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**CONSTRUCTING A FIELD LYSIMETER
TO MONITOR WATER NUTRIENT
AND PLANT DYNAMICS**

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SUMMARY

The design of an appropriate closure strategy for Alcoa of Australia (Alcoa) residue storage areas (RDAs) requires detailed understanding of the behaviour of water in outer residue sand embankments. This is because a significant proportion of the infiltrating water (via rainfall) will ultimately become deep drainage and leachate requiring treatment prior to disposal or re-use. Currently, detailed information of water movement in residue sand embankments is limited, despite the need to develop closure plans. This report describes the construction and instrumentation of a large (25 m x 25 m x 3 m deep) field lysimeter at the Pinjarra RSA. Use will be made of the data to quantify drainage volumes, based on field measurements of individual components of the water balance equation, and for selecting and calibrating models for simulating and predicting water and solute transport in rehabilitated residue sand embankments.

INTRODUCTION

Background

Alcoa World Alumina Australia (Alcoa) currently operates three bauxite processing Residue Storage Areas (RSAs) as part of its Western Australia Operations. As part of the Long Term Residue Management (LTRM) Plan, Alcoa progressively rehabilitates its outer residue sand embankments according to its current rehabilitation prescription. On closure, however, a more rigorous strategy will be required to manage water entry into the mudlake, thereby minimizing the production of contaminated drainage and the volumes of drainage requiring treatment prior to discharge.

Surface cover systems will need to be designed and constructed in a manner which satisfies environmental regulatory authorities, the local community, and Alcoa's internal high quality standards. To achieve these standards, cover design performance criteria based on the way Alcoa intends to manage closed RSAs in the short- and long- term need to be established as soon as possible. Here, short-term refers to the period over which the Refinery continues to operate (thereby accepting caustic drainage from the RSA), and long-term refers to time after Refinery closure (requiring alternative, sustainable methods of managing caustic drainage from RSA). Alcoa's long-term commitment to managing closed RSAs necessitates that functionality and integrity of the cover must play a major role in final design selection.

At present, Alcoa does not have a preferred cover design system that will be employed as part

of each Refinery's closure strategy, nor is there a reliable database on which potential cover design scenarios can be evaluated. Former Areas A, B and C at Kwinana (Motoplex) are presently being remediated however it is questionable if the same approach can be applied to larger RSAs such as Area F, which is due for closure in 2010. Furthermore, the contrasting environment of each of the RSAs (Kwinana – coastal, limited groundwater use, residential encroachment and underlain by sandy aquifer; Pinjarra and Wagerup – rural, extensive groundwater and surface water use and underlain by finer-textured geological materials) may necessitate site-specific cover systems be implemented as part of each Refinery's closure strategy.

Broadly speaking, there are currently two types of cover systems that can be utilized: (1) low permeability caps, and (2) evapotranspiration covers (also referred to as “store-and-release covers”). Low permeability caps are designed to minimise water entry into the underlying waste material by incorporating low permeability layers (e.g. compacted clay barriers, geosynthetic clay liners, and/or geomembranes) within the cap design. This type of cover system can consist of a single- or multi- layer design, and can be extremely effective in restricting water entry if constructed properly. However, over the past decade there has been increasing interest in alternative final cover designs that control infiltration into the underlying waste based on water storage principles (evapotranspiration (ET) covers). These designs rely on the use of vegetation and evaporation (i.e. evapotranspiration) to create a soil-water deficit during periods of low precipitation, which allows increased soil-water storage during high periods of infiltration. Albright *et al.* (2004) reported on the performance of a range of ‘low permeability’ and ‘ET’ landfill cover systems to control water percolation into 11 landfills across 7 states in the USA. They found that ‘low permeability’ cover systems incorporating a composite barrier (geomembrane over fine-textured soil) allowed about 1.4% of precipitation in humid environments and 0.4% of precipitation in arid, semi-arid and sub-humid environments, to enter the waste. Under the same climatic conditions, 6 - 18% of precipitation in humid environments, and < 2.2% of precipitation in arid, semi-arid and sub-humid environments, entered the waste where ET cover systems were employed. The detailed field program of Albright *et al.* (2004) showed that under specific conditions, ET cover systems may be as effective as low permeability systems in controlling deep drainage into the underlying waste.

Although “low permeability” caps can be highly effective in the short term, recent evidence

indicates that they may not be sustainable as their performance can deteriorate with time. A study by the US Environment Protection Agency (EPA) of randomly selected landfills with low permeability capping designs revealed that the vast majority were leaking and causing severe contamination to the surrounding ecosystems (Dwyer 1998; Albright *et al.* 2004). On the other hand, ET cover systems may be most-suitable for climatic zones in which evapotranspiration represents a major water loss mechanism over the major rainfall period (temperate zones with a summer rainfall pattern). As such, ET covers may not be suitable in south-west Western Australia where much of the annual rainfall occurs during winter (i.e. a Mediterranean-type climate).

An additional consideration in cover design selection will be the way in which Alcoa manages its closed RSAs in both the short and long term. For example, if rainfall was encouraged to infiltrate the underlying residue mud lake, then an ET cover would be appropriate. Allowing rainfall to infiltrate as drainage through the cover, then leaching of inherent alkalinity from the mud and return to the Refinery could (theoretically) significantly reduce “free” alkalinity (present in the interstitial pore water) and cause the release (albeit at a lower but more constant concentration) of residual alkalinity. Controlled infiltration could effectively provide a mechanism for caustic drainage for re-use within the Refinery, and reduce the potential for leakage of high strength caustic pore-water into the underlying groundwater after refinery closure. The effectiveness of alkalinity leaching will be fundamentally dependant on the water movement dynamics of the mud lake (i.e. macropore versus matrix flow) and the amounts of residual alkalinity (DSP and TCA6) capable of buffering pH and soluble alkalinity concentrations. A small-scale laboratory leaching study (Phillips 2010a) suggested that greater than 50 pore volumes of water must pass through residue sand (which contains significantly less alkalinity than residue mud) before leachate pH is reduced from pH 11 to pH 9.5. However, pH is not the most reliable estimate of the magnitude of leachate contamination, rather the buffering capacity (as measured by soluble hydroxyl (OH), carbonate (CO₃) and bicarbonate (HCO₃) concentrations) provides a more realistic measure of the extent of treatment required.

Following Refinery closure, leaching may not be an acceptable management strategy since the caustic drainage would no longer be returned to the Refinery, and an appropriate wastewater treatment plant capable of handling alkaline drainage (and associated inorganic and organic contaminants) will need to be constructed and maintained for as long as leachate

of “unacceptable environmental quality” is produced. This suggests that alternate cover systems (e.g. low permeability covers) will be required for long-term management of closed RSAs.

As part of the decision-making process, consideration must be given to the *in-situ* hydraulic properties of the mud lake. Due to residue mud’s fine-texture ($< 150 \mu\text{m}$), high bulk density (1800 kg/m^3) and increasing overburden potential (σ_o) with depth, it may exhibit an extremely low saturated hydraulic conductivity (k_{sat}) similar to that of compacted clay (10^{-9} m/s). Under these conditions, the use of a vegetated residue sand layer over the residue mud represents a combination of both the “low permeability” and ET cover systems. However, if the mud lake contains a significant proportion of preferential flow paths (e.g. presence of sand lenses, extensive cracking of mud to depth, etc.), then much of the matrix of the mud lake may be by-passed by infiltrating water. This will result in inefficient leaching of alkalinity from the residue mud matrix, and much greater leachate fluxes into the underdrain system or surrounding groundwater. If appreciable preferential flow occurs in the mud lake, then these pathways will need to be removed prior to constructing a cover system.

Water flow under saturated and near-saturated conditions is fastest when macropores are present. However, at lower water contents, macropores remain empty and contribute very little to water flow. Thus, the impact of macropores can be reduced significantly by ensuring the mud lake remains at water contents well-below saturation, and/or by minimising water entry into the macropores. The water content may be best-controlled by the cover design itself by which the rate of drainage from the cover into the mud lake is controlled and never exceeds a pre-determined value (e.g. 3 mm per year such as for landfill covers). The influence of macropores may be limited by placing a low permeability layer (e.g. compacted clay or mud, or HDPE) immediately above the area of concern. This will close-off water entry into the macropores, forcing water flow into the bulk mud matrix instead.

Current decision making on suitable cover systems needs to address the fact that (1) the outer embankments of the RSAs are largely constructed from residue sand, (2) the capacity of the native vegetation of rehabilitated outer embankments to use infiltrated water is unknown, (3) the outer embankments can comprise $> 50\%$ of the total surface area of a RSA, (4) residue sand has a saturated hydraulic conductivity of about 20 m/d, and (5) residue sand (or a by-product of) may be the primary material used in covering the top of a closed RSA. Thus, the

plant-water dynamics in residue sand profiles may play a major role in deciding the suitability of plant covers in RSA closure.

Critical criteria for evaluating cover design performance may be expected to include the maximum allowable (1) seepage/discharge from the base of the mud lake, and (2) chemical composition of this discharge. Both of these factors will be affected by the flux density of water into the mud lake, which will be governed by the drainage characteristics of the overlying cover system. There is an urgent need therefore to study water-plant-chemical dynamics in cover systems based on residue sand overlying residue mud (or combinations of these materials).

Lysimeters As A Means Of Studying Water-Nutrient-Plant Dynamics

Currently, Alcoa does not have a reliable database on water-nutrient-plant relationships for rehabilitated residue sand embankments and potential cover systems. As such, limited information is available for developing suitable design criteria for cover systems. For a cover system to be successful, it must satisfy and maintain its design criteria. For example, a cover system can have a drainage criterion that quantifies the maximum allowable amount of drainage into the underlying waste on an annual basis. Albright *et al.* (2004) stipulated a drainage criterion of < 3 mm per year was acceptable for comparing the relative performances of “low permeability” and “evapotranspiration” landfill cover systems. Alcoa therefore needs to identify performance criteria with respect to drainage volumes into and out of the residue mud lakes, and concomitant impacts on the surrounding soil, surface water and/or groundwater environments.

One method of generating this database involves the construction of field lysimeters, which enables mass-balance studies of water and nutrients in the presence of vegetation to be undertaken (Susan *et al.* 1992; Liedgens *et al.* 2000; Bensen *et al.* 2001; Albright *et al.* 2004). Lysimeters provide the added advantage of allowing site-specific interactions to be studied in detail, from which cover systems can be designed and performance criteria developed.

Four membrane lined cells (lysimeters with surface dimensions of $28 \times 28 \text{ m}^2$) were constructed at Pinjarra's RSA2 in 1998 (Figure 1). The depth of residue sand in cell 1, 2, 3 and 4 was 3, 2, 2 and 2 m. At each cell, 4 piezometers were installed for monitoring fluctuations in watertable depth, and 3 neutron probe access tubes were inserted for

monitoring changes in moisture content in the unsaturated zone. Drainage from the residue sand profile was removed by gravity-feed to a sump, and the volume of drainage measured by a tipping bucket. Irrigation was applied via sprinklers, and the amount of water applied was recorded using a flow meter. Daily rainfall and pan evaporation data were obtained from the Refinery fixed monitoring stations. The cells were vegetated with two tree species that are known to be tolerant of the conditions within residue sand; these being *Acacia saligna* and *Eucalyptus camaldulensis*.

The Pinjarra test cells (or lysimeters) have been used in a range of studies since 1998 (Wilkinson 2005). Much of these studies have concentrated on understanding the water balance of vegetated residue sand, and determining the appropriate depth of residue sand that is required to supply sufficient plant-available water over summer (e.g. Senathirajah 1999). A conclusion from these studies was that a residue sand profile depth > 2 m (about 3 m) would be required to avoid waterlogging in winter but would retain adequate moisture storage over summer. Eastham et al (2003) used the lysimeters to determine if water-use by vegetation could be enhanced by the presence of a watertable within the residue sand profile. This study found that plant water use was restricted by low water availability over summer, and plants with a watertable within the root zone were unable to sustain high water use. Water use was however greater by residue sand profiles with a high watertable relative to those with a deep watertable.

Unfortunately, the PJ lysimeters are currently in a state of disrepair. The integrity of the geomembrane liner is unknown and questionable, and the vegetative cover does not reflect that typical of current rehabilitation prescription. Also, the lysimeter cells have experienced flooding with caustic water in the past due to a failure with the sand slurry pumping pipe (Figure 2). The flooding with caustic slurry has severely compromised the integrity of this facility.

Furthermore, the existing design of these lysimeters does not realistically reflect water movement in residue sand profiles as the surface area ($28 \times 28 \text{ m}^2$) is much greater than the basal area ($20 \times 20 \text{ m}^2$). This difference in surface areas over a 2 m depth significantly compromises the quality of any water and/or nutrient transport data.

Before the lysimeters could be regarded as a research facility capable of generating reliable

information, considerable upgrade and replacement of all infrastructure is required. It is therefore recommended that a new facility be built.

Aims and Objectives

The aim of this study is provide a detailed description of lysimeter design and construction for quantifying water-nutrient-plant relationships in residue sand profiles. The specific objectives of this document are to (1) undertake a limited review of literature describing lysimeter design and construction principles; (2) from this review, prepare a list of monitoring and sampling equipment necessary to monitor and quantify water-nutrient-plant dynamics in residue sand profiles; (3) detail the steps involved in lysimeter construction and equipment calibration; and (4) provide examples of monitoring data.

