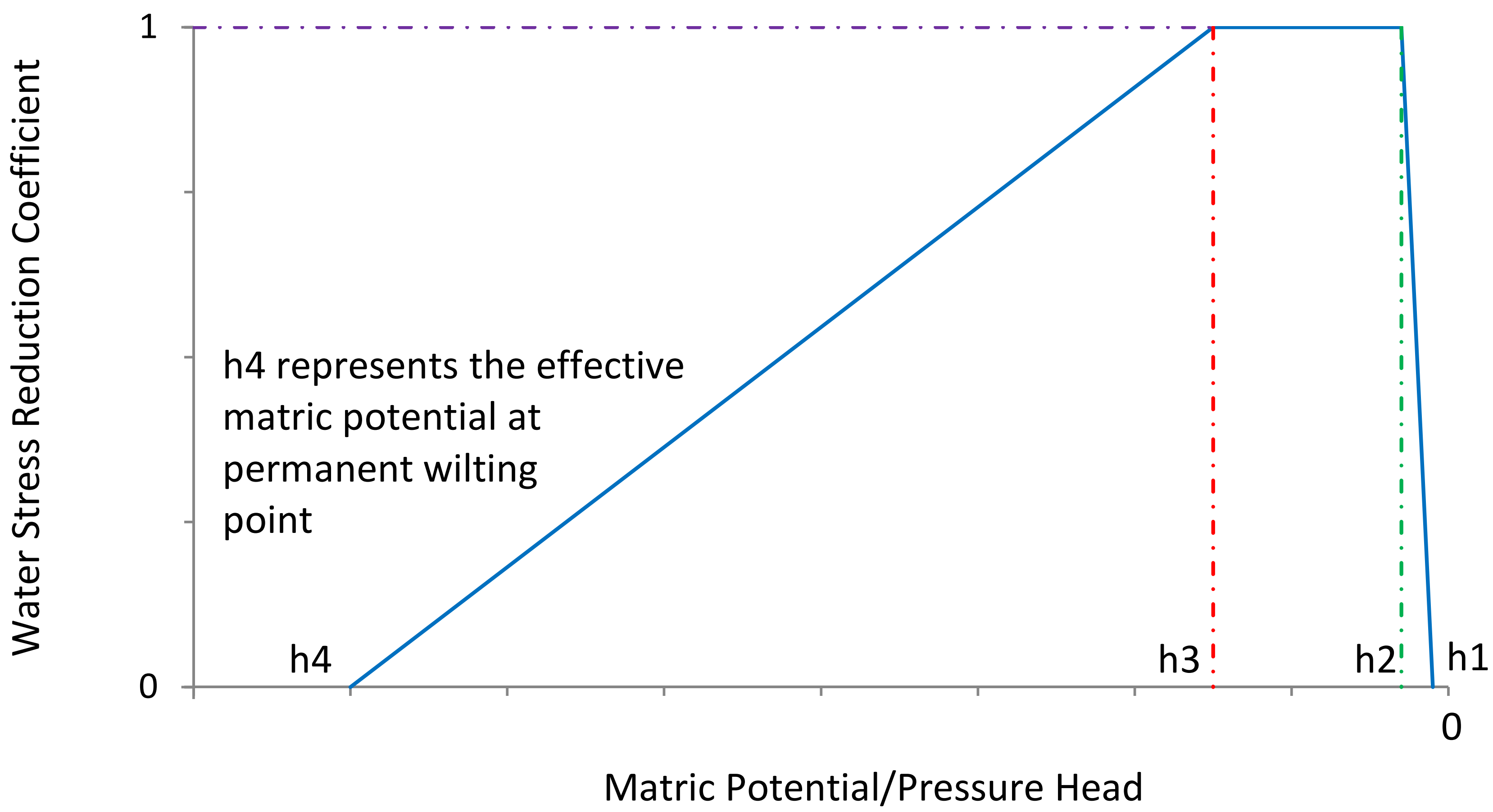


Figure 11. Schematic plot of Feddes water stress reduction coefficient



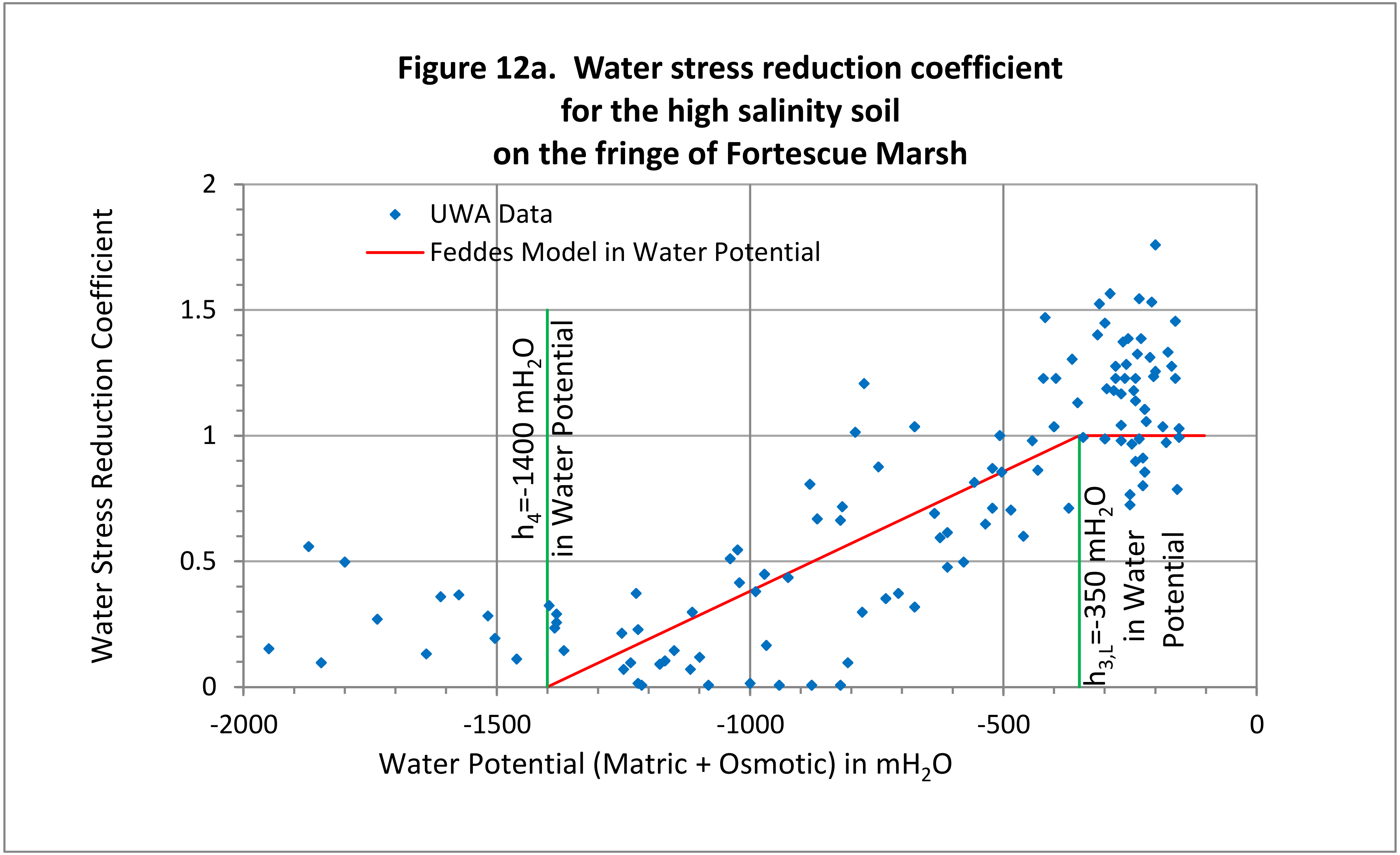


Figure 12a. Water stress reduction coefficient
for the high salinity soil
on the fringe of Fortescue Marsh
UWA Data
Feddes Model in Water Potential
h_4=-1400 mH_2O
in Water Potential
$h_{3,L}$=-350 mH_2O
in Water
Potential
Water Stress Reduction Coefficient
Water Potential (Matric + Osmotic) in mH_2O
2
1.5
1
0.5
0
-2000
-1500
-1000
-500
0

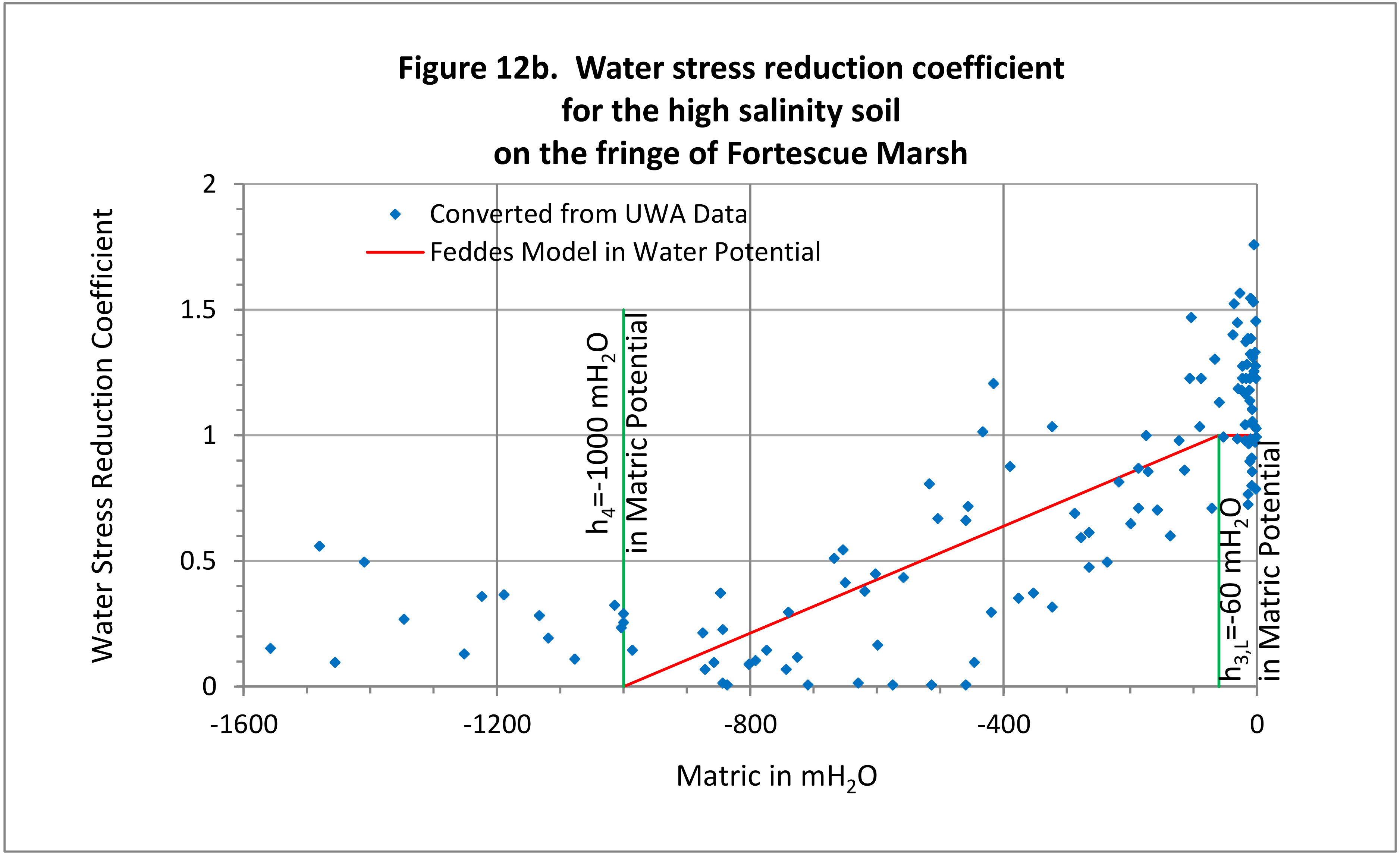
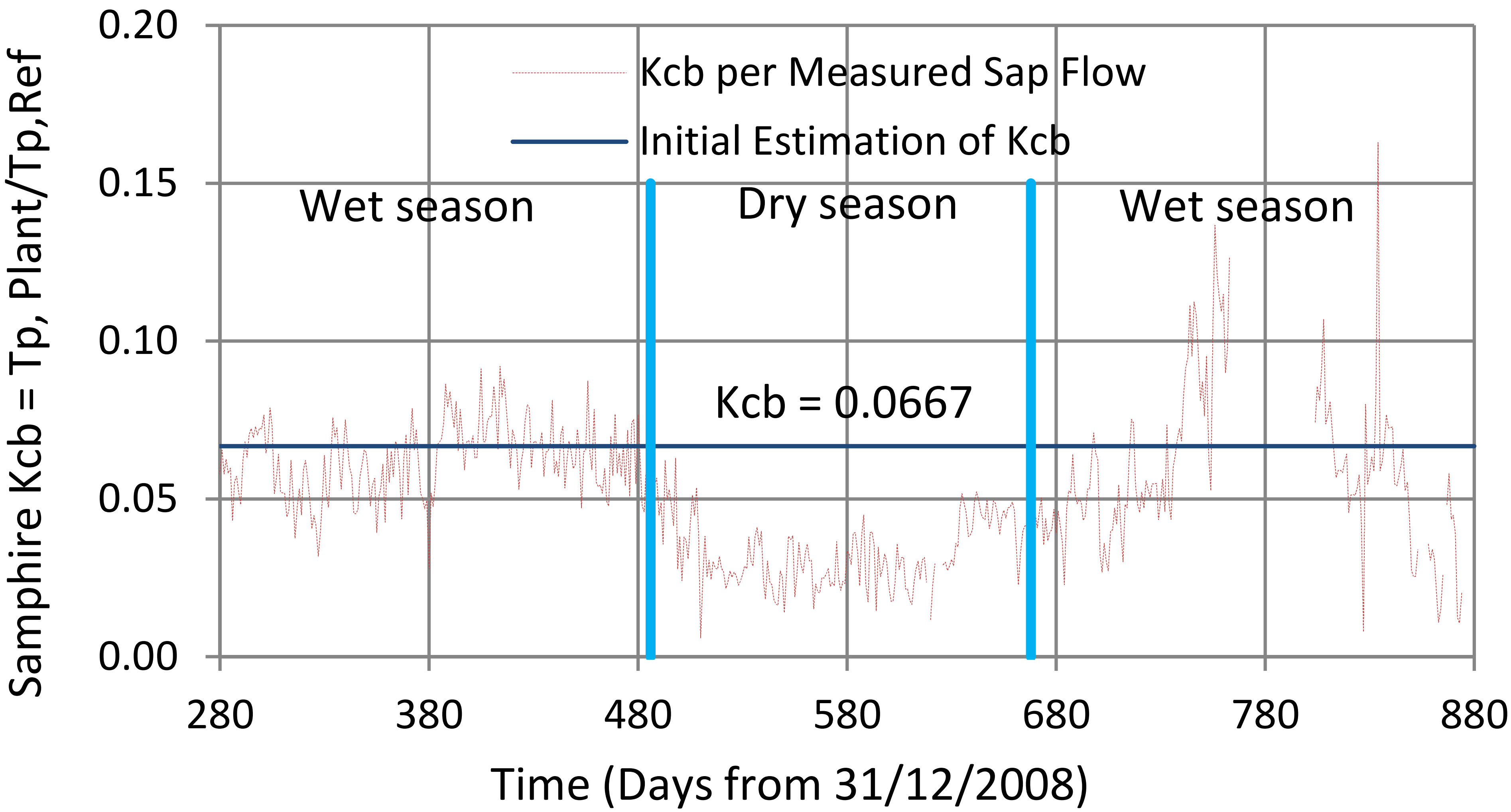