COVER SYSTEMS AND LYSIMETER DESIGN

Cover Systems Used For Managing Closed Waste Disposal Facilities

The final capping system employed on Alcoa's residue storage areas must (1) account for the ultimate site end-use, (2) be sustainable and require minimum long-term maintenance and monitoring, and (3) be part of an integrated management plan aimed at minimising risks to the surrounding environment. These risks must include those to the natural environment (land, water and air), and to the encroaching urban development as the demand for land around the disposal areas increase.

At present, capping systems can be engineered to (1) minimise water infiltration, or (2) can be designed to encourage water infiltration whilst minimising drainage by the use of plants. A brief discussion of these two capping systems is provided below.

Engineered capping design

Traditional capping of closed waste disposal facilities, such as landfills and mine tailing impoundments, has been engineered to minimise water entry through the waste area surface and batters. This has been achieved by the use of surface contouring to shed water by constructing a convex cover (thereby avoiding surface ponding of water), and by incorporating a low permeability cap (commonly referred to as a "conventional" final capping system). This conventional cap commonly includes a "composite barrier" consisting of a compacted clay layer (approx. 0.5 m thick with a saturated hydraulic conductivity $< 10^{-9}$ m/s) above the final waste surface, overlain by a HDPE liner. This composite barrier is

overlain by a gravel drainage/capillary break layer, which is overlain by geotextile fabric to minimise movement of colloidal material into the gravel, which is overlain by a layer of topsoil for vegetation establishment (typically grass cover). Alternatively, a geosynthetic clay liner (thin, factory-manufactured material consisting of 3.5 to 6 kg/m² of bentonite clay sandwiched between two geotextiles) can be substituted for the compacted clay subsoil in the above composite barrier.

Although conventional caps are effective in minimising infiltration into waste dumps, they are expensive to construct. In addition, care must be taken during construction of the composite liner system to ensure (1) uniform hydraulic properties (e.g. saturated hydraulic conductivity), and minimal desiccation, of the clay layer, and (2) all welds of the HDPE liner are sealed to minimise preferential flow/leakage of drainage at the clay/HDPE interface.

Alternative capping designs

Recently, less-costly capping designs have been investigated as an alternative capping system to engineered (conventional) cover systems. These alternative designs involve planting trees, shrubs and grasses directly into the waste surface cover material, or into a thin layer of topsoil (approximately 300 mm thick) above the waste material, and have been termed evapotranspiration (ET) or store-and-release (SAR) cover systems (Benson *et al.* 2001; Wels *et al.* 2001, 2002; Albright *et al.* 2004; Doley 2004; Phillips *et al.* 2004; Levitt *et al.* 2005; Nyhan 2005). Benson *et al.* (2001) refer to alternative cover systems as “alternative earthen final cover” rather than evapotranspiration covers because evapotranspiration occurs from nearly all final covers, regardless of design. For simplicity however, evapotranspiration covers will still be referred to in this report.

“Store-and-release” covers and “evapotranspiration” covers essentially are very similar in definition, design and conception. Evapotranspiration covers typically relate to alternative cover systems employed in the management of closed landfills, whereas store-and-release covers commonly relate to management of mine tailings facilities. Alternative cover designs are currently the focus of research within Australia’s waste management and mining industry, and as such, will be reviewed in these two broad categories.

The evapotranspiration (ET) cover principally involves the use of plants and cover soils that control seepage based on water-balance principles. The plants perform a variety of tasks,

which include (1) creating a soil-water deficit through transpiration, (2) encourage soil microbial activity for removing (within the soil biomass) and converting chemicals (e.g. organic nitrogen) into usable forms (inorganic nitrogen), (3) acting as a sink for contaminants through plant uptake, and (4) improving soil structure within the capping system.

In addition, conventional cover systems may not be warranted under particular climatic conditions (e.g. arid environments and locations where much of the rainfall falls over the plants' active growing period), and the long-term durability of compacted, fine-grained barrier soil layers is currently being questioned (Albright *et al.* 2004). These issues have stimulated interest in the development of alternative final cover designs that control infiltration into the underlying waste based on water storage principles. These designs rely on the use of vegetation and evaporation (i.e. evapotranspiration) to create a soil-water deficit during periods of low precipitation, which allows increased soil-water storage during high periods of percolation. Recently, Albright *et al.* (2004) reported on the performance of a range of 'conventional' and 'alternative' landfill cover systems to control water percolation into 11 landfills across 7 states in the USA. They found that conventional cover systems incorporating a composite barrier (geomembrane over fine soil) allowed about 1.4% of precipitation in humid environments and 0.4% of precipitation in arid, semi-arid and sub-humid environments, to enter the waste. Under the same climatic conditions, 6 – 18% of precipitation in humid environments, and < 2.2% of precipitation in arid, semi-arid and sub-humid environments entered the waste where alternative cover systems were employed. The detailed field program of Albright *et al.* (2004) showed that under specific conditions, alternative capping systems may be as effective as conventional systems in controlling percolation, and hence leachate production. Alcoa's Residue Storage Areas in WA experience a Mediterranean-type climate (cool, wet Winters and hot, dry Summers), which must be accounted for within cover design. Thus, plants which can effectively act as hydraulic pumps all-year round, or specifically over the Winter period (and tolerate near-drought conditions over Summer) should be selected for the cover system.

Cover systems are intended to minimise surface infiltration of water and subsequent seepage into buried waste for many (100's) of years; however, most studies involving alternative cover systems are limited to a few years of monitoring data. Furthermore, many of these studies have not been conducted for periods of sufficient time to observe changes in soil profile development, and the impacts of vegetation cover and rooting patterns, on seepage

rates. Of the few longer-term studies available, Breshears *et al.* (2005) observed the following changes in landfill cover integrity over a 10-year period. Firstly, vegetation changes induced increased biomass and species diversity, which affected the ability of the covers to lose water via evapotranspiration. Changes in vegetation from herbaceous plants to woody shrubs and trees resulted in deeper rooting depths, hence more effective removal of soil-water. Secondly, significant changes in soil-water dynamics occurred due to development of macropores from root channels and burrowing fauna (i.e. earthworms, gophers, and rabbits). The inclusion of biointrusion barriers may therefore be required for successfully designing sustainable cover systems, and demonstrates the need for better understanding the relationship between ecology, hydrology and engineering in soil cover design.

The study by Breshears *et al.* (2005) highlighted the fact that the performance of cover systems is dependent on both the engineering factors that form the basis of the initial cover, and the environmental factors that affect the cover through time. Engineering factors are those that can be manipulated during the installation phase of the cover, such as soil horization (layer thickness, slope, layering, capillary break and texture), and initial ground cover and vegetation cover. Environmental factors influence cover integrity with time after installation, and include plant succession (shallow-rooted grasses to deep-rooted shrubs and trees), soil profile development (particle aggregation, development of soil structure), erosion, and intrusion by plant roots and burrowing animals. This analogy implies that with time, the relative importance of environmental factors in determining cover performance increases, while the relative importance of engineering factors decreases (Suter *et al.* 1993). A hypothetical relationship between the relative importance of engineering and environmental factors on cover performance with time is presented in Figure 3.

A “store-and-release” (SAR) cover typically consists of a well-graded soil layer (or multiple soil layers) that stores precipitation during wet periods and releases the stored moisture back into the atmosphere via evapotranspiration during dry periods (Wels *et al.* 2001, 2002). The net effect is a significant reduction, or elimination, of deep percolation into the underlying waste. Wels *et al.* (2001, 2002) consider the advantages of SAR cover systems compared to conventional covers to be (1) a SAR cover will require the least long-term maintenance and has the lowest potential for long-term degradation (and ultimately failure); (2) the effectiveness of a SAR cover is expected to increase in time as the vegetation matures to the desired climax vegetation; and (3) the proposed SAR cover can be implemented for a fraction

of the cost of more complex engineered cover types. The performance of SAR cover systems generally is better under drier climatic regimes due to the higher evaporation and lower precipitation rates. However, problems with SAR covers can occur in dry environments due to desiccation of the soil surface.

Wels *et al.* (2001, 2002) describe the design and installation/instrumentation of test plots designed to study the performance of a SAR cover for final closure of a mine tailings facility in the semi-arid region of New Mexico. Three test plots were constructed exhibiting variations in cover thickness and vegetation development:

- Test Plot 1: Existing 0.28 m thick alluvial cover with mature grass/shrub vegetation overlying *in-situ* sandy tailings.
- Test Plot 2: 0.23 m thick alluvial cover with no vegetation overlying *back-filled* sandy tailings.
- Test Plot 3: 0.60 m thick alluvial cover with no vegetation overlying *back-filled* sandy tailings.

Test Plot 1 was most-representative of post-closure steady-state conditions, and allowed the effects of evapotranspiration to be included in the soil-atmosphere model, SoilCover. Test Plots 2 and 3 represented “free-draining” lysimeters, and allowed the influence of cover thickness on net drainage in the absence of vegetation to be monitored and modelled.

Wehr *et al.* (2005) investigated various layered capping sequences constructed of combinations of topsoil, subsoil, seawater-neutralised residue sand (a clayey sand) and low grade bauxite on growth and survival of Rhodes grass in terms of plant and soil water relationships. These workers found that the combination of soil with a high water-holding capacity and low soil-water diffusivity (e.g. clay) with soil having a high water-holding capacity and high diffusivity (e.g. clayey sand) gave best survival as the cap dried out. Clayey soil improved plant survival by triggering a water stress response during peak evaporative water demand once residue sand (clayey sand texture) dried down and its diffusivity became the primary mechanism of water transport.

A more detailed review of cover system design appropriate for RSA closure will be provided

in a later report that relates residue sand characteristics to vegetation performance, and the development of performance criteria.

Parameters To Be Monitored and Equipment Required

The knowledge of below ground soil-nutrient-plant interactions is limited by soil inaccessibility, and relies on representative sampling to identify and understand the key processes controlling these interactions. These processes are physical, chemical, microbial, and botanical. The design and construction of special facilities to study these interactions is an attempt to find a compromise between improved accessibility and environmental artificiality (Liedgens *et al.* 2000). Water dynamics is often described by the water balance equation (e.g. Benson *et al.* 2001):

$$D_r = P - ET - R - \Delta S \quad (1)$$

where D_r = equivalent depth of drainage from the lysimeter base per unit time (e.g. mm/d); P = equivalent depth of precipitation falling onto the lysimeter surface per unit time (e.g. mm/d); ET = evapotranspiration or equivalent depth of water lost at the lysimeter surface through evaporation plus transpiration per unit time (e.g. mm/d); R = equivalent depth of runoff from the lysimeter surface per unit time (e.g. mm/d); and ΔS = rate of change in soil-water storage (e.g. mm/d). From Eqn (1), the following parameters are required for understanding water dynamics in residue sand profiles:

Precipitation (P)

At each of the three RSAs, rainfall will represent the sole source of water input. Although irrigation should be installed as part of lysimeter design, it should only be used if specific experiments require additional water (e.g. preferential flow and solute transport studies), or the system being mimicked involves irrigation. Errors in rainfall of up to 30% can be experienced in this measurement parameter during high wind velocity (> 8 m/s) events. Even under ideal conditions, measurements of P have a precision of less than $\pm 10\%$ (Gee and Hillel 1988; Benson *et al.* 2001). Precipitation will be recorded using a tipping bucket rain gauge (0.2 mm tip) associated with an automated weather station (see below).

Soil water storage (ΔS)

This parameter can be measured more accurately than precipitation, but the best measurement devices (those employing nuclear or dielectric techniques) can only provide water contents

within $\pm 2\%$ (Topp *et al.* 1980). Thus, for a cover 1 m thick, measured ΔS can be determined with a precision of 20 mm at best (i.e. $2\% \times 1000 \text{ mm} = 0.02 \times 1000 \text{ mm} = 20 \text{ mm}$). Soil water storage will be monitored using an in-situ moisture sensor (MP406) system and a neutron moisture sensor probe (see below).

Evapotranspiration (ET)

This parameter cannot be measured directly at the canopy scale, and methods of estimating ET vary in precision and accuracy. Potential ET (PET) can be estimated with reasonable accuracy, but at most sites actual ET (AET) will be less than PET during at least some portion of the year. At sites where water stress exists (such as the RSAs in summer), AET may be much less than PET. Actual ET can be estimated from latent heat flux using micrometeorological methods (e.g. eddy correlation or Bowen ratio techniques; Benson *et al.* 2001), but errors of about 10% are typical (Twine *et al.* 2000). Measurement of ET can be estimated directly from Eqn (1) if all other parameters are known. Other methods utilise the Penman-Monteith method (FAO recommended; Allen *et al.* 1998), and the use of continuous logging of sapflow (heat pulse technique), and seasonal monitoring of plant-water use by pressure bombing and porometry techniques. The heat pulse technique combined with seasonal monitoring of plant transpiration and leaf water potential will be used for quantifying plant water use.

Runoff (R)

This parameter can be measured with a precision of 2 to 3% of precipitation if the catchment being monitored is well-defined and the outflow monitoring points are limited (Winter 1981). Good definition of the catchment requires delineation of the catchment area using diversion structures (e.g. diversion berms) that prevent run on from adjacent areas and direct runoff for measurement (Benson *et al.* 2001). Given the highly permeable nature of residue sand profiles ($> 20 \text{ m/d}$), runoff is not expected to represent an important component of the water balance. However, diversion berms in the form of bunding will be required to prevent run on of potentially caustic water.

Equivalent depth of drainage (D_r)

This parameter can be estimated using Eqn (1), or measured directly using various instruments. These include flow gauges that can be inserted into drainpipes, “v”-notch weir and suitable recording device, weighing and timing techniques, and large tipping bucket (up

to 1 L tip volume) with a continuous datalogging system. Most of these devices may be limited by the relatively low flow rate for leachate draining from the lysimeter (e.g. <1 m³ per day). Preliminary testing of “v”-notch weir confirmed this limitation. A tipping bucket flow gauge with a tip volume of 1 L has been found to accurately measure drainage from the lysimeter.

Bulk density (ρ_b)

The mass of oven-dry sand (M_s) per unit volume (V_T) is a measure of bulk density, and is represented using Eqn (2): Standard techniques (Blake and Hartge 1986) are available to measure this parameter at specific depths.

$$\rho_b = M_s \div V_T \quad (2)$$

Volumetric water content (θ_v)

Representative θ_v distributions can be measured directly, or estimated using indirect methods. The direct (gravimetric) method is a simple and robust method of proven accuracy (Topp and Ferre 2002). However, the method is destructive, difficult to obtain samples at depths >1 m, labour-intensive, and inappropriate for use where long term sampling can compromise the hydraulic properties of experimental sites. When using indirect methods, θ_v is derived by inference through the use of well-established relationships that link soil water content to a measured soil parameter. The two most common indirect methods in soil water movement studies are the use of neutron scattering and dielectric sensors. Of these two methods, neutron scattering has consistently been found to be the most efficient and accurate method of measuring moisture content profiles in the field (Mwale *et al.* 2005); however, this technique does not easily measure θ_v in the surface 0 – 200 mm depth. Thus, a combination of moisture sensor probes (MP406; Figure 4a) and neutron moisture probe (Didcot Moisture Meter; Figure 4b) are most appropriate.

Penetration resistance (P_r)

Representative P_r distributions can be determined in-situ using a field penetrometer. An example of this item of equipment is the Perth Sand Penetrometer, which will be used to measure P_r in 300 mm depth intervals throughout the profile (Figure 5).

Saturated hydraulic conductivity (k_{sat})

This parameter is a measure of the maximum rate that a porous medium can transmit water, and can be determined using various laboratory and field based methods (Amoozegar and Warrick 1986). *In-situ* values of k_{sat} can be determined using a constant or falling head permeameter (e.g. Guelph constant head permeameter; Figure 6).

Infiltration rate (I_R)

This parameter differs from k_{sat} in that it measures water entry through the soil surface rather than through the soil profile. This parameter is important for soils exhibiting clay texture, surface sealing, and/or high intensity rainfall events, and is often measured using tension infiltrometers and ring infiltrometers (Bouwer 1986). Representative I_R rates will be determined using a tension infiltrometer in combination with the Guelph Constant Head Permeameter.

Water retention and Soil moisture characteristic

Water retention over the 0 – 15 bar pressure range will be measured on repacked cores and “undisturbed segments” of residue sand using combined pressure membrane apparatus (dry end of curve) and hanging water column (wet end of curve) techniques (Figure 7a and b). Values corresponding to field capacity (θ_{fc}), wilting point (θ_{wp}) and available storage ($\theta_{awhc} = \theta_{fc} - \theta_{wp}$) will be determined from the soil moisture characteristic (SMC; Klute 1986). The hydraulic parameters of residue sand (residual soil-water content θ_r , saturated soil-water content θ_s , and coefficients α and n) will be estimated by fitting water retention data using the RETC software (van Genuchten *et al.* 1991).

Pore-water tension and Total hydraulic head (h_T)

Pore-water tension allows total soil-water potential (Ψ_T) to be measured, and is an important parameter for modelling water movement in soil. The matric potential can be measured *in-situ* using jet-fill tensiometers fitted with pressure transducers (Figure 8). Total soil-water potential can then be estimated as:

$$\Psi_T = \Psi_m + \Psi_g \quad (3a)$$

where Ψ_m = matric potential (A measure of the strength which water is held by the residue sand due to adhesion and cohesion forces. This value is close to zero at saturation and

becomes increasingly negative as soil dries out); and Ψ_g = gravitational potential (A measure of the energy required to move a weight of water away from a reference point and is position in the soil profile. If this position is above reference level, Ψ_g is positive; if this position is below reference level, Ψ_g is negative. Ψ_g is not related to soil texture).

Total hydraulic head (h_T) is calculated as:

$$h_T = h_m + h_g \quad (3b)$$

where h_m = matric or suction head and h_g is the gravitational head, and

$$h_m = z_L - 10.23G \quad (3c)$$

where z_L = distance from tensiometer cup to gauge and is positive in upward direction and G = gauge pressure reading in “kPa”.

Background chemical conditions (Control)

The initial characteristics of all materials are required in order to evaluate the effects of any imposed treatments. The range of analyses will vary according to imposed treatments and aims of the study, but can include the following parameters: pH, EC, organic carbon, amorphous Fe and Al oxides and hydroxides, particle-size analysis, water-soluble cations (Ca, Mg, K, Na, Fe, Al and NH_4) and anions (Cl, NO_3 , SO_4 , P, HCO_3 and CO_3), exchangeable (Ca, Mg, K, Na, Fe and Al), inorganic N (NH_4 and NO_3), available S, available P, Total N, Total P, and trace elements (Cu, Zn, Mn and Fe). An example of the chemical properties of residue sand are provided in Table 1. Soil microbial analyses are often required for studies involving site rehabilitation and ecosystem (Banning *et al.* 2010).

Mineralogy

Residue sand mineralogy provides a foundation for understanding the chemical composition of and nutrient reactions in residue sand. Mineralogy will be determined using x-ray diffraction techniques.

Surface charge properties

The surface charge properties of a soil are critical to understanding nutrient dynamics, aggregate stability, and water movement. The point of zero charge and proportion of permanent and variable charge as a function of pH form the basis for understanding surface charge, and will be measured using established techniques (Phillips and Chen 2010).

Sorption coefficient (K_c)

Sorption/adsorption/exchange coefficients estimate the ability of an ion to displace another ion from the solid phase (e.g. cation exchange). This parameter is also used for simulating chemical transport in soil using solute transport models (e.g. HYDRUS). Sorption coefficients for key elements such as NH_4 , Ca and P can be obtained using the standard batch technique, or from column leaching techniques (Bond and Phillips 1990). Values of K_c for binary and ternary exchange systems will also be undertaken to evaluate the effect of competition on cation adsorption.

Chemical depth profile as a function of time

Chemical profiles as a function of depth can be obtained by hand-augering or excavations at specific sampling times. Samples are to be collected and stored using established protocol, and analysed for appropriate parameters (see above).

Nitrogen transformations and Rate coefficients

The importance of nitrogen transformations such as nitrification, volatilisation and immobilisation in soils, and rate coefficients for mathematically describing reaction kinetics, are well-established in the soil science literature. Some calibration of these techniques for use in highly alkaline, highly saline residue sand is warranted (Chen *et al.* 2009a).

Phosphorus fractionation

Fractionation studies provide important information on the location of specific elements in the soil system. These fractions include the pore-water, exchangeable, adsorbed to carbonate minerals, hydrous Fe and Al oxides, clay minerals and organic matter, and indicate the proportion of an element that is available for plant uptake, leaching, etc. The association of adsorbed P with specific mineral components and phases will be measured using appropriate fractionation schemes (Chen *et al.* 2009b).

Plant Growth and Water Use

Plant characteristics such as species type, survival, richness, cover and density will be monitored as per the standard botanical monitoring criteria. This can be achieved by establishing permanent botanical monitoring plots within the lysimeter (Figure 9), each covering an area of 36 m^2 ($6 \times 6 \text{ m}$) for monitoring species survival, density and cover of

seeded and planted species. An aluminium tag marked with a permanent plot number and a fence dropper can be used to identify the north-west corner of each monitoring plot and wooden stakes will be used to mark the remaining plot corners.

Germination success and plant survival is measured as follows. A quadrat (2×2 m) will be laid within the 36 m^2 monitoring plots and the number and percent cover (of the 4 m^2 area) of each species will be recorded. Planted seedlings will be recorded separately from germinated seed. This process will be repeated until the entire 36 m^2 plot had been monitored (i.e. 9 quadrats per 36 m^2 plot). A single plant within a 36 m^2 plot is equivalent to 278 plants/ha ($10,000 \text{ m}^2 \div 36 \text{ m}^2$), assuming even distribution of the plants. Therefore, the density of a species required in the field to ensure that it occurs within the monitoring plot is at least 278 plants/ha. However, given the way seed is applied during rehabilitation (hand-seeding with preferential segregation of seeds of different mass) an even distribution of seed is highly unlikely. In fact, groups of plants of the same species can often be observed in the field.

Planted success will be measured as follows. The number of each planted species in the entire lysimeter will be recorded. Each plant will be identified, and a bamboo cane placed as close as possible to the base of the plant. Fluorescent paint will be sprayed on the top of the cane to indicate it had been counted. If the plant is dead, the death will be recorded and the cane removed. A single plant within the 625 m^2 area is equivalent to 16 plants/ha ($10,000 \text{ m}^2 \div 625 \text{ m}^2$), assuming even distribution of the plants. Therefore, the density of a species required to ensure that it is monitored should be at least 16 plants/ha.

CONSTRUCTION OF A FIELD LYSIMETER

Lysimeters are essentially soil-filled containers that are used for mass balance analysis of water (e.g. Susan *et al.* 1992; Caspari *et al.* 1993) and chemicals (e.g. Sorensen *et al.* 1994; Winton and Weber 1996). There are two types of lysimeters: *weighing* and *volumetric*. A *weighing* lysimeter uses a scale to measure the total weight of soil within the monitoring area and a drainage pipe at the base to collect percolation from the base of the cover profile. Changes in soil-water storage are inferred from the changes in weight recorded by the scale (i.e. the only significant changes in mass are assumed to be due to changes in soil-water storage). A *volumetric* lysimeter consists of a pan for collecting water percolating from the base of the profile being monitored. Changes in soil-water storage in a *volumetric* lysimeter

are determined by integrating profiles of water content measured using nests of probes inserted in the cover. *Weighing* lysimeters are normally limited to smaller test sections ($< 2 \text{ m}^2$) because of the capacity of scales. *Volumetric* lysimeters are employed when a large section of soil cover is being monitored (Benson *et al.* 2001).

One of, if not the most important advantage of lysimetry is the direct measurement of drainage volumes and rates, and allows measurement to precision of 0.5 mm/y or better (Gee and Hillel 1988). However, the most significant disadvantage of lysimetry is the artificial no-flow boundary induced by the barrier at the lysimeter base and sides. This boundary, which does not typically occur in actual field settings, prevents upward and downward flow of vapour and liquid across the base and through the sides of the lysimeter. All water that migrates downward to the base of the profile is collected and routed out of the system. Consequently, the collected water can never move upward as a result of natural upward gradients induced by temperature and evapotranspiration gradients, as may occur under natural conditions. Coons *et al.* (2000) indicated that percolation rates measured using lysimeters can be as much as 3 mm/y too large due to the artificial trapping of water vapour by the lower boundary. In residue sand however, upward flux density of water by capillary action is considered to be negligible due to its coarse-texture, and capillary rise from a saturation zone was found to be about 85 mm (Phillips 2010; Appendix A).

Most lysimeters also include an earthen or geosynthetic drainage layer directly on top of the lower boundary for directing percolation to a measuring point. The larger pores associated with drainage layers can induce a capillary break at the base of the cover profile that might not exist under natural conditions (Khire *et al.* 1999). As a result, an artificial increase in the storage capacity of the cover profile may be incurred relative to natural conditions, as well as an artificial reduction in percolation rate. However, this issue is only problematic if the drainage layer has very different pore size than the material over which the cover system is being installed, or the cover being monitored is very thin ($< 1 \text{ m}$). For residue sand profiles, the air and water entry suctions are expected to be low (possibly $< 10 \text{ mm}$) and the profile will have a thickness of about 3 m. Thus, the capillary break effect may have little effect on percolation estimates.

Lateral diversion can be a significant problem with lysimetry if the aerial extent of the lysimeter is insufficient and the lysimeter does not have vertical sidewalls. Diversion occurs

under unsaturated conditions due to the tendency of water to be retained within finer textured cover soils rather than coarser-textured drainage layers (i.e. due to capillary break). Under near-saturated conditions, diversion can occur through macropore or by-pass flow. Lysimeters that are too small or too narrow collect too little water and underestimate the percolation rate. Chiu and Shackelford (2000) suggest that the breadth of a lysimeter should be at least five times the depth of the profile being monitored to prevent diversion from affecting the percolation rate. Thus, a lysimeter 25 m in breadth with a 3 m profile should not be adversely affected by diversion and sidewall flow as long as the walls are near-vertical.

Other factors that need to be considered as part of the water balance of lysimeters are leakage through poor liner construction, and artificial water uptake by plants from the drainage collection system that would normally pass below the zone of root extraction under natural conditions.

Site Preparation

A field lysimeter was constructed at the existing lysimeter facility at the Pinjarra RSA (PJ RSA), immediately on top of the existing Cell 4 (most-western cell, currently grassed only) (Figure 1). All existing infrastructure (such as neutron probe access tubes, and monitoring well PVC standpipes) were removed prior to site preparation commencing. The surface 0.2 m (which included all surface vegetation) of the existing residue sand profile was then removed and the surface re-contoured to obtain a new horizontal surface.