Figure 12b. Water stress reduction coefficient
for the high salinity soil
on the fringe of Fortescue Marsh
Converted from UWA Data
Feddes Model in Water Potential
h_4=-1000 mH_2O in Matric Potential
$h_{3,L}$=-60 mH_2O in Matric Potential
Water Stress Reduction Coefficient
Matric in mH_2O
2
1.5
1
0.5
0
-1600
-1200
-800
-400
0

Figure 13. Estimating Samphire from Measured Sap Flow Data.



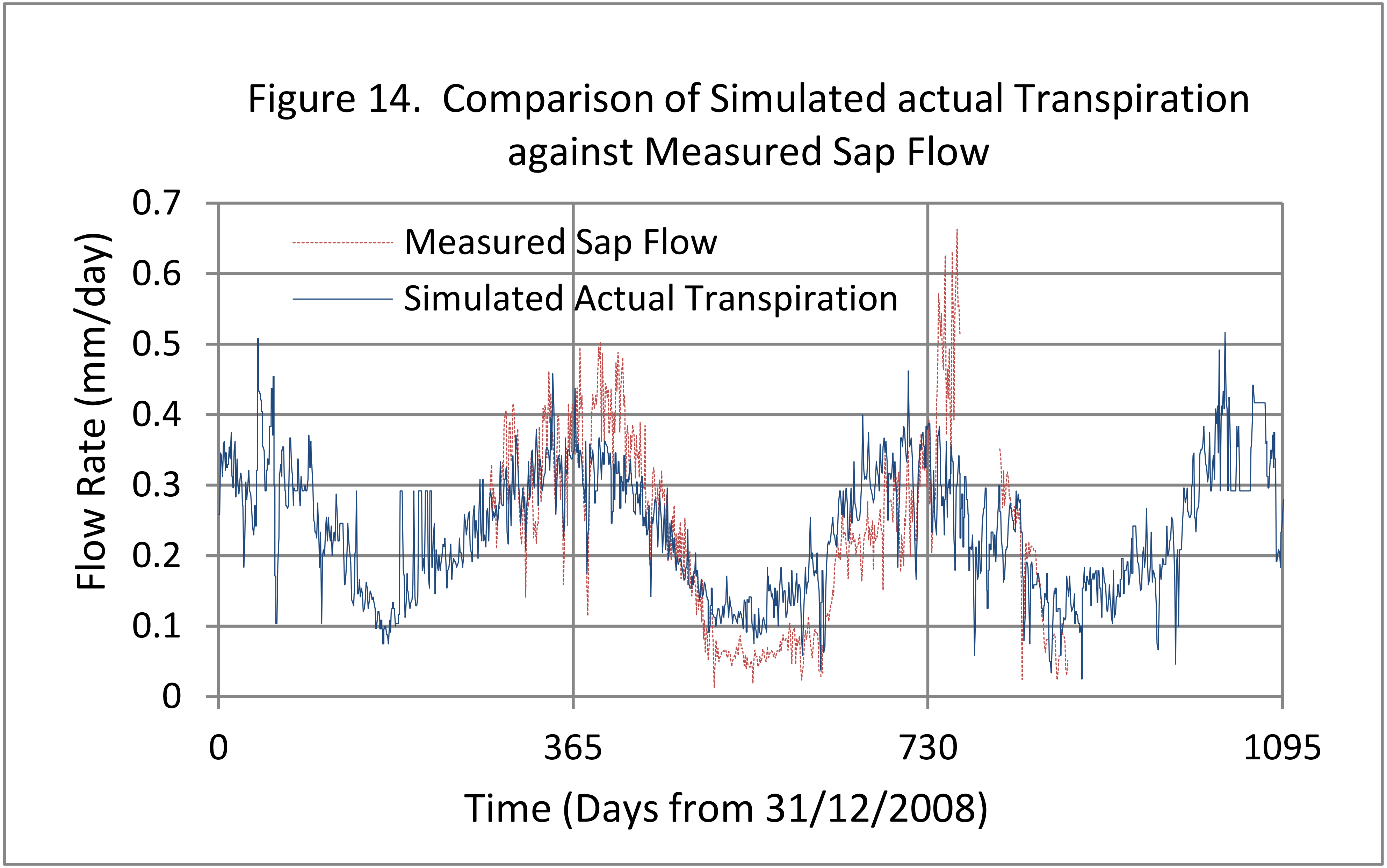


Figure 14. Comparison of Simulated actual Transpiration against Measured Sap Flow
Measured Sap Flow
Simulated Actual Transpiration
Flow Rate (mm/day)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
365
730
1095
Time (Days from 31/12/2008)

Figure 15. Comparison of Simulated Soil water Content against Sampled Profile at UWA Pit CC1

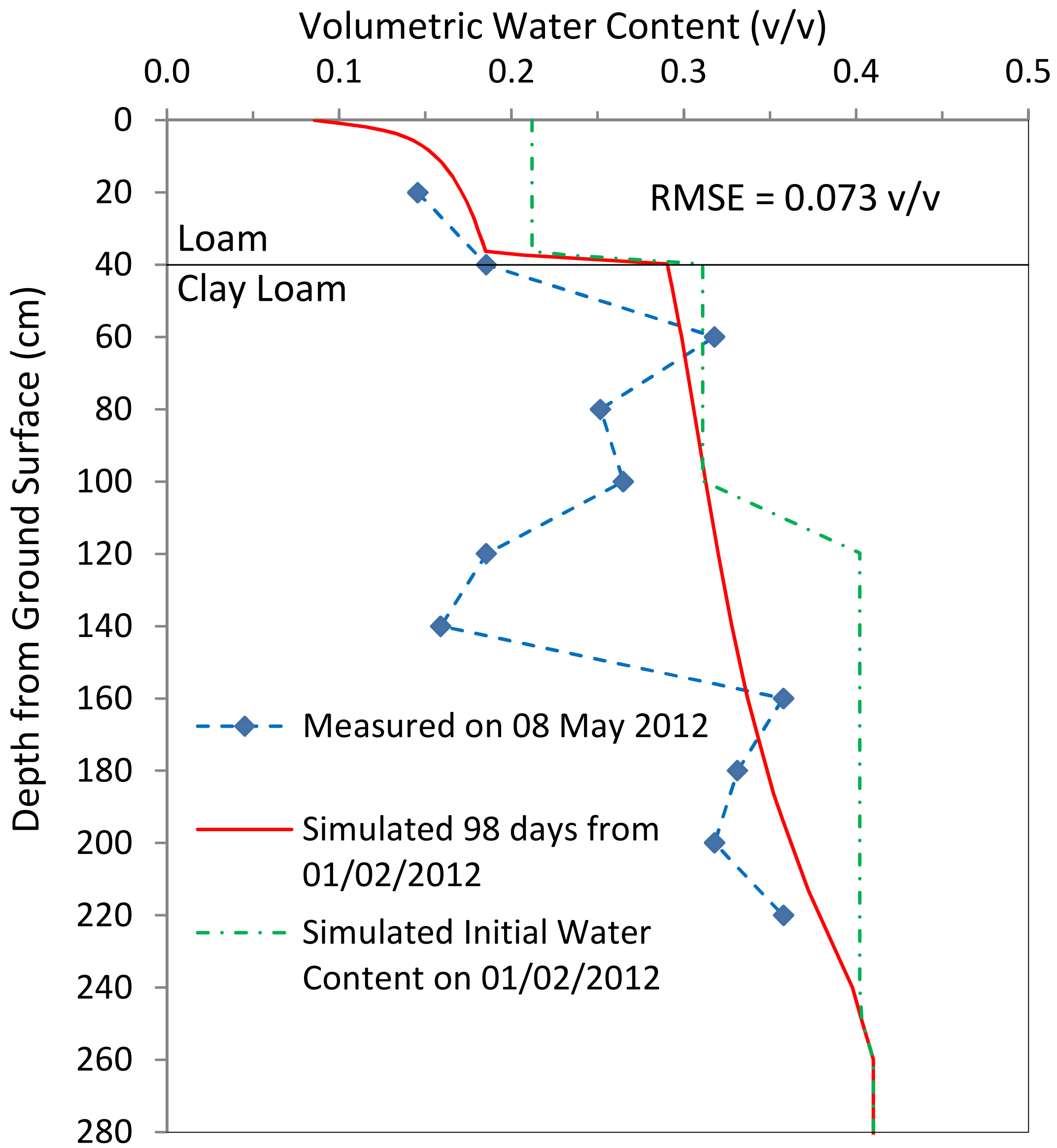


Figure 16. Comparison of Simulated Soil water Content against Sampled Profile at UWA Pit CC3