Lysimeter Design and Construction

The lysimeter was constructed using a depth profile of 3 m as previous research had suggested that this depth of residue sand was adequate to minimise water-stress in summer and waterlogging in winter (Phillips unpublished data). However, an estimate of the required profile thickness can be calculated as (Benson *et al.* 2001):

$$L \geq P_0 \div (F \times \theta_{awhc}) \quad (4)$$

where L = layer thickness (m), P_0 = depth of precipitation received outside the growing season (i.e. when ET is low), θ_{awhc} = soil-water storage (m/m), and F = a scaling factor and has been estimated to be about 0.7. Thus, for $P_0 = 0.7$ m (assumes about 10% uptake of rainfall by plants) and $\theta_{awhc} = 0.15$ m, equation [1] predicts that $L = 7$ m. Although equation [1] excludes water loss through runoff (assumed = 0) and via evaporation, it suggests that a 3

m profile would retain about 50% of the precipitation, with the remainder lost via drainage. Equation [1] is an over-simplification of water dynamics in BRS and so must be considered as a qualitative guide only.

The following provides a detailed description of construction of the lysimeter at PJ RSA2.

1. Site preparation commenced 1st February 2007. Initial preparation involved removing and discarding all unwanted materials (e.g. existing liner, PVC pipes, neutron meter access tubes, etc) and scrape off the upper 0.2 m of residue sand (Figure 10).
2. After initial preparation, the lysimeter area was surveyed by Bunbury Engineering Surveys (BES), and corner points marked.
3. The new surface was compacted to produce a firm, relatively flat base for the lysimeter (Figure 11).
4. Residue sand was trucked to site to commence construction of vertical walls along the eastern and southern boundaries. The western and northern boundaries were untouched at this point in time as they were considered stable enough to construct the initial 1.5 m lift (Figure 12).
5. It was decided to construct the vertical walls using cement mixed with residue sand in two main lifts. First, the eastern and southern boundaries were constructed to a height above ground level (agl) of 1.5 m. Second, the western and northern walls would be cut from the existing embankments. This provided a “box” with sidewalls about 1.5 agl. After filling this depth with unamended residue sand, an additional 1.5 m lift would be constructed above the existing sidewalls to give a total height agl of 3 m. The final 1.5 m height was filled with gypsum-amended residue sand.
6. This was done as follows.
 - 6.1. Construction of vertical sidewalls commenced along the eastern boundary, followed by the southern boundary.
 - 6.2. Prior to commencing construction, however, a “sleeve” for the sump drain pipe was required to be placed through the eastern sidewall. The location of the sump drain pipe was identified by Bunbury Engineering and Surveys, which was 200 mm below the north-east corner of the lysimeter (Figure 13). A sleeve was made using 1 m length of 250 mm diameter pipe, which was laid in the north-east corner in a west to east orientation. This sleeve was positioned on a downward angle (0.2 m fall over 25 m distance) to facilitate unimpeded drainage from the lysimeter along the sump drain pipe.

- 6.3. Vertical side-walls were constructed by compacting residue sand to form a bench approximately 6 m wide and 1.5 m high. For construction purposes, this bench extended across the inside lysimeter boundary approximately by 2 m, however material within the lysimeter boundary was subsequently removed prior to placing the PVC liner (Figure 14).
- 6.4. The initial height of the bench was 1 m agl to minimise workplace hazards associated with deeper trenches given the unknown stability of the compacted sand wall face.
- 6.5. Following construction of this compacted bench, a “string-line” was set up along the eastern boundary of the lysimeter area to accurately mark out the position of the proposed trench.
- 6.6. A trench (using a Volvo V10 excavator fitted with a 1.2 m wide excavator bucket) was progressively excavated along the eastern and southern lysimeter boundaries to a depth of 1 m in approximately 10 m lengths (Figure 15).
- 6.7. For each 10 m length of trench, the excavated material was windrowed on the bench outside the lysimeter and thoroughly mixed with cement (until no cement could be visually detected) at a residue sand to cement ratio of 5:1 using the excavator and bucket (Figure 15).
- 6.8. The cement/sand mix was then replaced into the 10 m long trench in 0.3 m depth increments (Figure 15).
- 6.9. The cement/sand mix for each increment was then wetted with water and compacted to produce a firm layer, after which the next increment of cement/sand mix was added, wetted and compacted (Figure 15).
- 6.10. Residue sand/cement mixture was added until a height of 1 m agl was attained.
- 6.11. This process was repeated in 10 m long sections until the western and southern boundaries were completed.
- 6.12. The height of the bench and cement-sand trench was then extended a further 0.5 m along the eastern and southern boundaries. However, the width of the trench was reduced to 0.6 m and the residue sand to cement ratio was increased to 1:5.
- 6.13. After completion of the 1.5 m high cement-sand trenches, the western and northern embankments were excavated to produce a vertical (free-standing) wall approximately 1.5 m agl (Figure 16).
- 6.14. The northern boundary was extended 200 mm below ground level for placing

the (200 mm diameter) sump drain pipe, and the fall in this shallow trench/excavation was 0.2 m over a 25 m length (surveyed by Bunbury Engineering and Surveys).

- 6.15. All sand within the inside lysimeter boundary was then removed (from all four boundary walls) to expose four vertical faces. (Note: the sand inside the lysimeter perimeter was removed using the excavator until the cement face was reached. Thus, the cement face became the vertical wall along the eastern and southern boundaries).
 - 6.16. After cleaning-up, a box with free-standing vertical walls to a height of 1.5 m agl was produced. The base of the lysimeter was again surveyed (Bunbury Engineering Surveys) to obtain lysimeter floor dimensions and slope angles.
 - 6.17. The remaining 1.5 m lift was commenced after installation of the PVC liner.
7. Prior to installing the PVC liner, a sump drain pipe was constructed using 200 mm internal diameter poly-pipe (Figure 17). Three lengths of pipe (each pipe was 12 m long) were poly-welded together. Starting from the western end of this pipe, smaller diameter polypipe (125 mm OD, 100 mm ID) connectors were poly-welded at 2.5 m spacings (first one was 0.5 m from western end). Ten connectors were poly-welded to connect the drain-coil to the sump drain pipe. The integrity of each welded connector was tested for leaks and strength by first filling the entire sump drain pipe with water and checking for leaks, and then manually trying to break the welds with slight shearing force (i.e. pushing against). There were no failures.
 8. During excavation of the northern and western faces, a layer of “blue-metal” gravel with sharp edges was detected. This was most likely used for dust suppression during construction of the original lysimeter (Figure 18). To remove the risk of puncturing the PVC liner, “scrap” 2 mm thick HDPE from RSA9 construction was retrieved and used to line the walls. This effectively formed a barrier between the exposed “blue-metal” gravel and the PVC liner (Figure 18).
 9. The PVC liner installed into the 1.5 m deep box by pulling on one end. Five people assisted in this task and required approximately 6 hours to initially install. An additional 4 – 6 hours was required by 1 to 2 persons to remove most of the floor wrinkles (Figure 19).
 10. Following installation, the integrity of the liner was inspected During this inspection a number of issues were revealed.
 - 10.1. A couple of “wear and tear” areas were observed and needed patching. This

work was completed by Lleytons (as they were on-site for installing the liner at RSA9).

- 10.2. During patching, Lleytons observed that the integrity of the welded liner seams was found to be questionable. Testing of the welds by Lleytons using an on-site tension meter found that the welds peeled at < 10 psi, and the liner did not stretch (or elongate) prior to peeling. A passable liner weld should not peel before the liner elongates and tears. Since the welds could be easily peeled apart with no elongation, the weld was regarded as a failure (Figure 20). The liner manufacturer was contacted and a representative came to inspect the liner weld integrity. Failed welds were found in various sections of the liner, and the manufacturer sent two technicians to re-check all welded seams and to re-weld any seam deemed a failure. This work was completed over a 2-day period. The welds were evaluated by the manufacturer and independently by Lleytons and three random samples found that the weld strength had increased from 10 psi to > 30 psi, and elongation occurred before the weld broke. A shear test also revealed that the weld strength was greatly improved (> 30 psi) after re-welding. Although the welds failed on a peel-test (10 to 95% peeling of the weld), the overall conclusion was that the liner would now be classed as Passed. It was recommended that little vertical strain be placed on the liner (such as being too tight in the vertical sections of the wall face with 3 m of residue sand placed on top), and that a reasonable amount of slack and folding be retained in the liner that is placed up the lysimeter walls. This was done during final installation.
11. Once the liner integrity was assured and fitted into lysimeter, a hole was required to be cut in the liner to allow the sump drain pipe to exit the lysimeter. The exit position was marked on the liner and a hole cut through it immediately adjacent to the “sleeve pipe” installed earlier when constructing the eastern embankment. A piece of liner (500 mm x 500 mm) was used to construct a “sleeve” through which the sump drain pipe will pass for later sealing of the PVC liner around the sump drain pipe (Figure 21).
12. The sump drain pipe was lowered along the northern boundary and passed through the liner “sleeve”. Each end of the pipe was supported by an excavator, which effectively lowered the pipe and then fed it horizontally into and through the lysimeter “sleeve” (Figure 21). Once the pipe was through the PVC liner “sleeve” and pipe “sleeve” in

the eastern embankment, it was lowered into the 200 mm deep floor trench along the northern lysimeter wall. The drain-coil connectors were positioned as horizontal as possible to the lysimeter floor to ensure unimpeded water entry from the lysimeter drainage into the sump drain pipe.

13. The ten lengths (25 m long by 100 mm diameter) were then laid in a south to north orientation on the lysimeter floor on top of the PVC liner. Prior to laying however, the filter sock encasing the drain coil was replaced due to faulty workmanship. Each length of drain coil was sealed at the southern (up-slope) end and sealed into the connectors with duct tape. The end of each drain coil was pushed far enough into the sump drain pipe to ensure that if the connectors broke off at any stage that water flow into the sump drain pipe would not be affected (Figure 22).
14. An additional survey to register the height of drain coil above the lysimeter floor was undertaken by Bunbury Engineering and Surveys.
15. Filling of the lysimeter commenced 8th March (approximately 2 weeks behind schedule). “Clean” unamended residue sand was sourced from RSA2 and trucked to site. Tipping of the sand had to be done inside the lysimeter. This was done by first constructing a ramp of clean residue sand at the south wester corner of the lysimeter and driving the truck into the lysimeter. It was then tipped from the truck and placed using a V10 Volvo Excavator. This caused a degree of compaction of the lysimeter residue sand profile, and similar to what would occur during mechanical construction of BRS embankments (Figure 23).
 16. To relieve this compaction (to better simulate hydraulically poured embankments), the excavator upturned the sand profile to a depth of 1 m (as it was though the effect of compaction would probably be limited to the upper 1 m depth but also to ensure no contact between the excavator bucket and the liner) as it backed out from the lysimeter. Permeability and bulk density testing was carried out on the resulting profile, which represented the 1.5 to 3 m of the finished lysimeter residue sand profile.
 - 16.1. The average hydraulic conductivity ($n = 5$) was 19.3 m/d with a standard deviation of 3.8 m/d (see text for more detail).
 - 16.2. The average bulk density was 1300 kg/m³ and the Perth Sand Penetrometer consistently gave readings of < 3 blows per 300 mm.
17. Prior to filling the lysimeter with clean residue sand, a standpipe for inspecting the sump drain pipe was omitted. Originally, this standpipe was to be placed at the western end of the sump drain pipe as a means for inspecting and if required cleaning

the pipe if excessive clogging (with residue sand or Fe precipitates) occurred and impeded drain flow conditions. Since the sump drain pipe could not be re-excavated in case the liner integrity was compromised, the standpipe was placed immediately outside the eastern boundary of the lysimeter. The sump drain pipe was cut and a “t” piece welded to the cut pipe ends. A 160 mm standpipe was then inserted vertically into the “t” piece and the drainage line filled with sand (Figure 24). The fall of the sump drain pipe was validated by surveying to ensure a fall of 200 mm per 25 m length of drain pipe.

18. After the initial 1.5 m of sand had been placed into the lysimeter and permeability and bulk density testing undertaken, the PVC liner was folded flat into the lysimeter so it laid on the sand surface. A protective layer of 2 mm HDPE was then placed across the entire lysimeter surface to ensure that the next lift of 1.5 m could be undertaken with minimal risk of penetrating or ripping the PVC liner (Figure 25).
19. Construction of the walls for the next 1.5 m lift commenced 16th March. The four walls were constructed using cement to residue sand ratio of 1:5 in the same manner as for the eastern and southern boundary walls (Figure 26).
20. Following the final 1.5 m lift, a BRS bund (\approx 0.3 m high) was placed around the lysimeter outer perimeter. This bund will act as a protective mechanism to limit run-on waters entering the lysimeter (see Step 23).
21. During excavation, three tears were made in the PVC liner (1 along western wall about half-way along, 1 along southern wall about half-way along, and 1 along eastern wall about half-way along). All were professionally repaired by Lleytons polywelding staff.
22. The protective HDPE was removed from inside the lysimeter. Sections of this material were cut up to lay against the exposed sand wall for additional protection of the PVC liner.
23. The PVC liner was dragged up the wall face and laid over the bund to provide a low permeability zone for run-on water. The PVC liner extended about 2 m away from the lysimeter boundary on all four sides. The excess PVC liner was placed over this bund and then covered with \approx 0.2 m of BRS to retain the liner in place (Figure 27).
24. Once the PVC liner was in place, the remaining 1.5 m depth of the lysimeter was filled with gypsum-amended residue sand.
25. Gypsum-amended residue sand was produced by constructing a pad of known dimensions, and incorporating the required amount of gypsum to achieve a 1% rate

(see below) (Figure 27).

26. The gypsum-amended residue sand was then transported to the lysimeter and tipped into the lysimeter to progressively fill to ground level (Figure 28).
27. Once filled, the surface 1 to 1.2 m was “fluffed up” by the excavator to minimise any compaction produced by the excavator and haul truck during filling. Permeability and bulk density testing was carried out on the resulting profile, which represented the 1.5 to 3 m of the finished lysimeter residue sand profile.
 - 27.1. The average hydraulic conductivity ($n = 5$) was 19.3 m/d with a standard deviation of 3.8 m/d (see text for more detail).
 - 27.2. The average bulk density was 1300 kg/m³ and the Perth Sand Penetrometer consistently gave readings of < 3 blows per 300 mm.
28. The area outside the lysimeter was graded to provide a slope falling away from the lysimeter to avoid run-on waters, and the surface covered with wood mulch as a dust suppressant (Figure 29).
29. Samples of unamended and gypsum-amended BRS were collected for chemical analysis.
30. A sprinkler system was installed for dust control until the lysimeter was covered with wood mulch, and if subsequent experiments required the use of water inputs additional to that supplied by rainfall (Figure 30).
31. Prior to mulching, di-ammonium phosphate (DAP) based fertiliser (Appendix C) was hand-spread across the lysimeter at the recommended rate of 2.7 t/ha (Appendix B). Fertiliser was then manually incorporated using a small-scale motorised rotary hoe.
32. Native seed was hand-sown at a rate of 2 kg/ha (Appendix D).
33. Following seed application, wood mulch was applied to achieve a depth of 30 mm across the lysimeter surface.
34. Tubestock that was planted and accompanying composition of fertiliser tablet are provided in Appendix D and Appendix C respectively. About 100 plants were planted across the lysimeter, representing a planting rate of about 1700 stems/ha. The fertiliser tablet was applied at a depth of about 0.1 m below the surface and about 0.1 m away from the plant.
35. Leachate draining from the lysimeter was collected in the underdrain system and transported via a 0.15 m polypipe to the leachate volume measuring flow gauge (see below).
36. A chain mesh fence was constructed around the lysimeter facility to exclude grazing

by kangaroos and rabbits, and a small carpark constructed at the entry to the facility (Figure 30).

37. Finally, an information sign outlining the key steps in lysimeter construction was erected for site tours.

Calibration and Installation of Field Monitoring System

The following instruments have been installed at the lysimeter to allow estimation of soil-water-atmosphere-plant dynamics.

Weather station

A standard weather station (Fieldstation™) was purchased from ICT International (www.ictinternational.com.au) and installed centrally on the lysimeter surface (Figure 31). The basic components of the system are an SL5 Smart Logger, logger housing, solar panel, lower mast and freestanding base. The (Plug & Play) Smart Logger can read up to 250 channels, with a memory of 500,000 Date & Time Stamped, High Resolution (16 Bit) readings. The logger includes an LCD display, 6V/7 Ampere hour battery, with a 110/240V (12V, 2.5Amp DC output) power supply. The battery is charged using a 10 Watt solar panel. Data is downloaded to a laptop computer via a RS232 cable using the commonly available HyperTerminal software.

This system was customised by selecting the following suite of environmental sensors:

- Air temperature sensor (range of $-20^{\circ}\text{C} - 60^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$).
- Relative humidity sensor (range of $0\% - 100\% \pm 2\%$).
- Solar radiation sensor (range of $0 \text{ Wm}^2 - 2000 \text{ Wm}^2 \pm 5\%$).
- Wind direction sensor (range of $0.01^{\circ} - 359.99^{\circ} \pm 0.5^{\circ}\text{C}$).
- Wind speed sensor (3-cup with a range of $0.2 \text{ m/s} - 50 \text{ m/s} \pm 2\%$).
- Rainfall using a tipping bucket rain gauge (0.2 mm tip with a range of $0 \text{ mm/h} - 720 \text{ mm/h} \pm 2\%$). Calibration of these gauges is presented in Figure 32.
- Evapotranspiration is logged as a virtual sensor and is based on the calculation proposed by Meyer (1999). However this relationship was developed for regional south-east Australia and so may not be applicable to south-west Western Australia's Mediterranean climatic conditions. Therefore, evapotranspiration rates specific to

native coastal vegetation growing on residue sand embankments will need to be determined in separate studies.

Soil moisture sensors

Moisture content of the residue sand was monitored using MP406 sensors with a direct output in units of volumetric water content ($\theta_v\% \pm 3\%$) (www.ictinternational.com.au). Prior to installation, all sensors were calibrated over a moisture range of 0 – 25% (Figure 33). This was achieved by moistening approximately 0.2 kg of residue sand to a pre-determined gravimetric moisture content ($\theta_g = 0.008, 0.045, 0.093, 0.131, 0.188$ or 0.239 kg/kg). The sand was placed into a 125 mL polycarbonate container to achieve a bulk density (ρ_b) of ≈ 1000 kg/m³. Each MP406 sensor was connected to a Smart Logger (using HyperTerminal software) and then pushed into the residue sand. The resulting volumetric water content (θ_v) was recorded. Each probe was calibrated over the full moisture content range, thereby giving 28 separate readings for each θ_g . Linear regression analysis yielded a regression equation of the form:

$$\text{MP406} = 1.068 \times \text{Measured} - 0.0298 \quad r^2 = 0.986 \quad (5)$$

which is not dissimilar to the manufacturer's calibration of:

$$\text{MP406} = 1.013 \times \text{Measured} + 0.0043 \quad r^2 = 0.993 \quad (6)$$

However, the measured calibration curve is considered more accurate than the manufacturer's since it was developed specifically for residue sand (Figure 32). The MP406 data can be revised based on the measured data using Equation 7:

$$\text{Actual} = 0.924 \times \text{MP406} + 0.0244 \quad r^2 = 0.986 \quad (7)$$

MP406 moisture sensors were installed at a depth of 75, 150, 400 and 800 mm below ground level (bgl). Sensors were installed as follows:

- The surface mulch was cleared away and stored in a plastic bag for re-placement after installation.
- A small trench to a depth of 800 mm was excavated using a shovel.

- At a depth of 800 mm bgl, the MP406 was gently pushed into the exposed trench face, ensuring a slight downward angle to minimize the potential for water accumulation around the sensor probes.
- The performance of each sensor was checked prior to covering with residue sand.
- Residue sand was then replaced over the MP404 sensor in depth increments of about 100 mm. After each increment, the residue sand was lightly tamped down by hand to re-establish a bulk density of about 1300 kg/m³.
- Residue sand was added until a depth of 400 mm bgl, at which another MP406 sensor was installed.
- Additional sensors were sequentially installed at depths of 150 and 75 mm bgl as outlined above.
- Placement of sensors immediately above the underlying sensor was avoided.
- After all residue sand had been replaced, the wood mulch was returned to the surface and the MP406 sensor cables ran into a protective plastic pipe and to the weather station databus and datalogger.

Pore-water tension sensors

Pore-water tension was monitored using Jet-fill tensiometers fitted with a pressure transducer (range of -100 to 200 kPa with a resolution of 0.1 kPa or 1 cm water;

www.ictinternational.com.au) (Figure 34). Prior to installation, all tensiometer transducers were calibrated over a vacuum range of 0 to 80 kPa (Figure 35). This was achieved by:

- Placing a jet-fill tensiometer (1 bar ceramic tip) into a sealed flask containing sufficient de-aired water to cover the ceramic tip.
- A vacuum line and in-line vacuum gauge were connected to the flask to allow a vacuum to be applied.
- The tensiometer transducer was connected to a databus to a Smart Logger to a laptop computer.
- A vacuum between 0 and 80 kPa was applied and the voltage output measured. Readings were recorded as output using the software HyperTerminal.
- The calibration curve for applied vacuum against voltage output is presented in Figure 35.

Chemical Characteristics of Residue Sand

Selected properties of residue sand before and after gypsum incorporation, and following addition of di-ammonium phosphate based inorganic fertiliser, were measured (Table 1). The primary benefits of adding gypsum and fertiliser are:

- A reduction in pH
- A reduction in alkalinity
- An increase in soluble and exchangeable calcium
- A decrease in soluble and exchangeable sodium
- A decrease in soluble aluminium.

A more detailed description of the chemical, physical and microbial properties of residue sand is provided in related documents (e.g. Chen et al. 2009a,b; Phillips and Chen 2010).

Preliminary Botanical Monitoring

Results from preliminary botanical monitoring are presented in Appendix D. More detailed information on species survival, species density and percentage cover will be obtained from 15-month botanical monitoring. An estimate of Leaf Area Index (LAI) will also be determined and results presented in a subsequent report.

MODELLING

Software Available

A wide range of mathematical models have been developed over the past few decades which are capable of simulating water and nutrient transport in residue sand. Many of these are based on well-established theoretical frameworks, and often demonstrate strengths and weaknesses in the variety of processes affecting water-nutrient-plant dynamics. For example, solute transport models that have been specifically developed to simulate solute transport in the absence or presence of “simple” ion exchange mechanisms may not describe the use of water by plants or geochemical speciation within the pore water in chemically complex systems (such as residue sand). As an initial approximation, the following models will be tested and validated for use in lysimeter trials.

RETC

The RETC code was developed for analysing the soil-water retention and hydraulic conductivity functions of unsaturated soils. A detailed description of the various theoretical models used by the software is provided in van Genuchten *et al.* (1991). The water retention function of van Genuchten (1980), and the hydraulic conductivity model of Mualem (1976) have commonly been used to predict experimental data. The van Genuchten equation is given as (van Genuchten *et al.* 1991):

$$\text{for } h < 0, \quad \theta(h) = \theta_r + (\theta_s - \theta_r) / (1 + xh^n)^m \quad (2a)$$

$$\text{for } h \geq 0, \quad \theta(h) = \theta_s \quad (2b)$$

where h = soil-water pressure head (cm), θ_r = residual water content (cm^3/cm^3), θ_s = saturated water content (cm^3/cm^3), x = an empirical parameter whose inverse is commonly referred to as the air entry value (1/cm), and n = pore-size distribution parameter affecting the slope of the retention curve and $m = 1 - 1/n$.

The hydraulic conductivity model by Mualem is (van Genuchten *et al.* 1991):

$$k(h) = k_s (((1 - (xh^{n-1})) (1 + (xh^n)^{-m})^2) / ((1 + xh^n)^{m/2}) \quad (3)$$

where $m = (1 - 1/n)$, and the remaining symbols have the same meaning as in Eqn 2.

PHREEQC

PHREEQC (pH Redox Equilibrium) is a chemical speciation and reaction path program developed by the US Geological Survey (Parkhurst and Appello 1999). PHREEQC uses the C language and is capable of performing speciation and solubility, reaction path, inverse mass balance modelling, and 1-dimensional advective-dispersive-reactive transport calculations. A detailed description of geochemical speciation models such as PHREEQC and its application to environmental chemistry is provided in Zhu and Anderson (2002).

HYDRUS-1D and HYDRUS-3D

HYDRUS-1D and HYDRUS-3D (hereafter referred to as HYDRUS) are interactive software systems developed for simulating 1-, 2- and 3- dimensional water and chemical transport in uniform or multi-layered unsaturated, partially-saturated and fully-saturated soil systems. Water movement is modelled using Richards' equation, and chemical transport is modelled

using convection- dispersion type equations. The transport equations include non-linear, non-equilibrium reactions between the solid and liquid phases for reactive chemicals, and first-order degradation reactions for chemicals undergoing transformations such as nitrification of NH_4^+ to NO_3^- . Detailed description of the governing equations in HYDRUS and their application can be found in Simunek and van Genuchten (1999), Simunek *et al.* (1999) and Rassam *et al.* (2003).

HYDRUS requires information on the hydraulic properties of each soil material, the sorption properties of each soil material for each chemical modeled, and the transformation properties of each chemical studied.

Evaluating Model Performance

The performance of RETC, PHREEQC and HYDRUS to simulate the observed laboratory and/or field data will be assessed using ANOVA, linear regression analysis, and a measure of model efficiency. These statistical evaluations have been used to compare observed and modeled data by many workers (e.g. Phillips 2006). The coefficient of model efficiency (CME) is an indicator of the overall agreement between the measured and predicted data. Values of CME can vary from 1, where there is a perfect agreement between the measured and predicted data, to $-\infty$. A negative value of CME means that model predictions are no worse than predictions using a constant equal to the mean measured value.

$$\text{Coefficient of model efficiency (CME)} = \frac{\sum_{i=1}^n (O_i - O_m)^2 - \sum_{i=1}^n (P_i - O_m)^2}{\sum_{i=1}^n (O_i - O_m)^2}$$

where O_i and P_i are the measured and predicted values in sample i , and O_m is the mean of the measured data.

CONCLUSIONS

This report describes a method for constructing a field lysimeter for understanding water-nutrient-plant interactions. The findings from this study will provide essential fundamental information on the major processes affecting rehabilitation performance at Alcoa's RSAs, and assist in designing site closure strategies. A key short term outcome of this study will be

to evaluate whether store-release cover systems are appropriate for use at Alcoa's Western Australia operations as a means of minimizing the production of deep drainage and ultimately leachate requiring treatment prior to discharge and/or re-use.