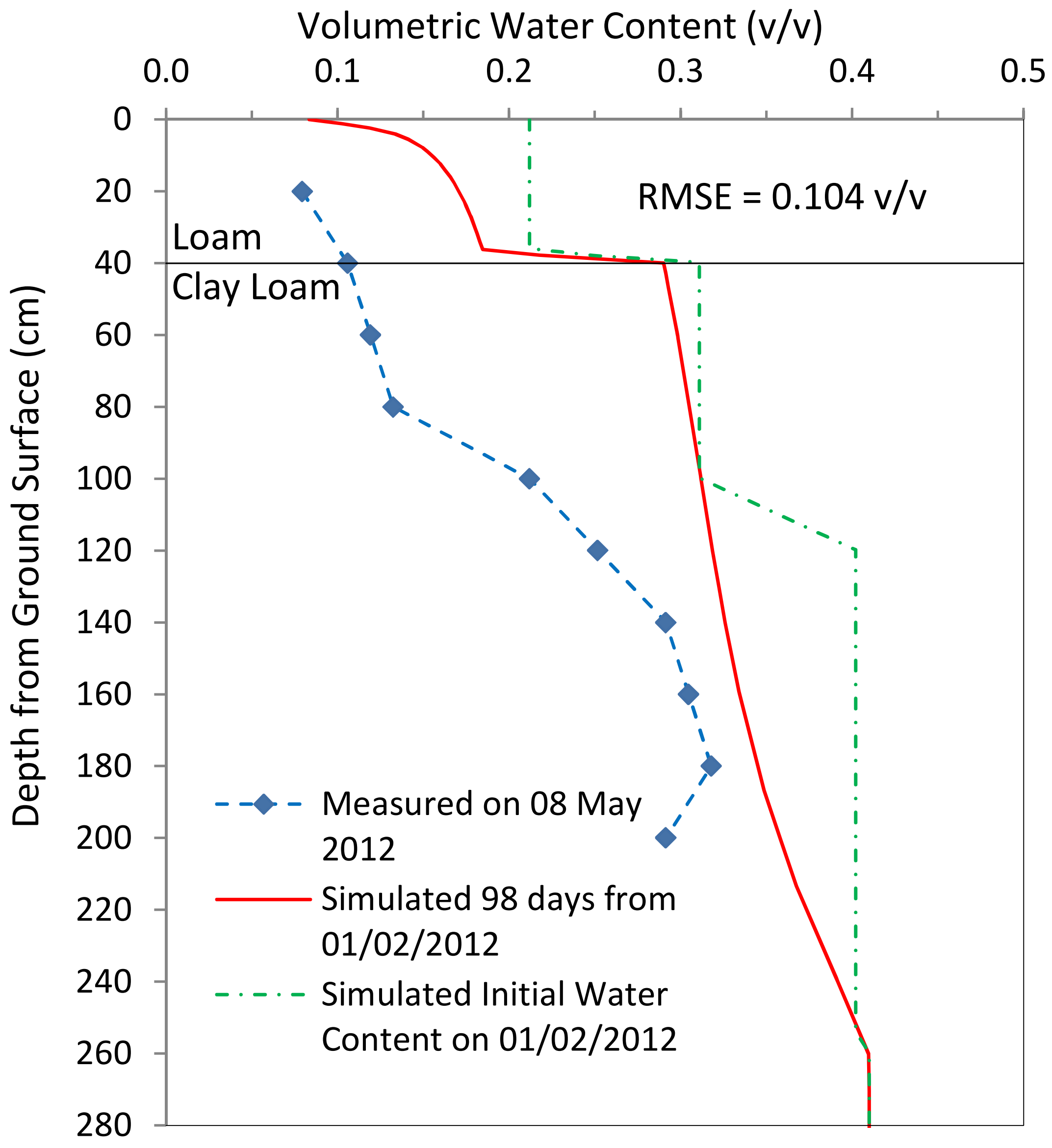
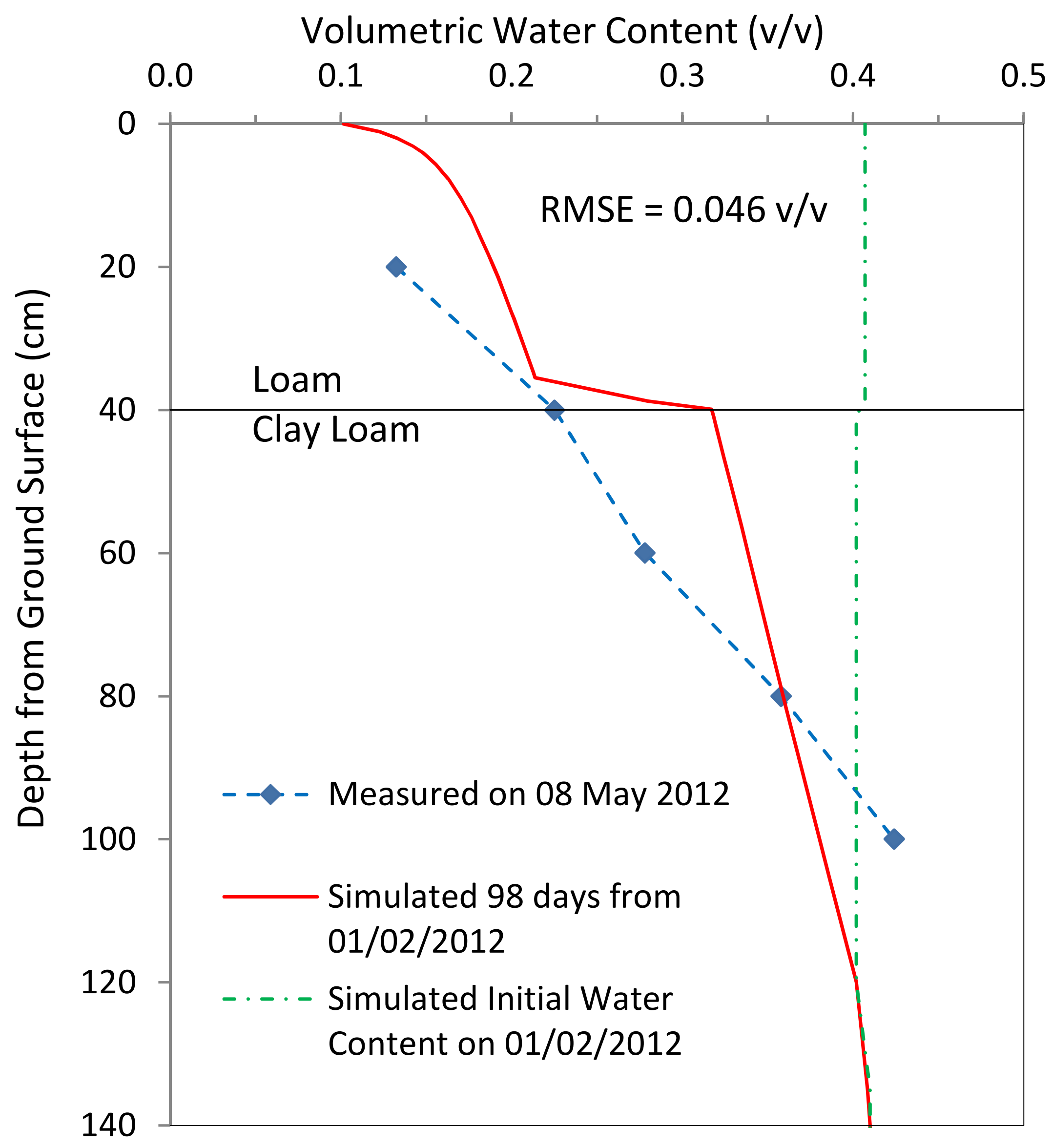


Figure 17. Comparison of Simulated Soil water Content against Sampled Profile at UWA Pit CC4



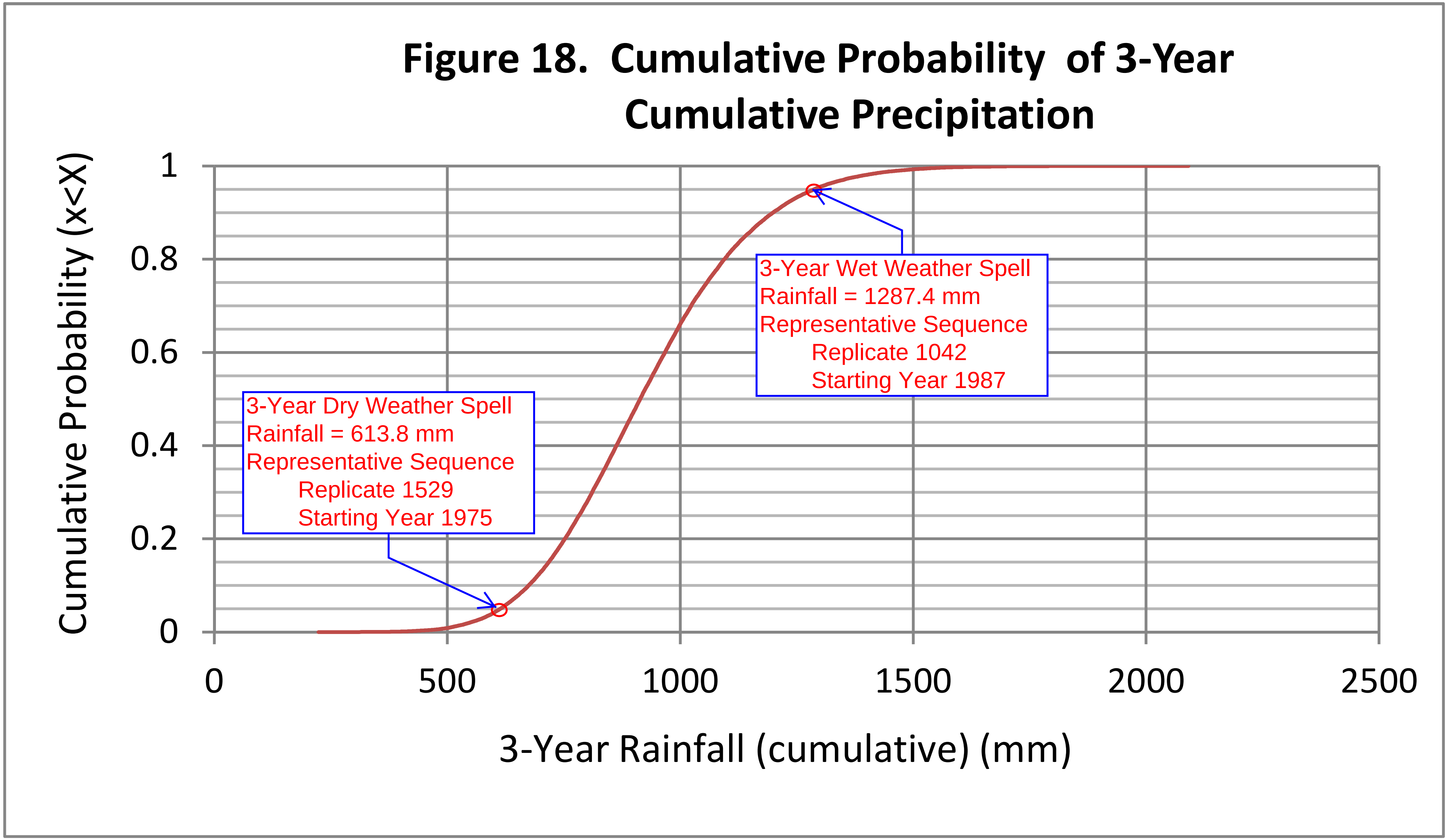


Figure 18. Cumulative Probability of 3-Year Cumulative Precipitation
Cumulative Probability (x<X)
1
0.8
0.6
0.4
0.2
0
0
500
1000
1500
2000
2500
3-Year Rainfall (cumulative) (mm)
3-Year Wet Weather Spell
Rainfall = 1287.4 mm
Representative Sequence
Replicate 1042
Starting Year 1987
3-Year Dry Weather Spell
Rainfall = 613.8 mm
Representative Sequence
Replicate 1529
Starting Year 1975

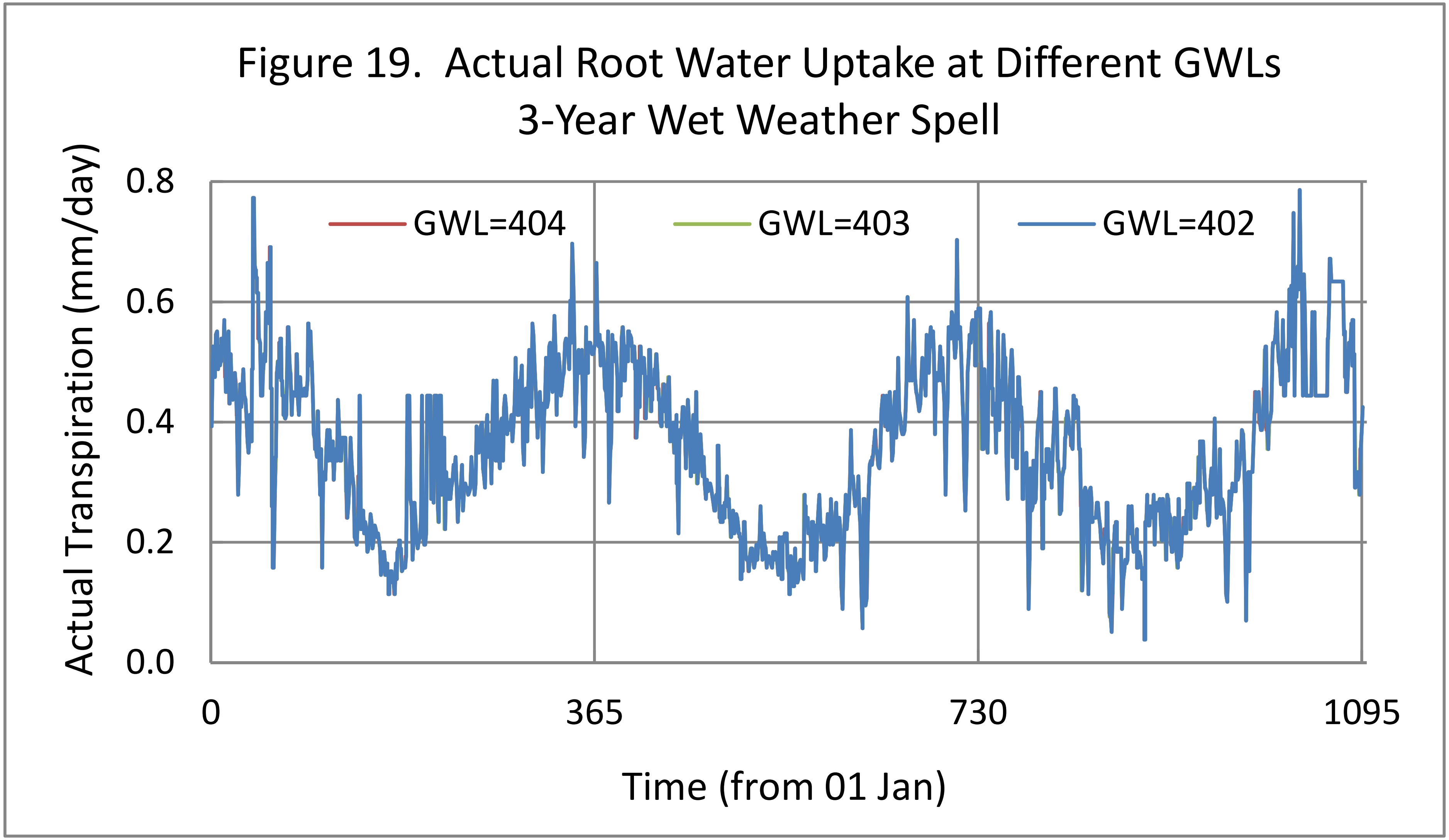


Figure 19. Actual Root Water Uptake at Different GWLs
3-Year Wet Weather Spell
GWL=404
GWL=403
GWL=402
Actual Transpiration (mm/day)
0.8
0.6
0.4
0.2
0.0
0
365
730
1095
Time (from 01 Jan)