ACKNOWLEDGEMENT

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Table 1. Mean and standard deviation ($n = 3$) for selected chemical properties of unamended residue sand, gypsum-amended residue sand and gypsum-amended residue sand plus di-ammonium based inorganic fertiliser. (a) Water-soluble chemical composition for a saturated paste extract, and (b) Chemical composition of the solid phase

(a)

<i>Na</i>	<i>Mg</i>	<i>Al</i>	<i>P</i>	<i>SO₄</i>	<i>Cl</i>	<i>K</i>	<i>Ca</i>	<i>Fe</i>	<i>NH₄-N</i>	<i>NO₃-N</i>	<i>EC</i>	<i>pH</i>	<i>HCO₃</i>	<i>CO₃</i>
(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mS/m)		(mg/L)	(mg/L)
Unamended Residue Sand														
2229	4.4	10.9	1.6	53.4	72.3	4.3	0.9	0.7	0.0	5.8	11.0	10.1	0	4034
194	0.5	1.2	0.2	5.6	12.9	0.4	0.3	0.2	0.0	2.1	0.8	0.0	0	544
Gypsum-amended Residue Sand														
2947	5.1	9.6	2.2	1805.7	79.3	6.7	1.1	0.3	0.0	6.2	15.3	9.8	531	789
166	0.1	0.5	0.1	133.4	4.0	0.3	0.0	0.0	0.0	2.3	0.9	0.0	19	35
Gypsum-amended Residue Sand plus DAP Fertiliser														
307	5.9	0.9	0.8	185.2	18.5	53.7	5.3	0.8	0.7	3.6	1.9	8.8	270	0
26	1.4	0.1	0.2	23.8	1.0	17.8	0.6	0.1	1.3	2.7	0.2	0.1	16	0

(b)

<i>Org C</i>	<i>Oxalate-</i>		<i>NO₃-N</i>	<i>NH₄-N</i>	<i>PO₄-P</i>	<i>SO₄-S</i>	<i>EDTA-</i>				<i>Exchangeable-</i>				
	<i>Fe</i>	<i>Al</i>					<i>Cu</i>	<i>Zn</i>	<i>Mn</i>	<i>Fe</i>	<i>Ca</i>	<i>Mg</i>	<i>Na</i>	<i>K</i>	<i>Al</i>
(%)	(%)	(%)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)				(cmol/kg)				
Unamended Residue Sand															
0.06	0.63	0.14	2.00	1.00	4.17	13.8	0.30	0.56	0.60	89.7	2.98	0.10	7.18	0.05	0.05
0.01	0.07	0.01	0.00	0.00	0.35	2.6	0.19	0.01	0.07	1.1	0.04	0.02	0.72	0.01	0.00
Gypsum-amended Residue Sand															
0.05	0.44	0.14	2.33	1.00	4.79	381.6	0.24	0.53	0.82	93.7	4.09	0.09	7.71	0.05	0.04
0.00	0.01	0.01	0.58	0.00	0.73	48.3	0.08	0.06	0.05	5.3	1.00	0.01	0.97	0.01	0.01
Gypsum-amended Residue Sand plus DAP Fertiliser															
0.06	0.54	0.14	2.67	1.00	35.93	68.9	0.23	5.09	2.59	102.8	5.02	0.12	1.45	0.19	0.03
0.01	0.02	0.01	1.15	0.00	1.52	32.8	0.03	1.25	0.57	10.8	0.16	0.02	0.05	0.02	0.00



Cell Number	1	2	3	4
Sand Depth	3	2	2	2
Vegetation	acacia saligna, eucalyptus camaldulensi	acacia saligna, eucalyptus camaldulensi	acacia saligna, eucalyptus camaldulensi	wild oats
Tree Spacing	1	1	1.5	na
Summary	deep, high density	shallow, high density	shallow, low density	baseline



Cell 1



Cell 2



Cell 3



Cell 4

Figure 1. Location, properties and layout of lysimeters at Pinjarra's RSA2



Figure 2. Evidence of previous flooding of lysimeters at Pinjarra's RSA4 with caustic discharge

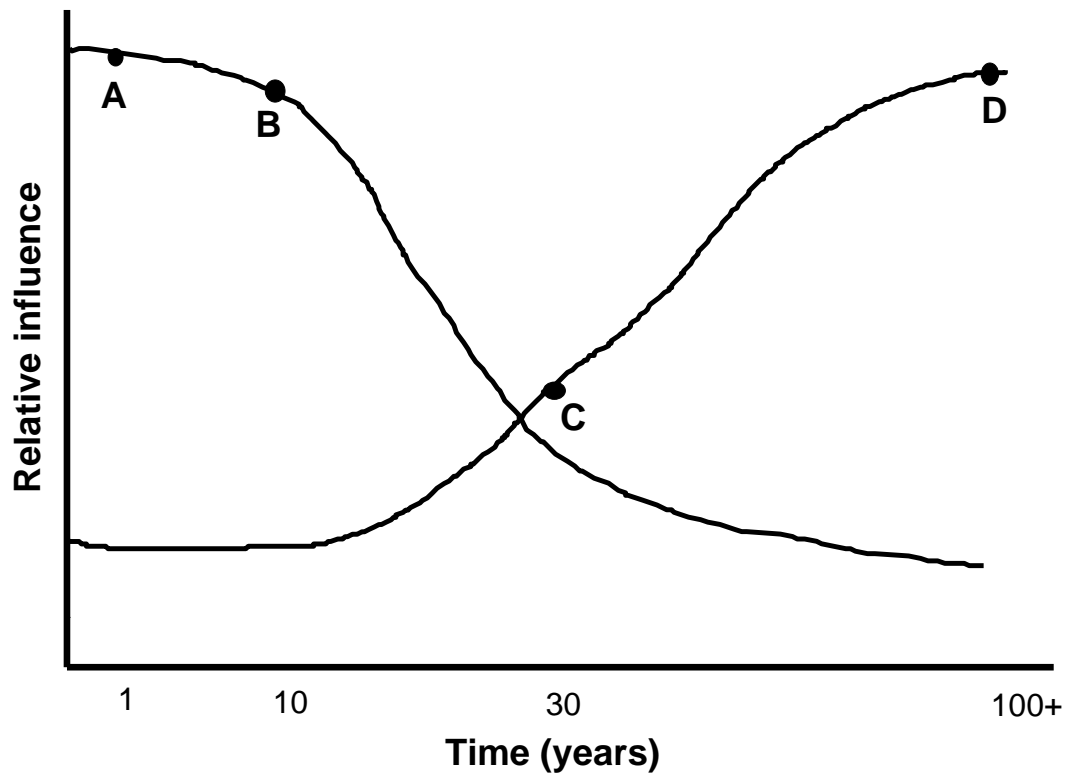


Figure 3. Conceptual relationship illustrating trends in the relative influence of engineering versus environmental factors in the long-term effectiveness of engineered landfill covers. (A) 3 years or less after installation; (B) 10 years after installation; (C) 30 years after closure; (D) 100 years or more after closure (Breshears *et al.* 2005) (Note: points A & B are on engineering line and C & D are on environmental line)

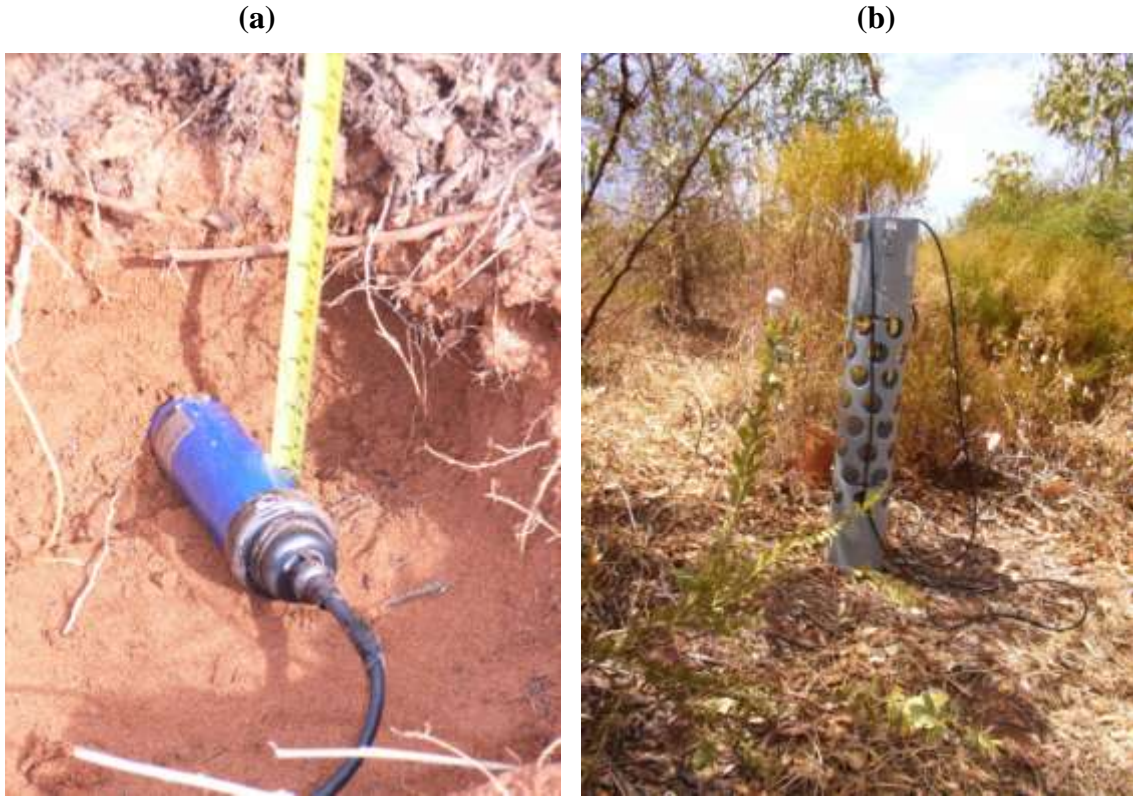


Figure 4. Field equipment for monitoring moisture profiles of residue sand embankments
(a) MP406 moisture sensors and (b) Didcot moisture gauge



Figure 5. Perth sand penetrometer used for measuring penetration resistance within residue sand profile



Figure 6. Guelph constant head permeameter used for measuring saturated hydraulic conductivity within residue sand profile

(a)



(b)



Figure 7. (a) Pressure plate apparatus and (b) hanging-water column equipment used to construct moisture characteristic curve for residue sand



Figure 8. Jet-fill tensiometer fitted with pressure transducer for monitoring in-situ pore-water tension within residue sand profile

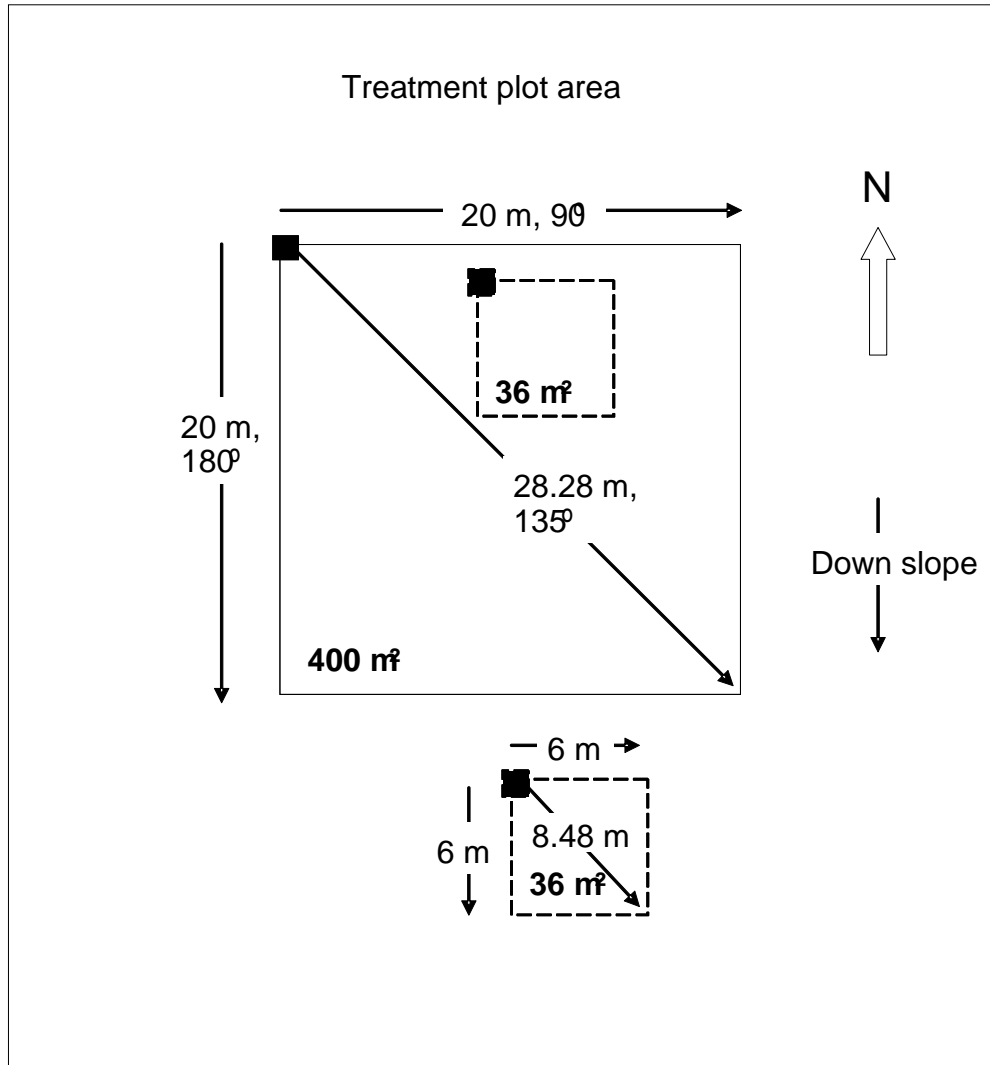


Figure 9. A diagram (not to scale) of the botanical monitoring plots set up within each treatment plot. Distances for the different plots and compass bearings are shown. The dark square (■) is the North-west corner of the plot and is marked in the field by a fence dropper and a permanent plot number



Figure 10. Clearing existing vegetation and infrastructure from Cell 4 in preparation of new lysimeter construction



Figure 11. Base of new lysimeter after removal of 0.2 m of residue sand and vegetation



Figure 12. Western and northern boundaries were considered stable and so were not excavated for the initial 1.5 m lift



Figure 13. Pipe sleeve was installed through the eastern wall of lysimeter for sump drain exit



Figure 14. Construction of benches 1.5 m in height along eastern and southern boundaries



Figure 15. Mixing cement with residue sand before replacing back into trench. Once replaced the cement/sand mixture was wetted up and compacted



Figure 16. Removal of excess residue sand to produce a vertical wall around lysimeter perimeter



Figure 17. Sump drain pipe constructed from polypipe with connectors for receiving draincoil

(a)



(b)

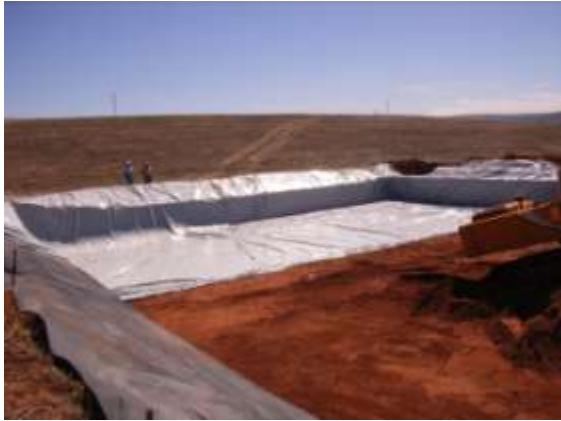


Figure 18. (a) Presence of gravel road base material in perimeter wall and (b) use of HDPE to provide a protective layer for the PVC liner prior to installation

(a)



(b)



(c)



(d)



Figure 19. (a) Preparing liner for installation, (b) about half way through liner installation, (c) liner fully installed, and (d) preparing to remove large creases in PVC liner

(a)



(b)

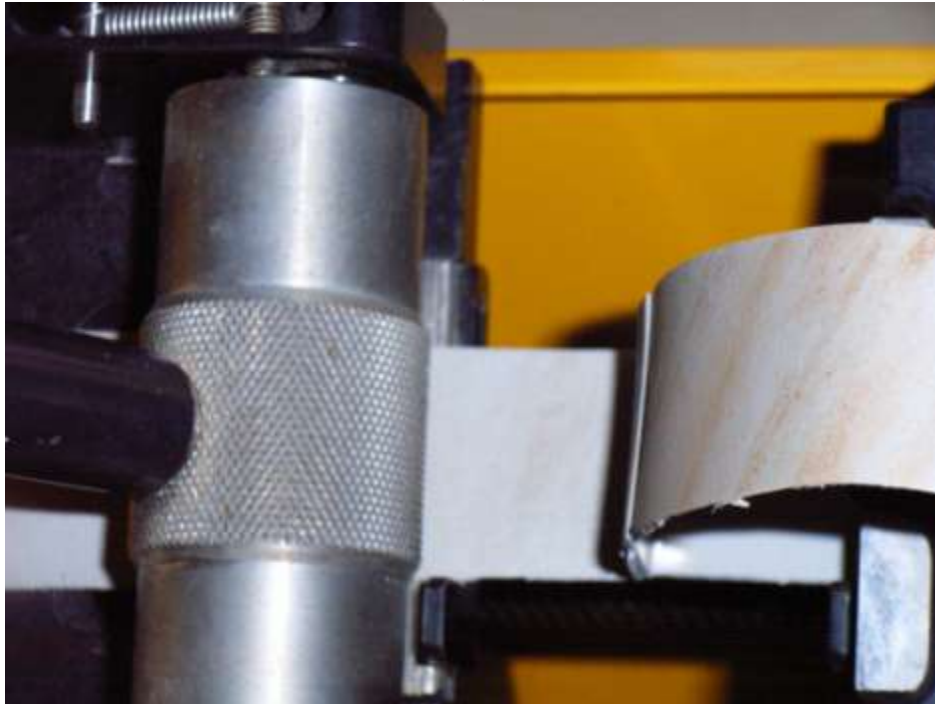


Figure 20. (a) Testing the strength of the PVC liner welds, and (b) obvious peeling of the welds under low shear strength



Figure 21. (a) Making a sleeve in PVC liner to allow sump drain pipe to pass through, (b) placing the sump drain pipe into the floor of the lysimeter along the northern boundary, (c) gluing the PVC sleeve around the sump drain, and (d) successful sealing of PVC liner to ensure no water loss through PVC liner

(a)



(b)



(c)



(d)



Figure 22. (a) Replacing filter sock on draincoil, (b) draincoil attached to sump drain pipe, (c) sealing draincoil to sump drain connector, and (d) installed draincoil at 2.5 m spacings

(a)



(b)



Figure 23. (a) Commencing to fill the lysimeter (1.5 – 3 m depth) with unamended residue sand, and (b) completion of filling the 1.5 – 3 m depth interval with unamended residue sand

(a)



(b)



Figure 24. (a) Inspection standpipe installed into sump drain pipe, and (b) ensuring the standpipe connection is well-sealed

(a)



(b)



(c)



Figure 25. (a) Prior to commencing 2nd lift, the PVC liner and protective HDPE liner were folded flat across the lysimeter surface, (b) an additional layer of HDPE liner was placed across the lysimeter surface to protect the liner, and (c) final protective layer before commencing 2nd 1.5 m lift

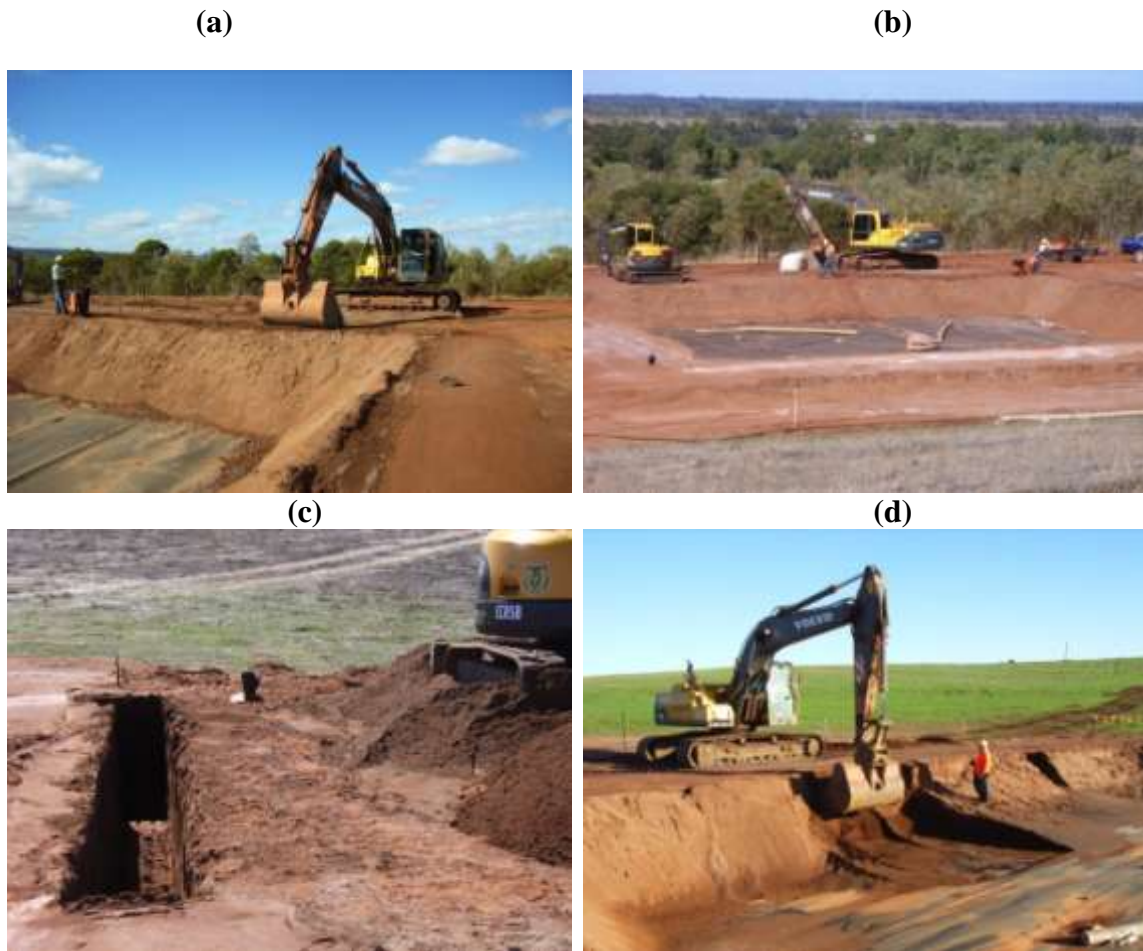


Figure 26. (a) Commencing construction of 2nd lift, (b) each side of the lysimeter has been completed, (c) a trench is cut along the lysimeter perimeter and the excavated sand mixed with cement, replaced and compacted, and (d) after sand/cement mix has hardened, the sand on the internal side of the lysimeter wall is excavated to produce four vertical walls

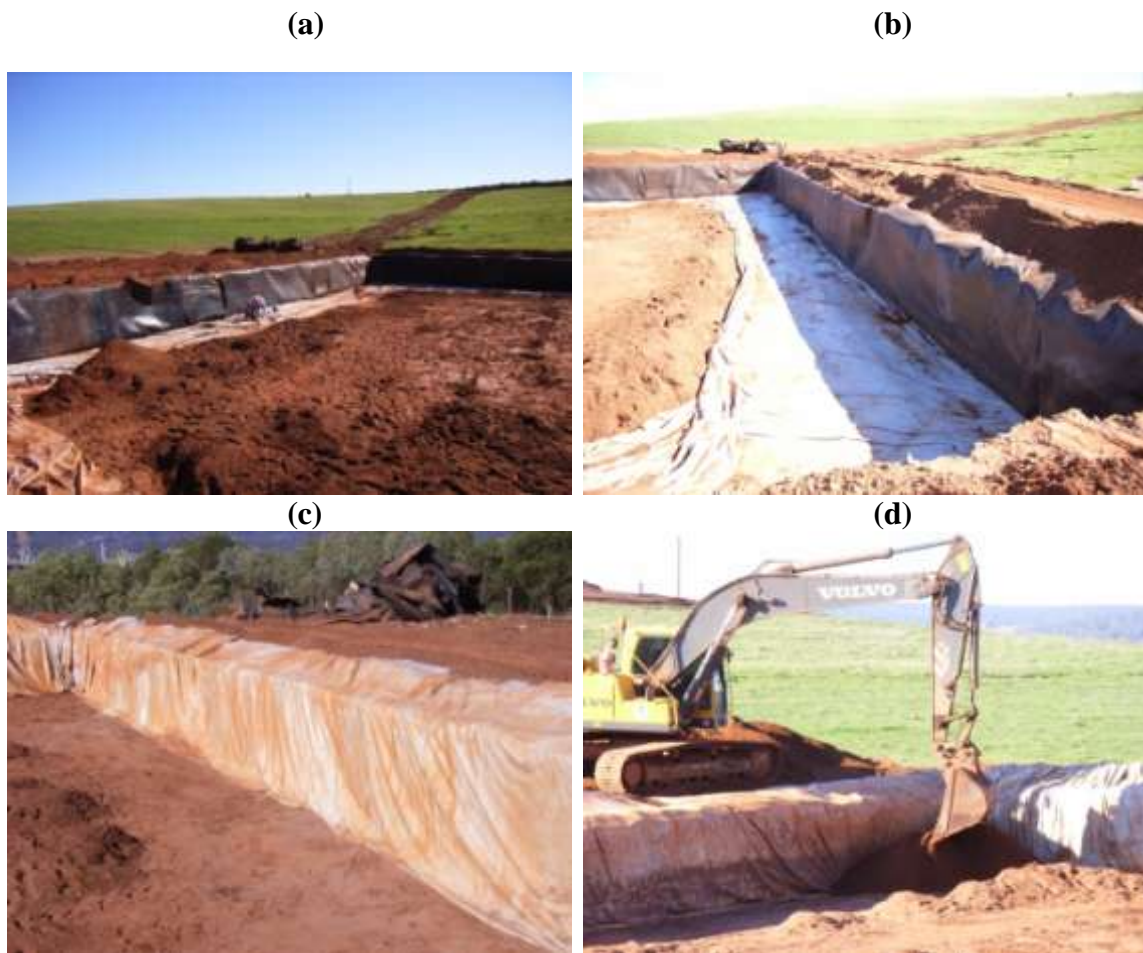


Figure 27. (a) Repairing small tears in PVC liner, (b) installing protective HDPE along walls of lysimeter before pulling PVC liner up, (c) PVC liner pulled up vertical walls and over small bund, and (d) commencing filling of 2nd lift with gypsum-amended residue sand



Figure 28. (a) Mixing gypsum with residue sand by disc harrowing, (b) final product containing 1% gypsum, (c) gypsum-amended residue sand was stockpiled then loaded into haul truck, and transported sand to lysimeter, and (d) final load of gypsum-amended residue sand to lysimeter

(a)



(b)



(c)



Figure 29. (a) Grading the outside area of the lysimeter facility to minimise any run-on water, (b) applying wood mulch to outside area for dust control, and (c) final wood mulch cover outside lysimeter