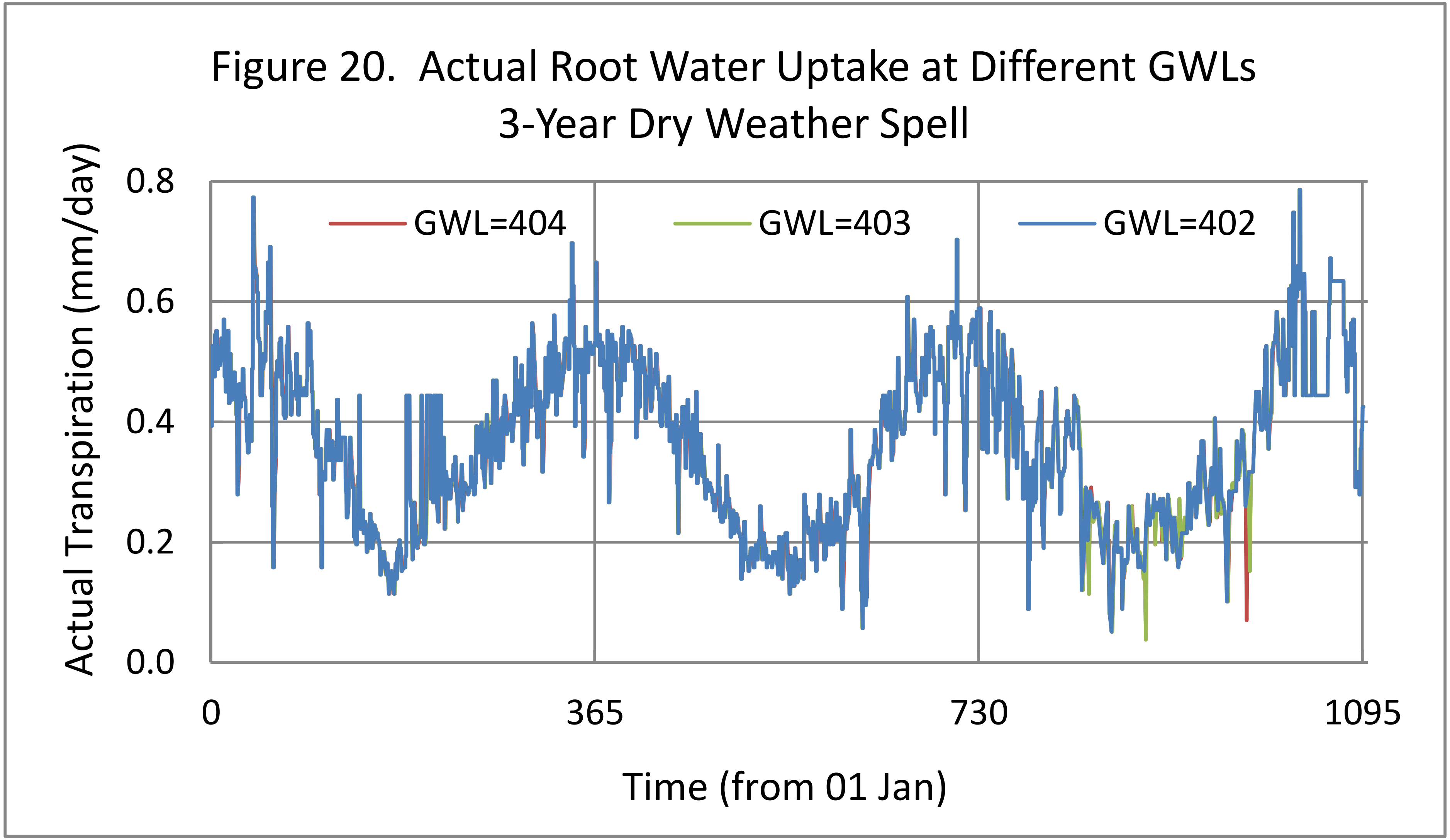
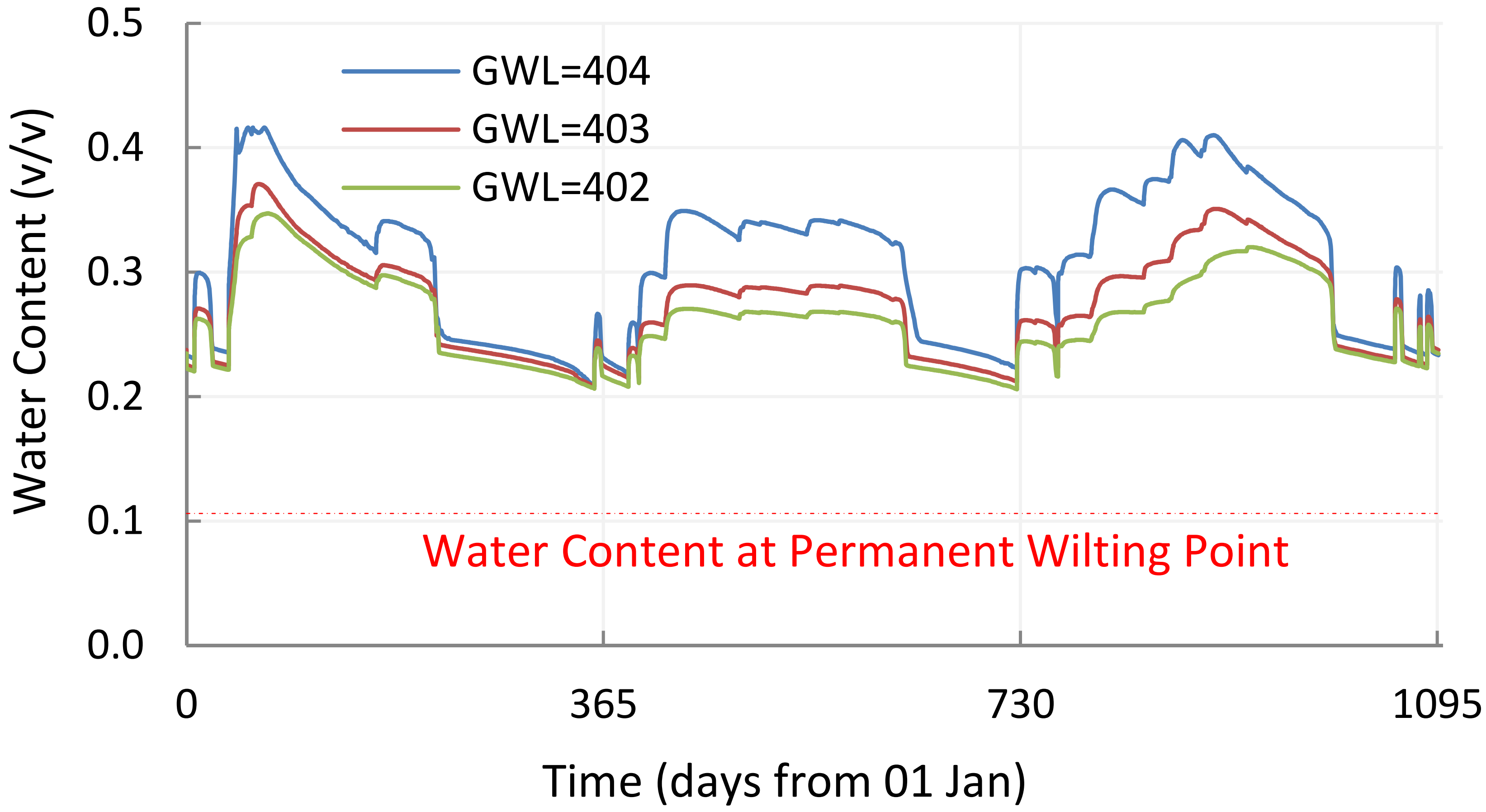


Figure 20. Actual Root Water Uptake at Different GWLs
3-Year Dry Weather Spell
GWL=404
GWL=403
GWL=402
Actual Transpiration (mm/day)
0.0
0.2
0.4
0.6
0.8
0
365
730
1095
Time (from 01 Jan)

Figure 21. Root Zone Water Content at Different GWLs
3-Year Wet Weather Spells



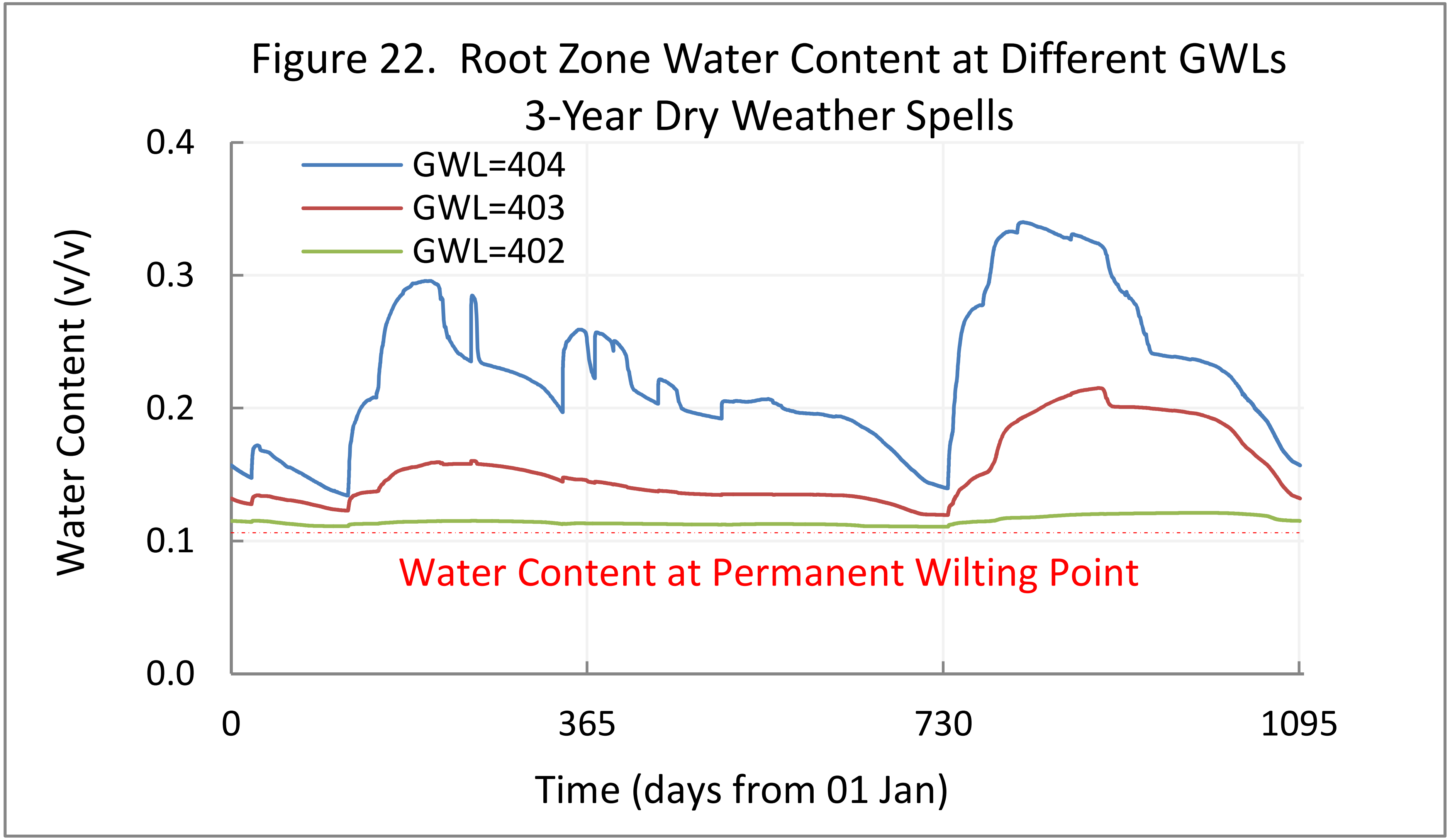


Figure 22. Root Zone Water Content at Different GWLs
3-Year Dry Weather Spells
0.4
0.3
0.2
0.1
0.0
Water Content (v/v)
GWL=404
GWL=403
GWL=402
Water Content at Permanent Wilting Point
0
365
730
1095
Time (days from 01 Jan)

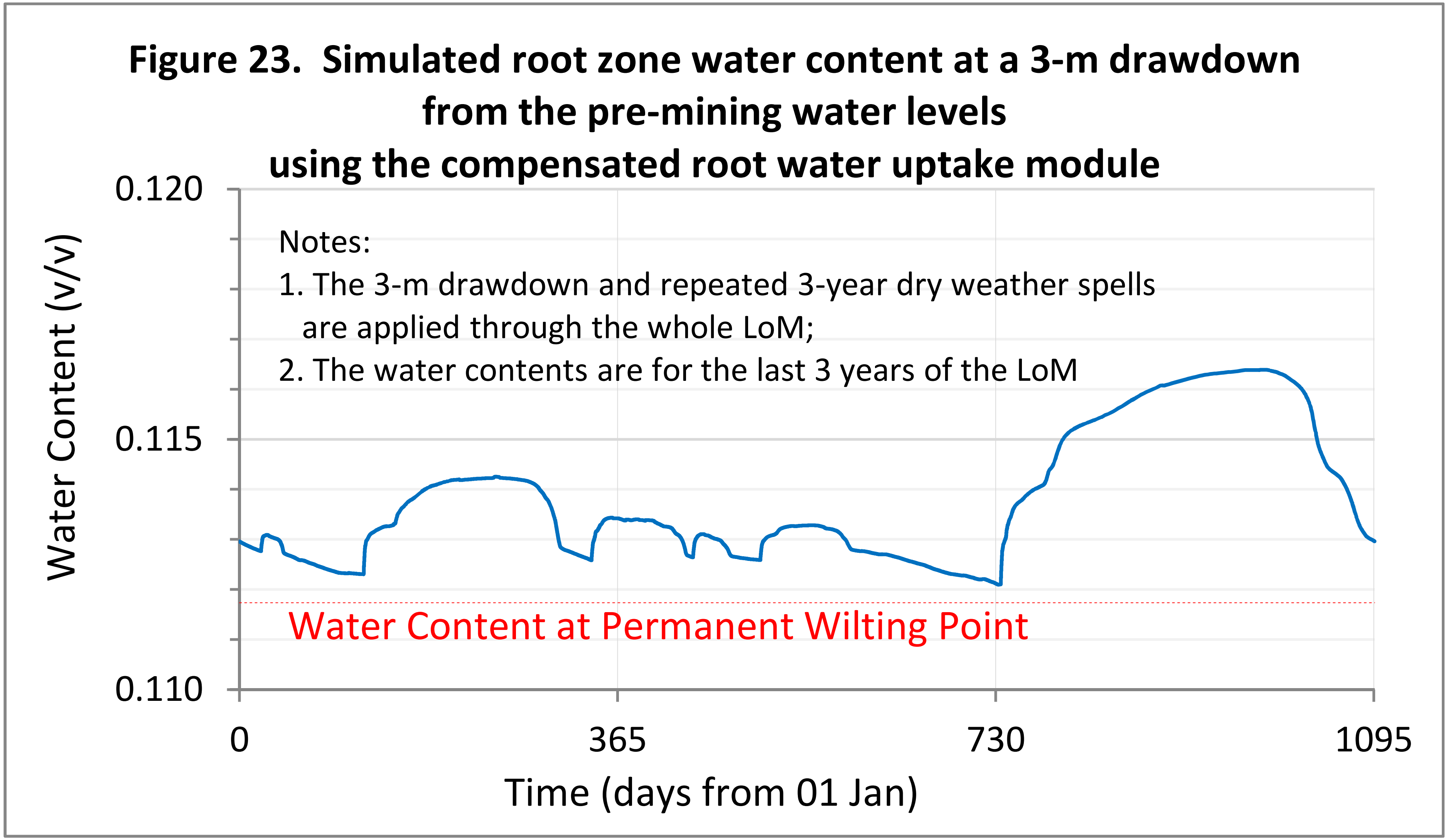


Figure 23. Simulated root zone water content at a 3-m drawdown from the pre-mining water levels using the compensated root water uptake module
Notes:
1. The 3-m drawdown and repeated 3-year dry weather spells are applied through the whole LoM;
2. The water contents are for the last 3 years of the LoM
Water Content at Permanent Wilting Point
0.120
0.115
0.110
Water Content (v/v)
0
365
730
1095
Time (days from 01 Jan)

Figure 24. Simulated water stress index at a 3-m drawdown from the pre-mining water levels using the uncompensated root water uptake module

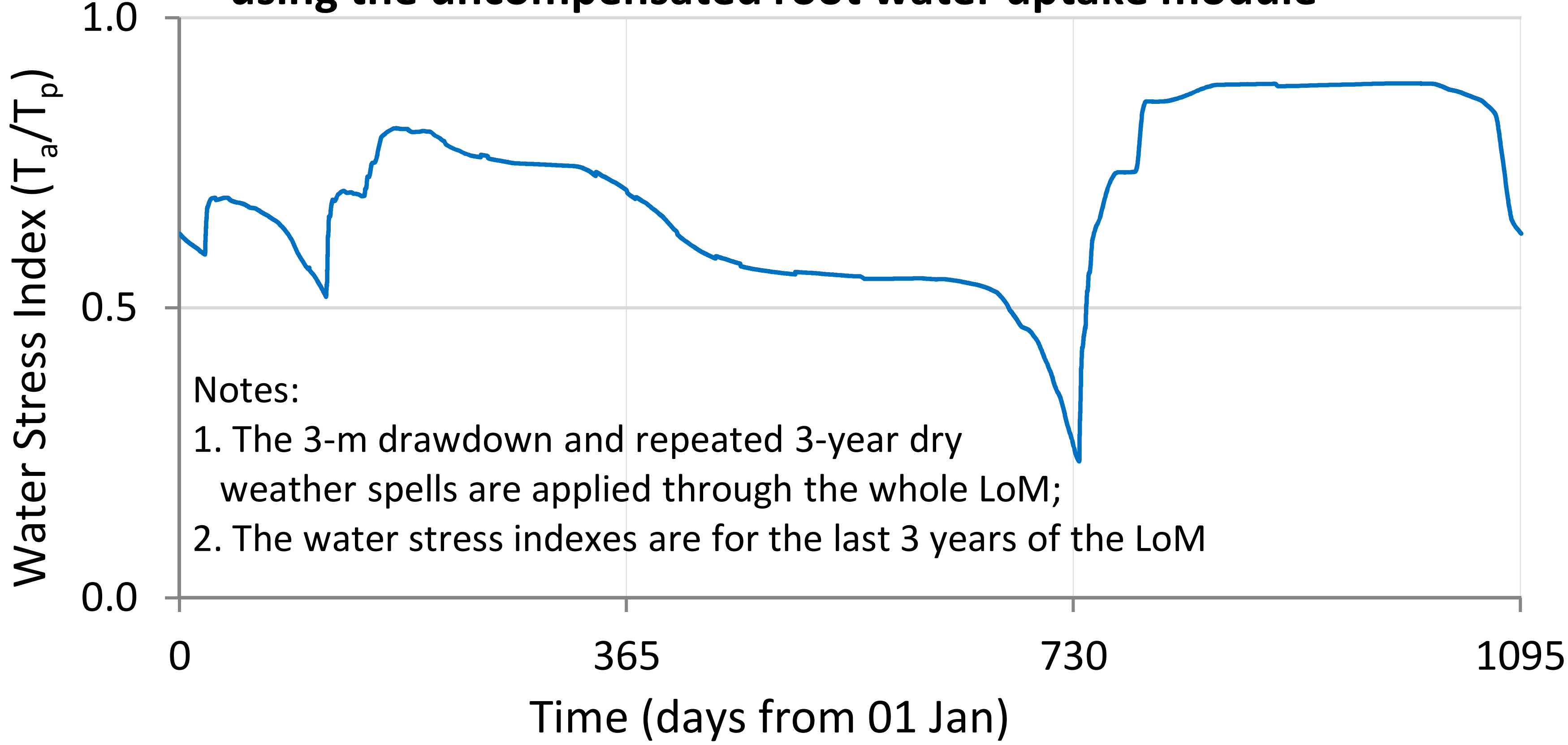
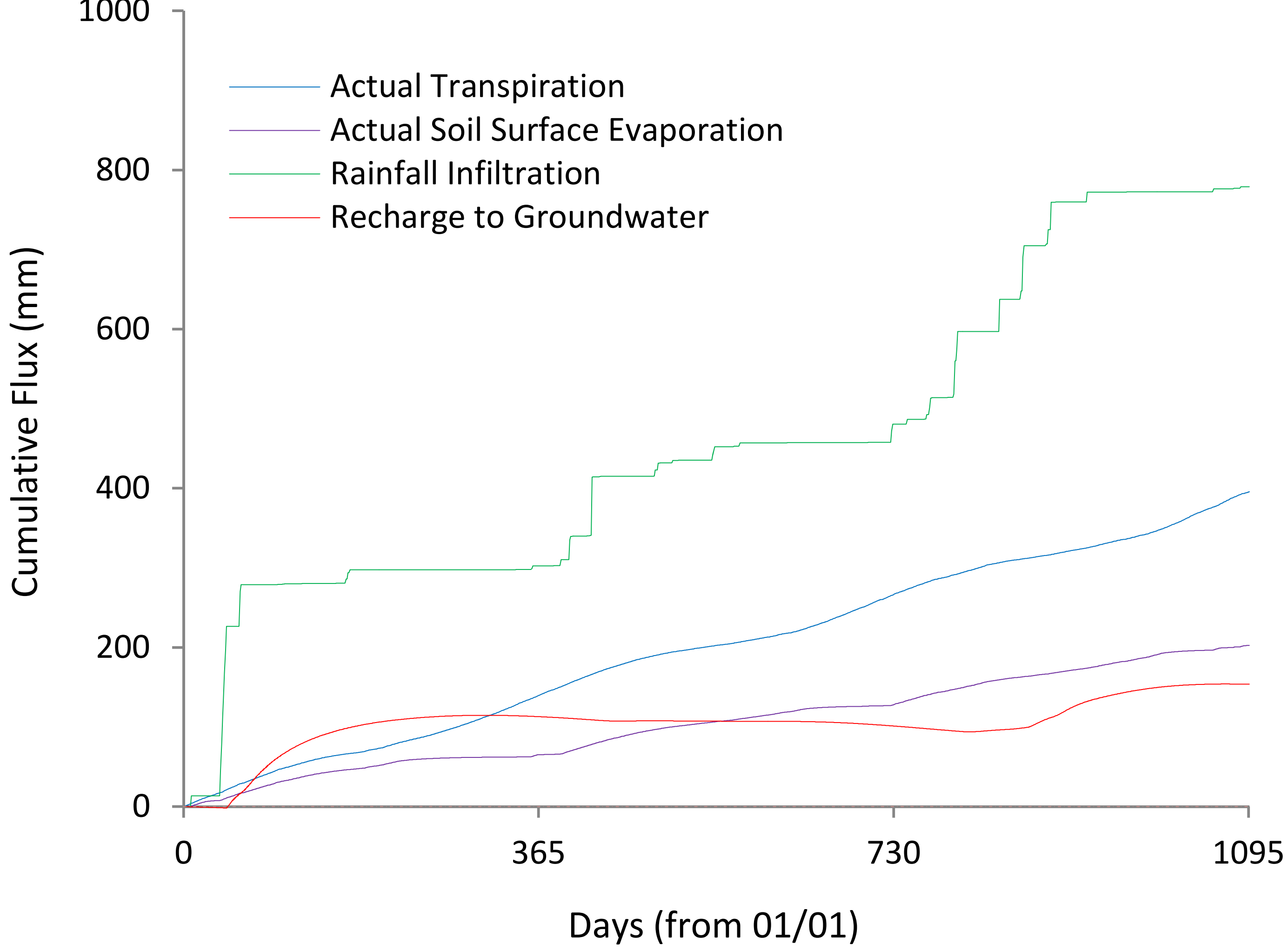


Figure 25. Cumulative Fluxes for Dense Samphire Area Under 3-Year Wet Weather Spell with GWL = 404 mAHD



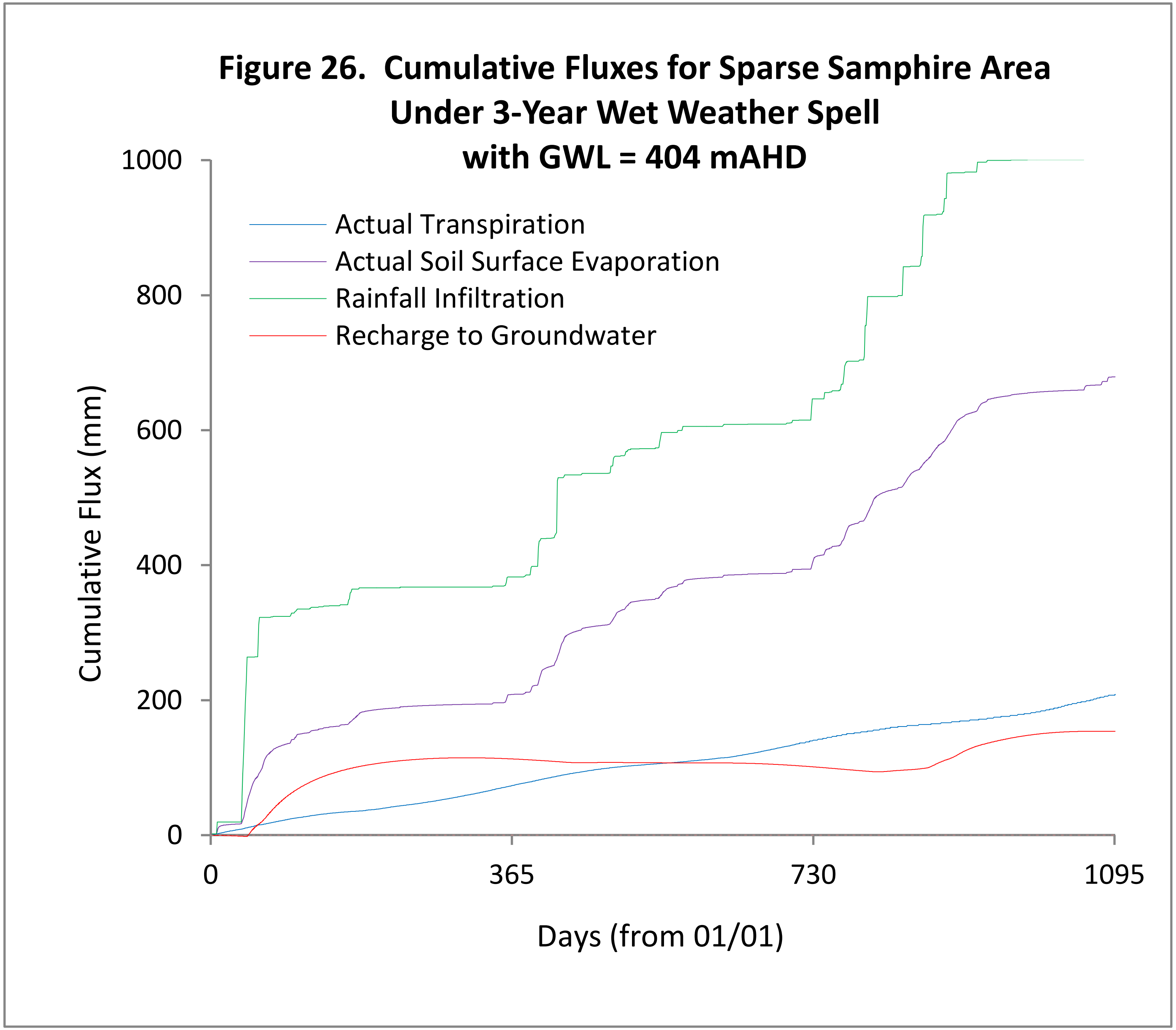
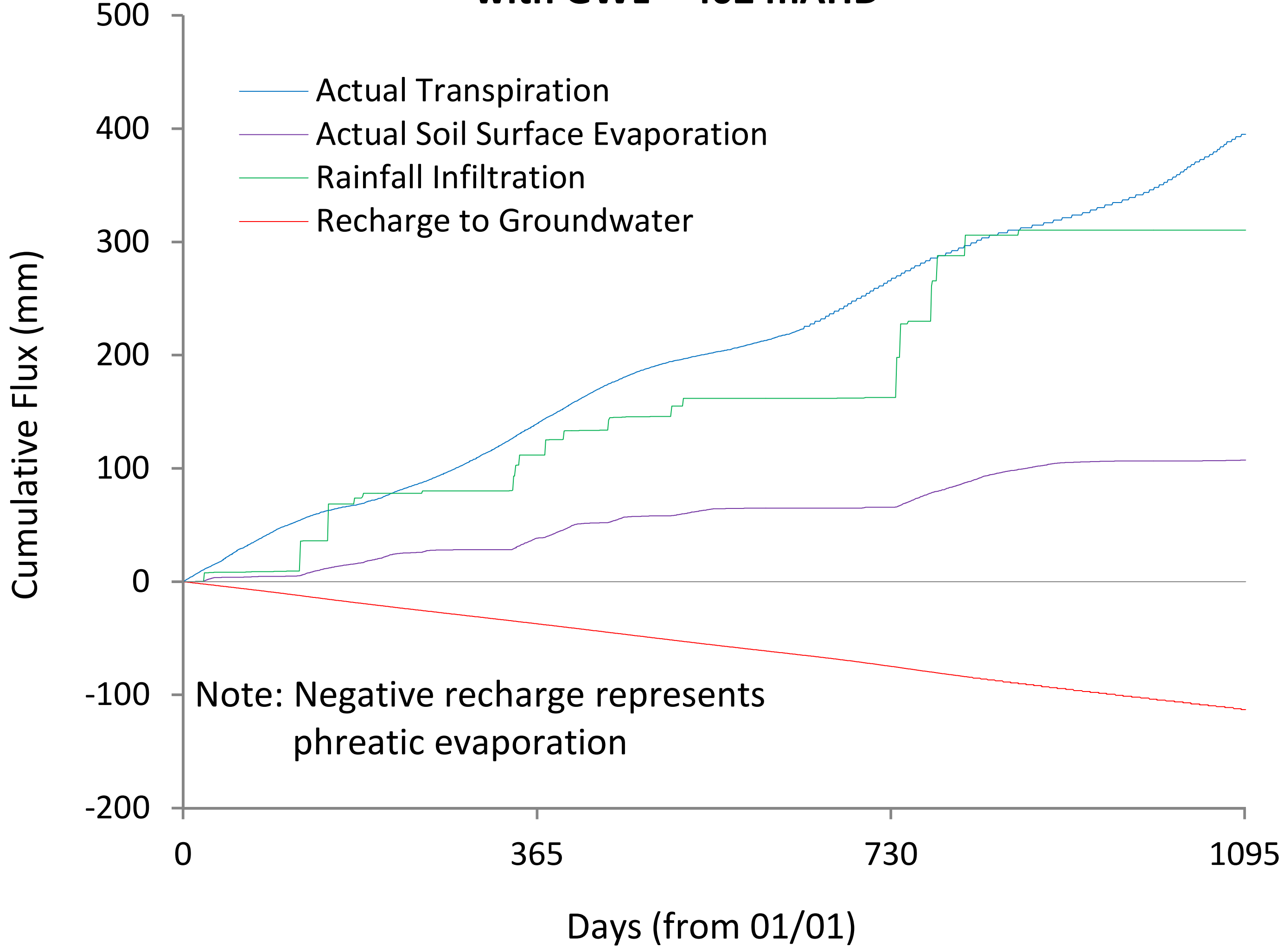


Figure 26. Cumulative Fluxes for Sparse Samphire Area
Under 3-Year Wet Weather Spell
with GWL = 404 mAHD
Actual Transpiration
Actual Soil Surface Evaporation
Rainfall Infiltration
Recharge to Groundwater
Cumulative Flux (mm)
0
200
400
600
800
1000
0
365
730
1095
Days (from 01/01)

Figure 27. Cumulative Fluxes for Dense Samphire Area Under 3-Year Dry Weather Spell with GWL = 402 mAHD



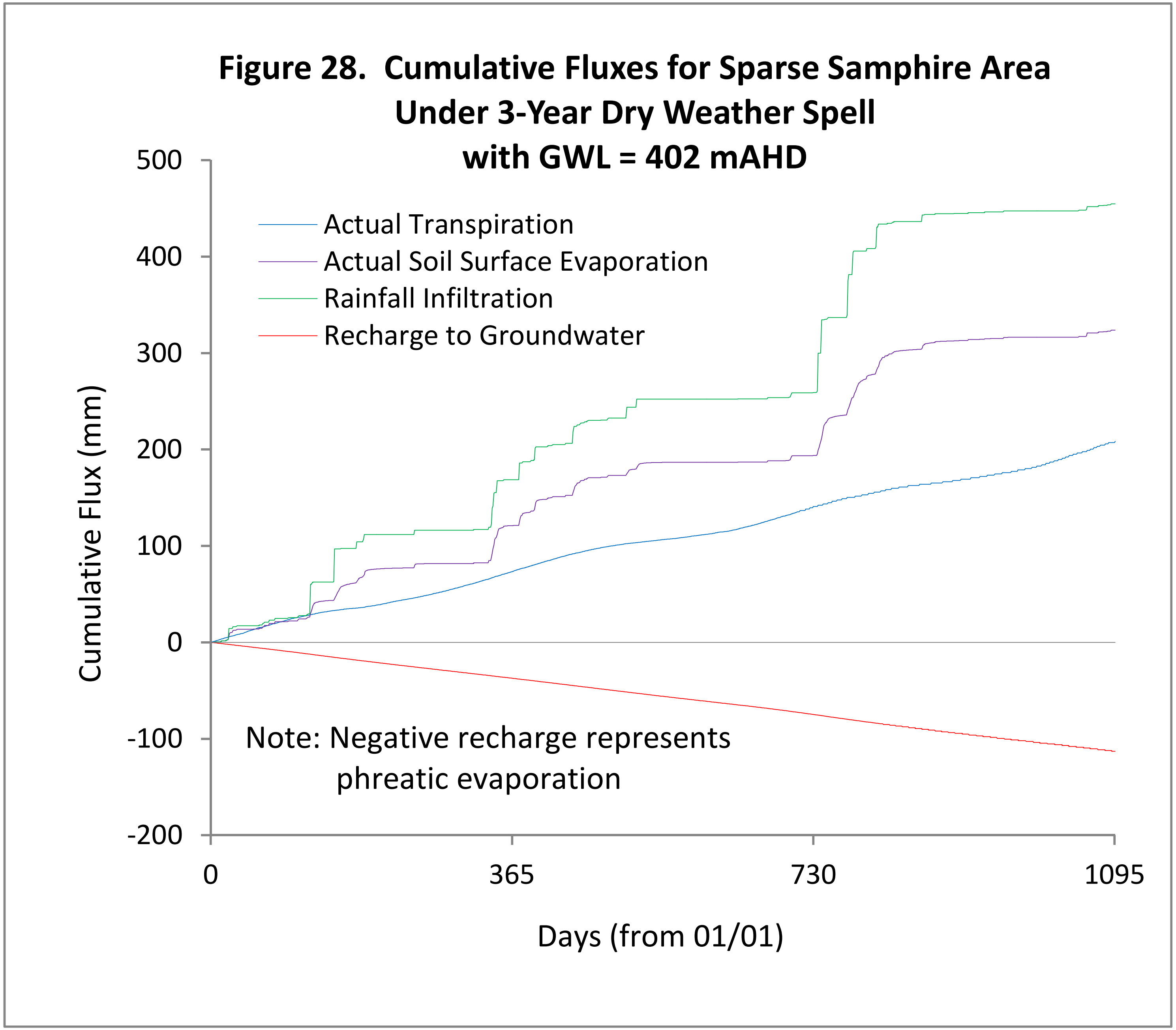


Figure 28. Cumulative Fluxes for Sparse Samphire Area Under 3-Year Dry Weather Spell with GWL = 402 mAHD

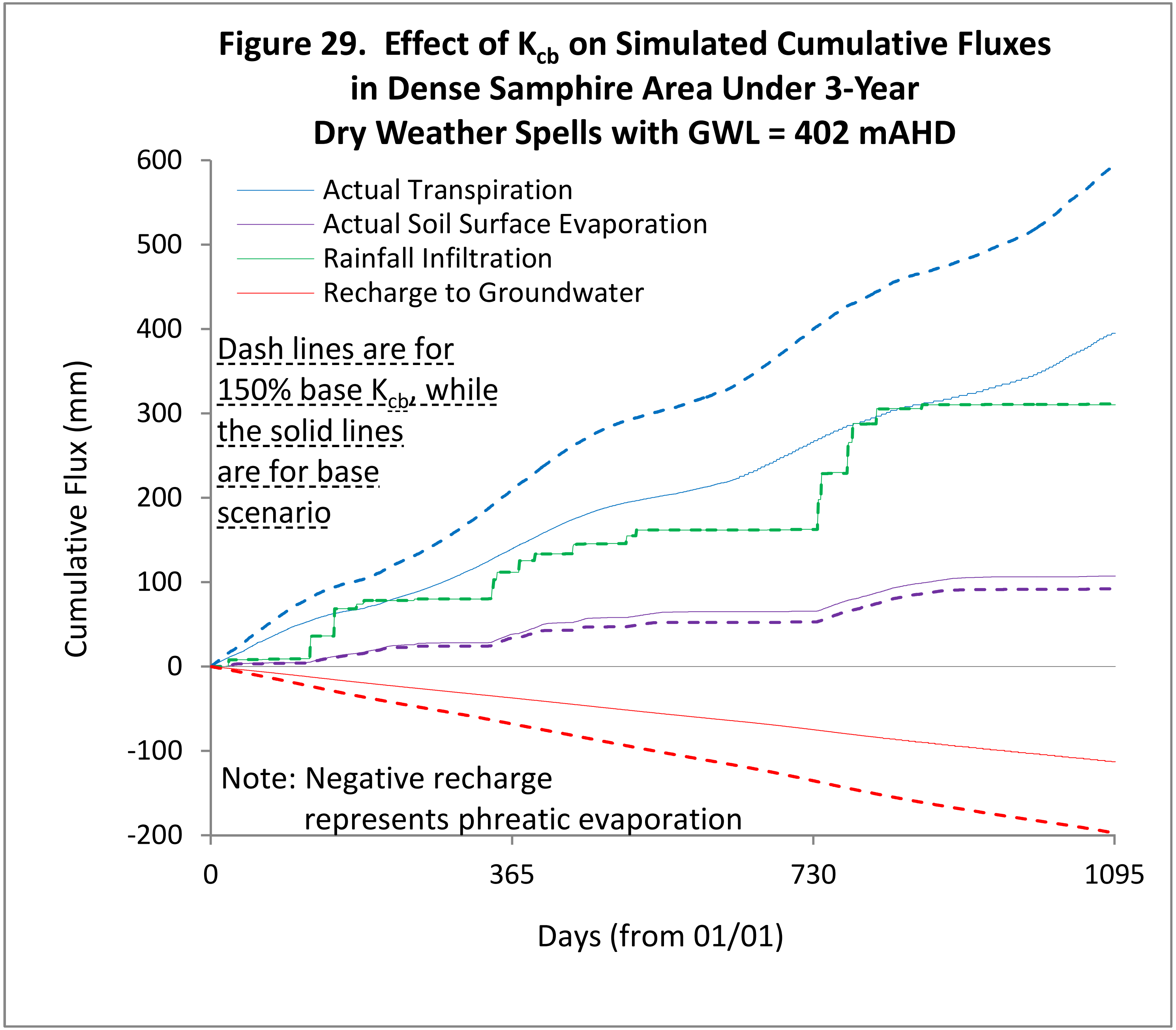


Figure 29. Effect of K_cb on Simulated Cumulative Fluxes in Dense Samphire Area Under 3-Year Dry Weather Spells with GWL = 402 mAHD
600
500
400
300
200
100
0
-100
-200
Cumulative Flux (mm)
Actual Transpiration
Actual Soil Surface Evaporation
Rainfall Infiltration
Recharge to Groundwater
Dash lines are for 150% base K_cb, while the solid lines are for base scenario
Note: Negative recharge represents phreatic evaporation
0
365
730
1095
Days (from 01/01)

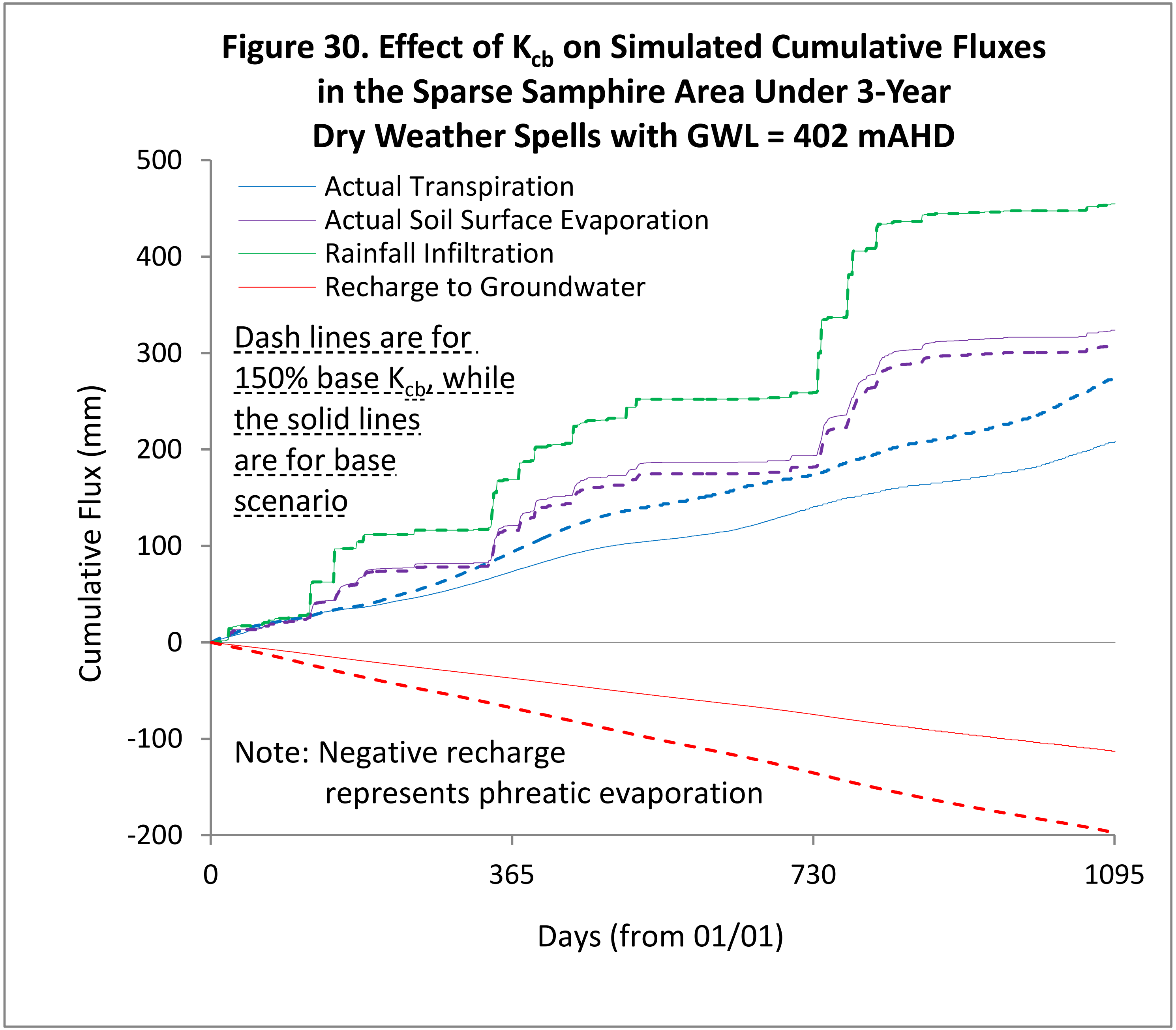
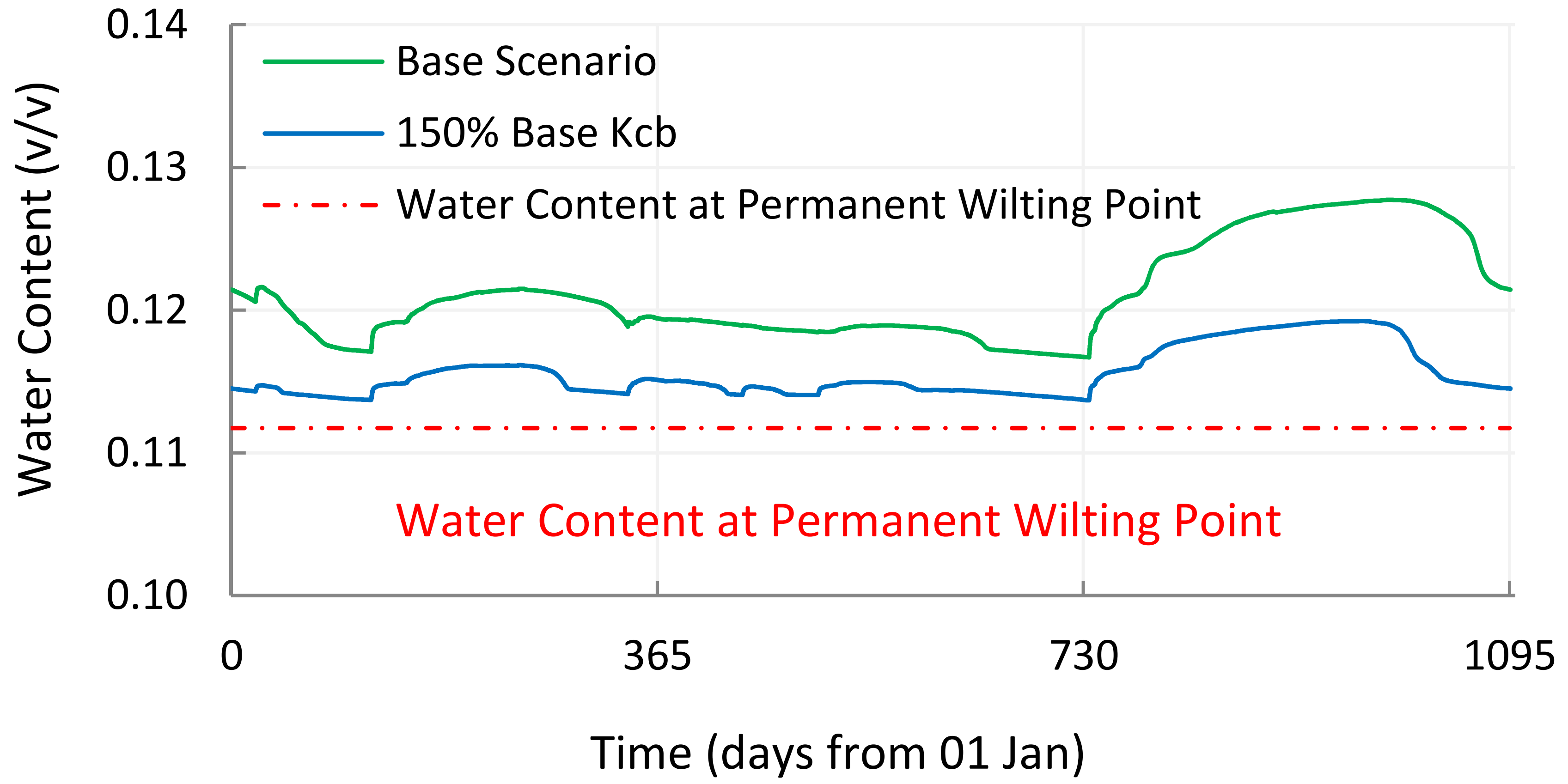


Figure 30. Effect of K_{cb} on Simulated Cumulative Fluxes in the Sparse Samphire Area Under 3-Year Dry Weather Spells with GWL = 402 mAHD
Actual Transpiration
Actual Soil Surface Evaporation
Rainfall Infiltration
Recharge to Groundwater
Dash lines are for 150% base K_{cb}, while the solid lines are for base scenario
Note: Negative recharge represents phreatic evaporation
Cumulative Flux (mm)
500
400
300
200
100
0
-100
-200
0
365
730
1095
Days (from 01/01)

Figure 31. Average Root Zone Water Content of Dense Samphire at Different K_{cb}s under 3-Year Dry Weather Spells



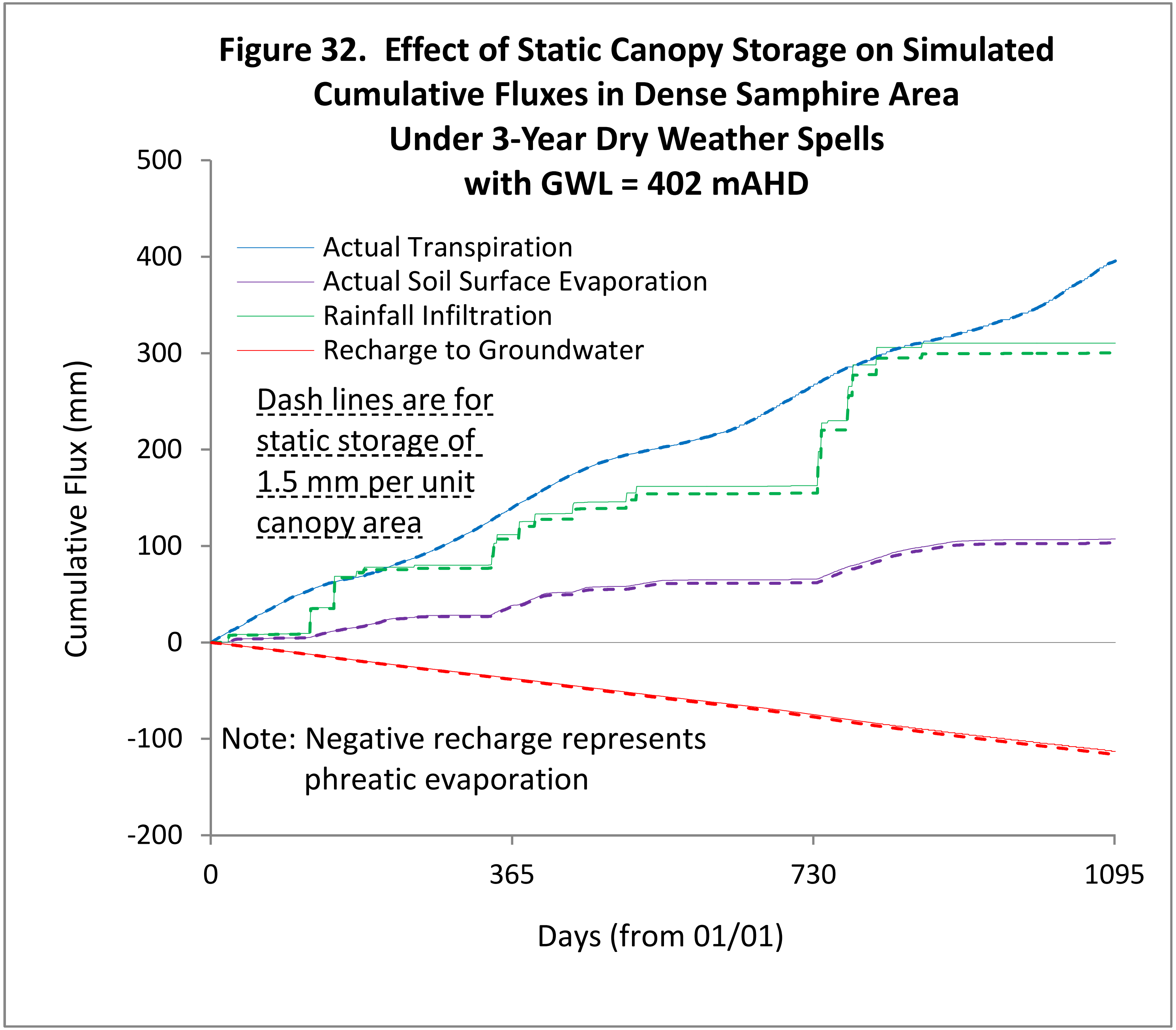


Figure 32. Effect of Static Canopy Storage on Simulated Cumulative Fluxes in Dense Samphire Area Under 3-Year Dry Weather Spells with GWL = 402 mAHD
Actual Transpiration
Actual Soil Surface Evaporation
Rainfall Infiltration
Recharge to Groundwater
Dash lines are for static storage of 1.5 mm per unit canopy area
Note: Negative recharge represents phreatic evaporation
Cumulative Flux (mm)
500
400
300
200
100
0
-100
-200
0
365
730
1095
Days (from 01/01)

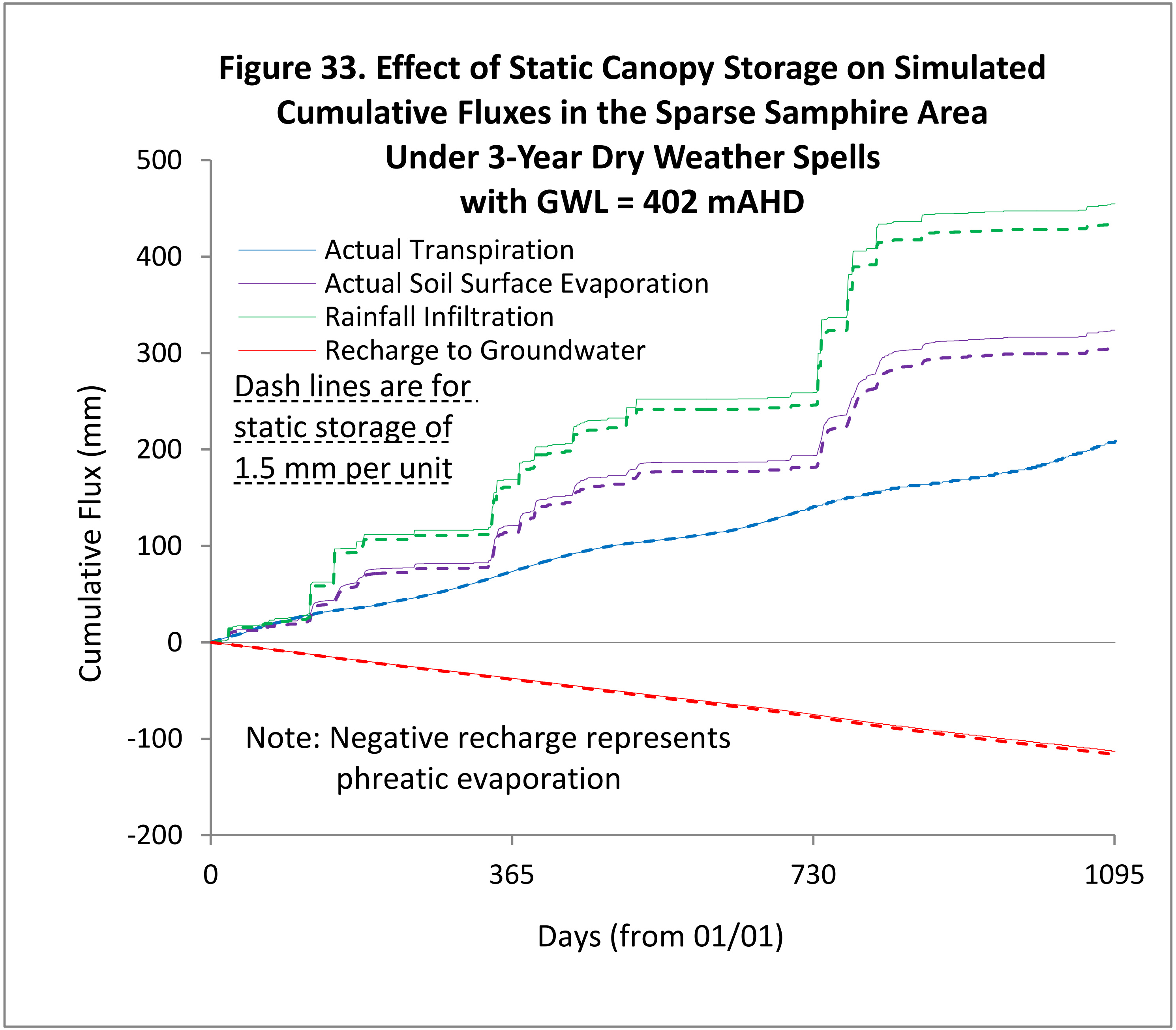


Figure 33. Effect of Static Canopy Storage on Simulated Cumulative Fluxes in the Sparse Samphire Area Under 3-Year Dry Weather Spells with GWL = 402 mAHD
Actual Transpiration
Actual Soil Surface Evaporation
Rainfall Infiltration
Recharge to Groundwater
Dash lines are for static storage of 1.5 mm per unit
Note: Negative recharge represents phreatic evaporation
Cumulative Flux (mm)
500
400
300
200
100
0
-100
-200
0
365
730
1095
Days (from 01/01)

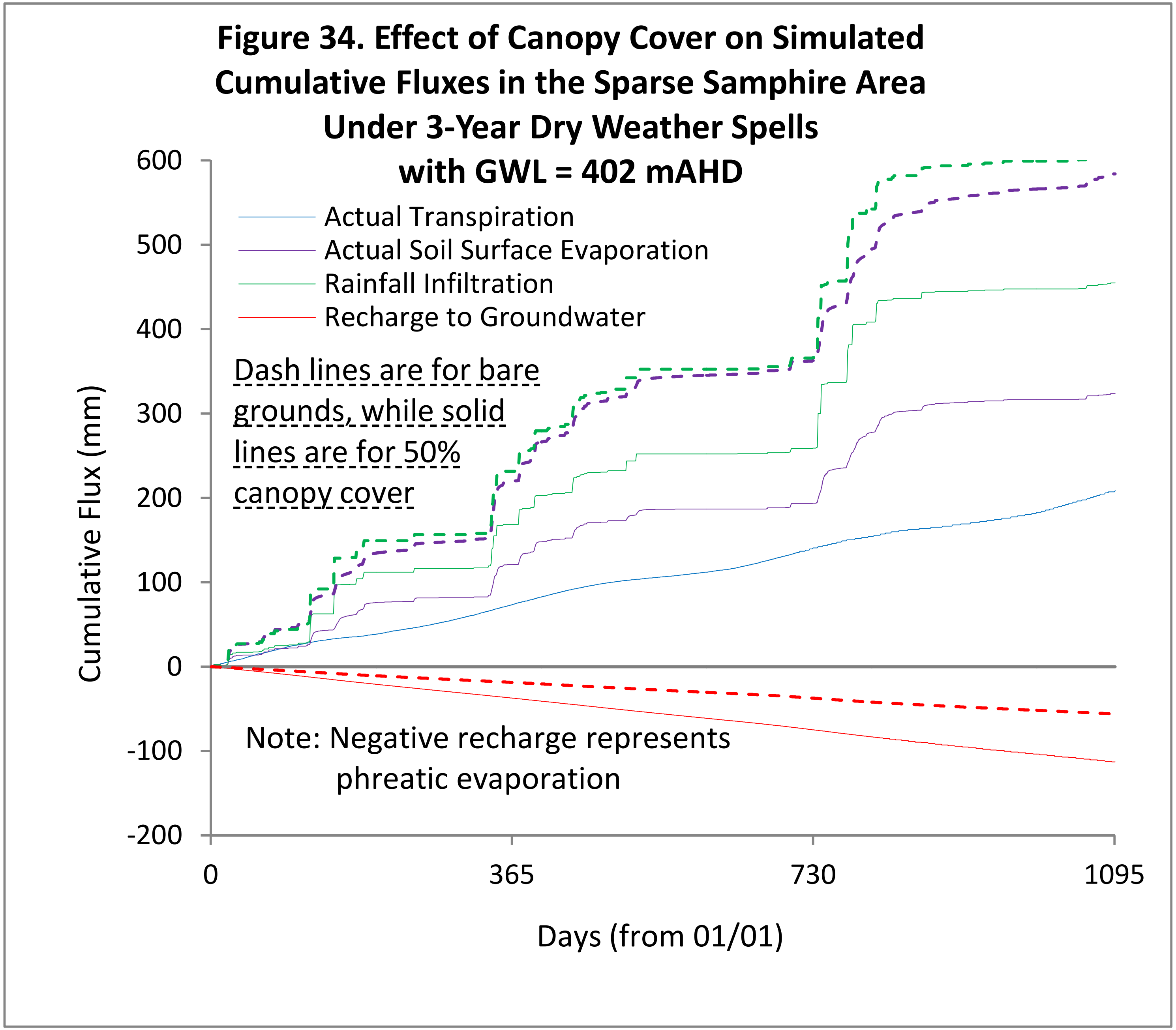


Figure 34. Effect of Canopy Cover on Simulated Cumulative Fluxes in the Sparse Samphire Area Under 3-Year Dry Weather Spells with GWL = 402 mAHD
Actual Transpiration
Actual Soil Surface Evaporation
Rainfall Infiltration
Recharge to Groundwater
Dash lines are for bare grounds, while solid lines are for 50% canopy cover
Note: Negative recharge represents phreatic evaporation
Cumulative Flux (mm)
600
500
400
300
200
100
0
-100
-200
0
365
730
1095
Days (from 01/01)

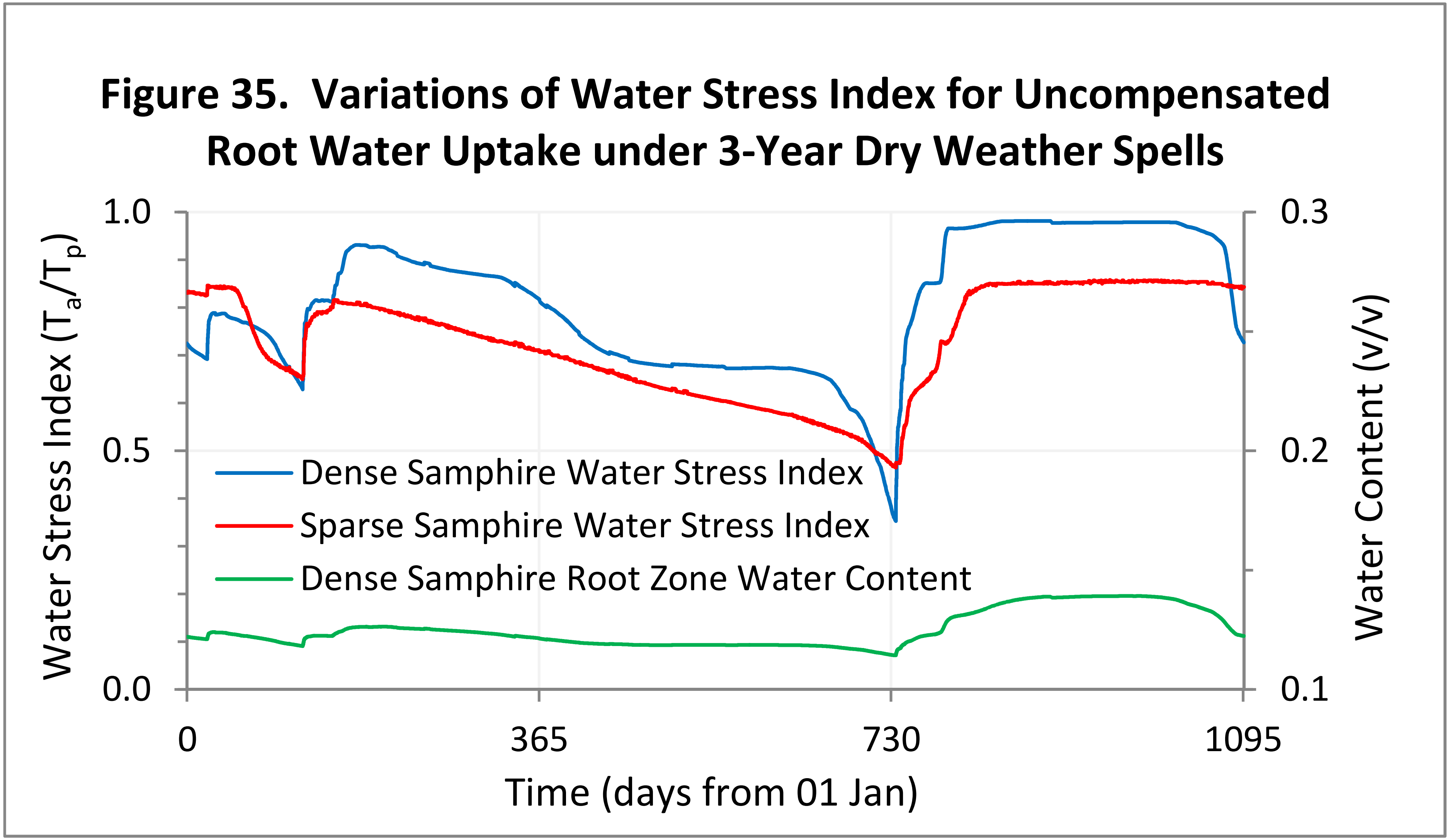


Figure 35. Variations of Water Stress Index for Uncompensated Root Water Uptake under 3-Year Dry Weather Spells
Water Stress Index (Ta/Tp)
Water Content (v/v)
1.0
0.5
0.0
0.3
0.2
0.1
0
365
730
1095
Time (days from 01 Jan)
Dense Samphire Water Stress Index
Sparse Samphire Water Stress Index
Dense Samphire Root Zone Water Content

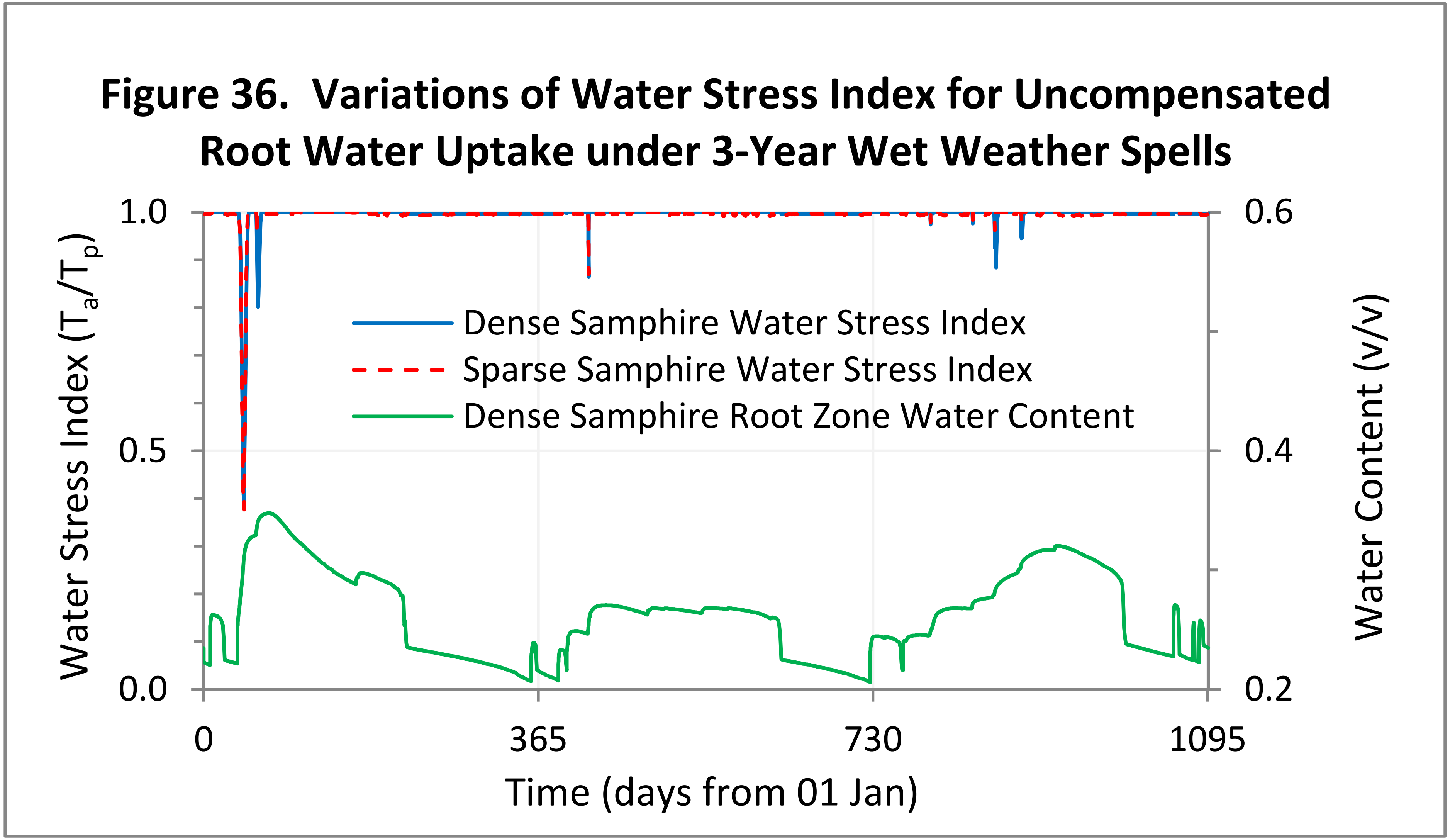


Figure 36. Variations of Water Stress Index for Uncompensated Root Water Uptake under 3-Year Wet Weather Spells
Water Stress Index (T_a/T_p)
Water Content (v/v)
Time (days from 01 Jan)
Dense Samphire Water Stress Index
Sparse Samphire Water Stress Index
Dense Samphire Root Zone Water Content
1.0
0.5
0.0
0.6
0.4
0.2
0
365
730
1095

Figure 37. Profile of pressure head at the end of a clustered rainfall events (day 44).