(a)



(b)



(c)



Figure 30. (a) Before and (b) after surface mulching of the lysimeter facility, and (c) after seeding and planting and construction of fence enclosure

(a)



(b)



(c)



(d)



(e)



(f)



Figure 31. (a) Complete weather station, (b) SL5-1 smart logger and IB14 databus hub in waterproof enclosure (c) TA1 Air temperature sensor and HU1 Relative humidity sensor, (d) Sensor shelter that allows air through flow but not direct sunlight, (e) WD2 Wind direction sensor, SR2 Solar radiation sensor and AN2 Anemometer, and (f) Tipping bucket rain gauge

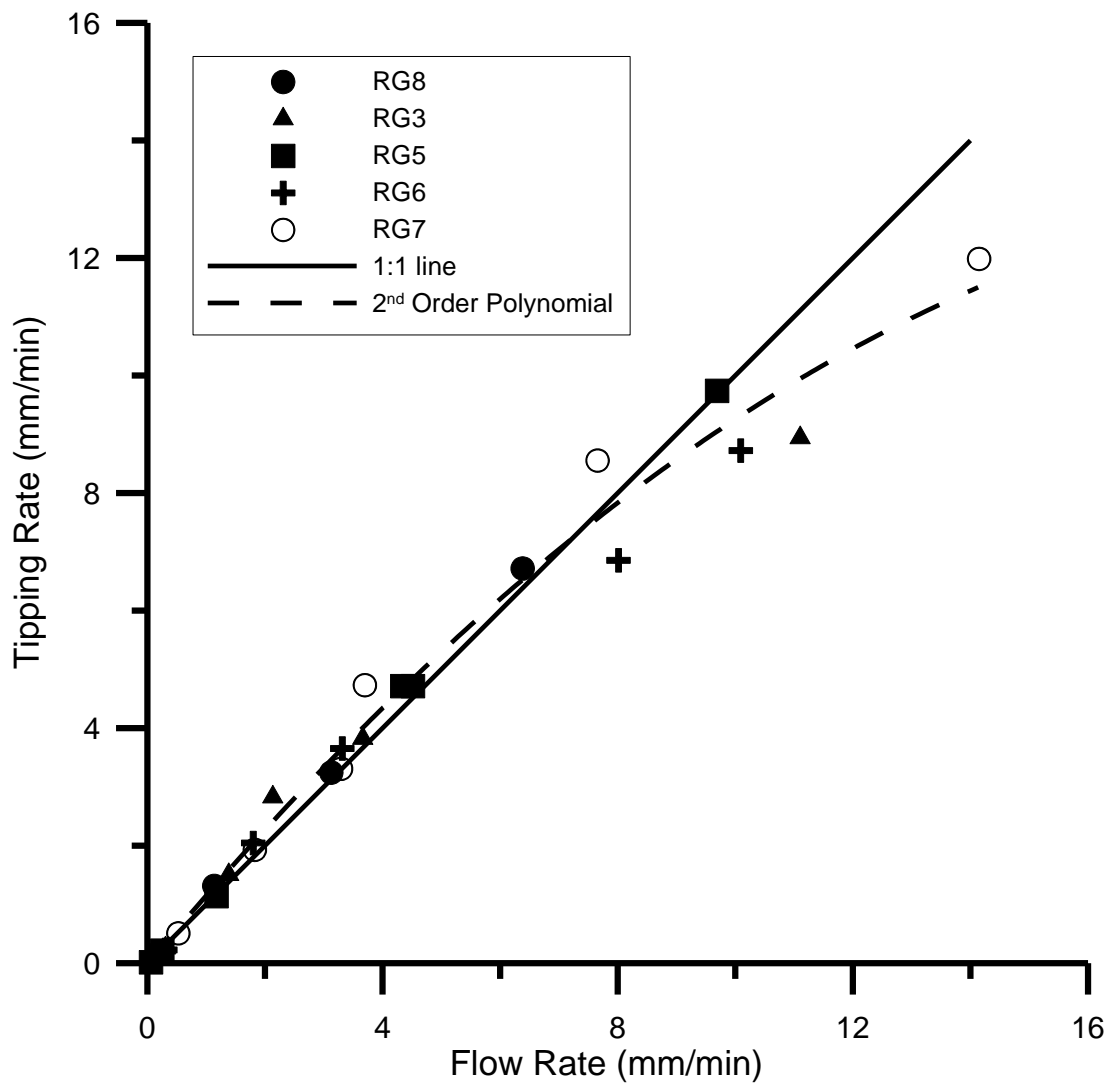


Figure 32. Calibration of tipping bucket rain gauges

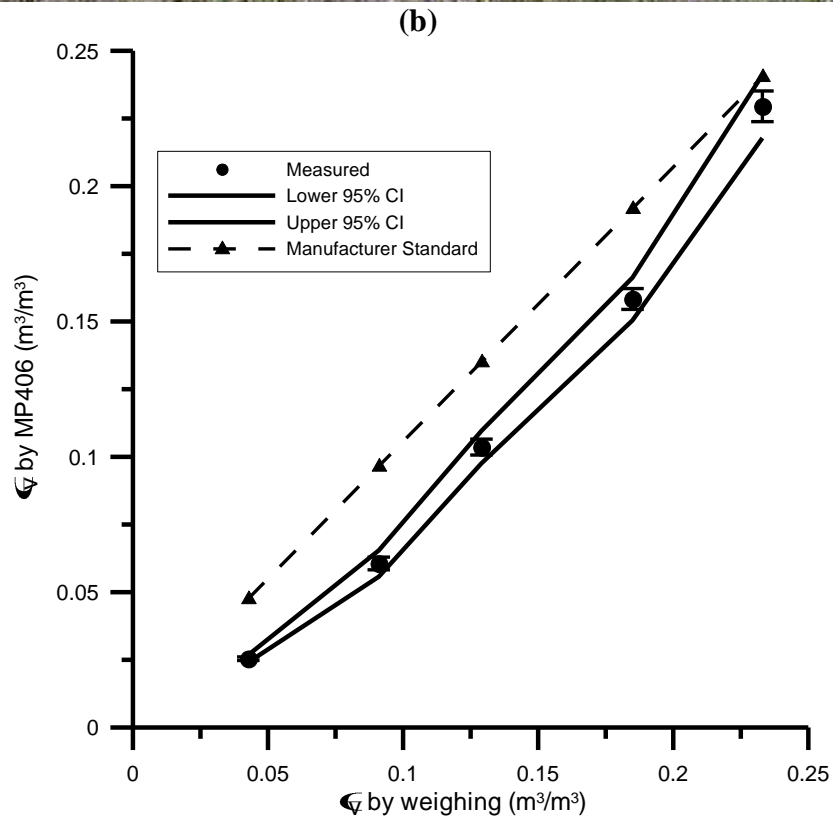
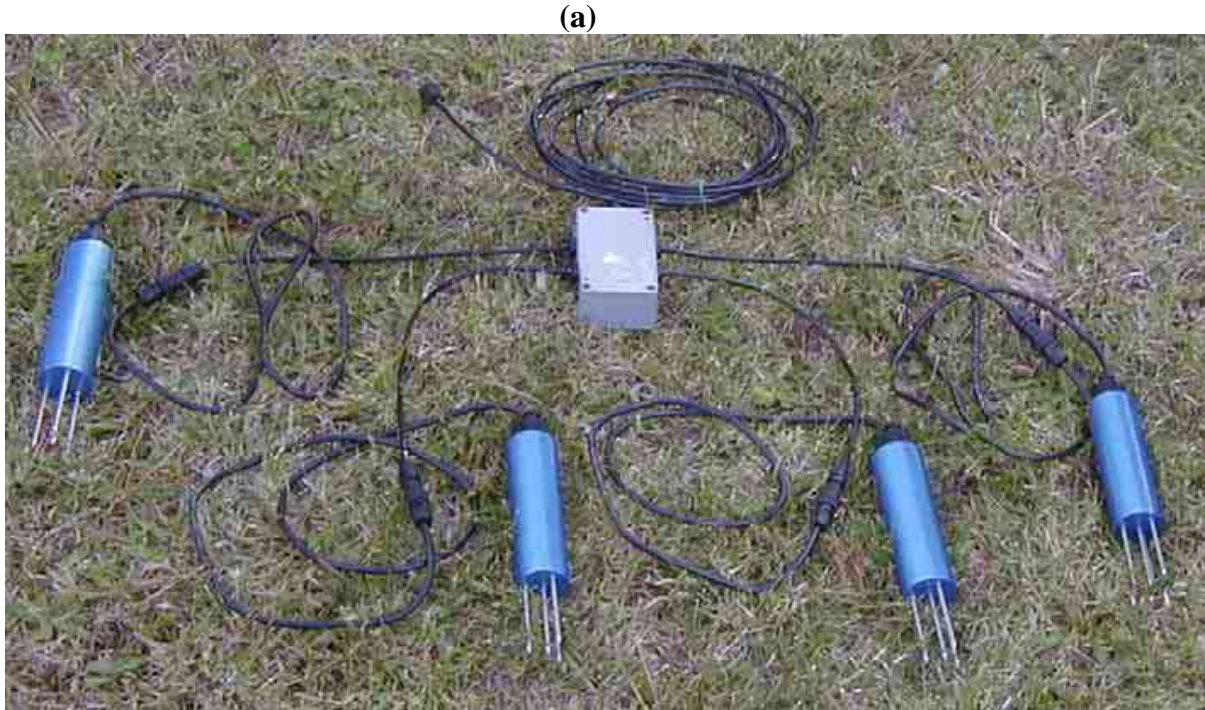


Figure 33. (a) MP406 sensors for measuring moisture content of residue sand, (b) calibration of MP406 sensors against known moisture content (mean \pm 1sd). For measured values ($n = 28$ for each moisture content) linear regression analysis yielded the equation: $MP406 = 1.06785 \times \text{Measured} - 0.029876$ $r^2 = 0.986$

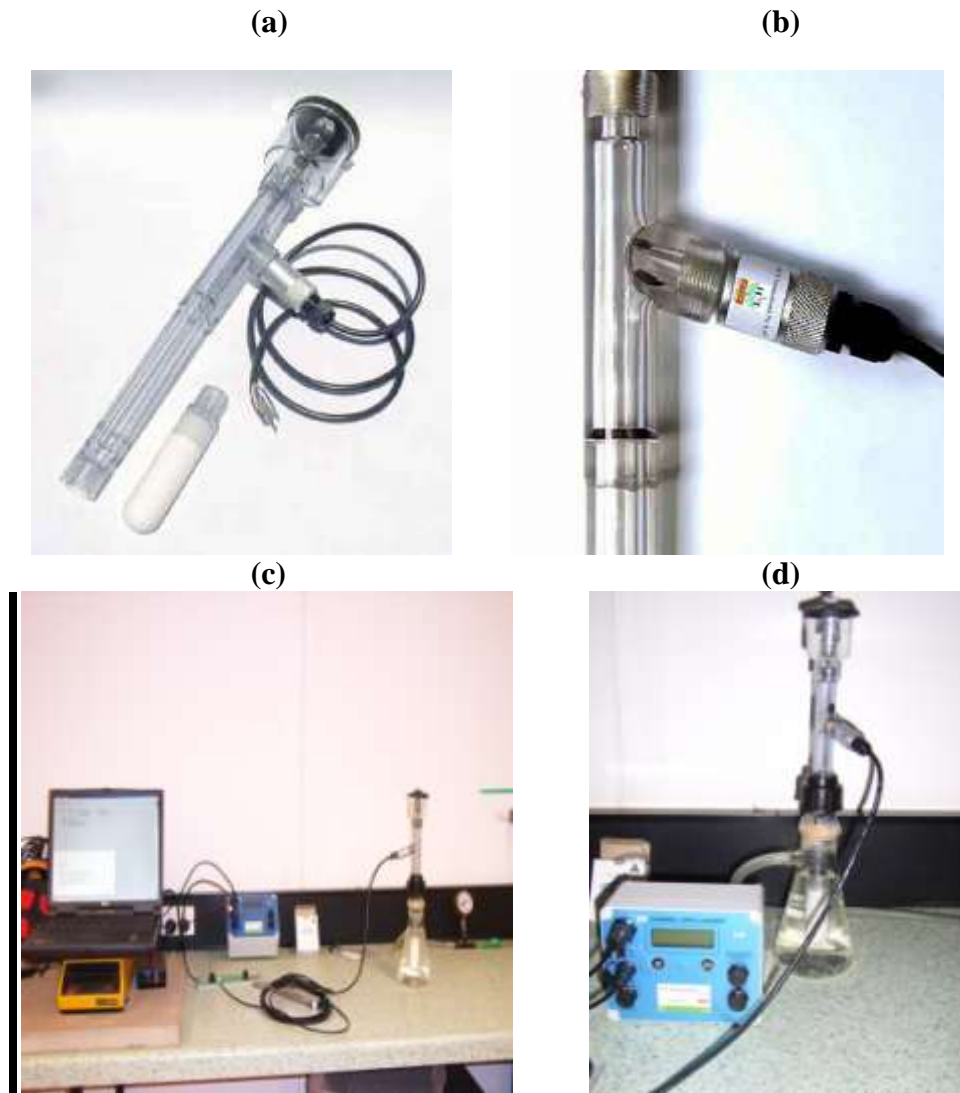


Figure 34. (a) Jet-fill tensiometer, (b) GT3-30 Tensiometer transducer for measuring pore-water tension, and (c) and (d) set-up for calibrating tensiometer transducers

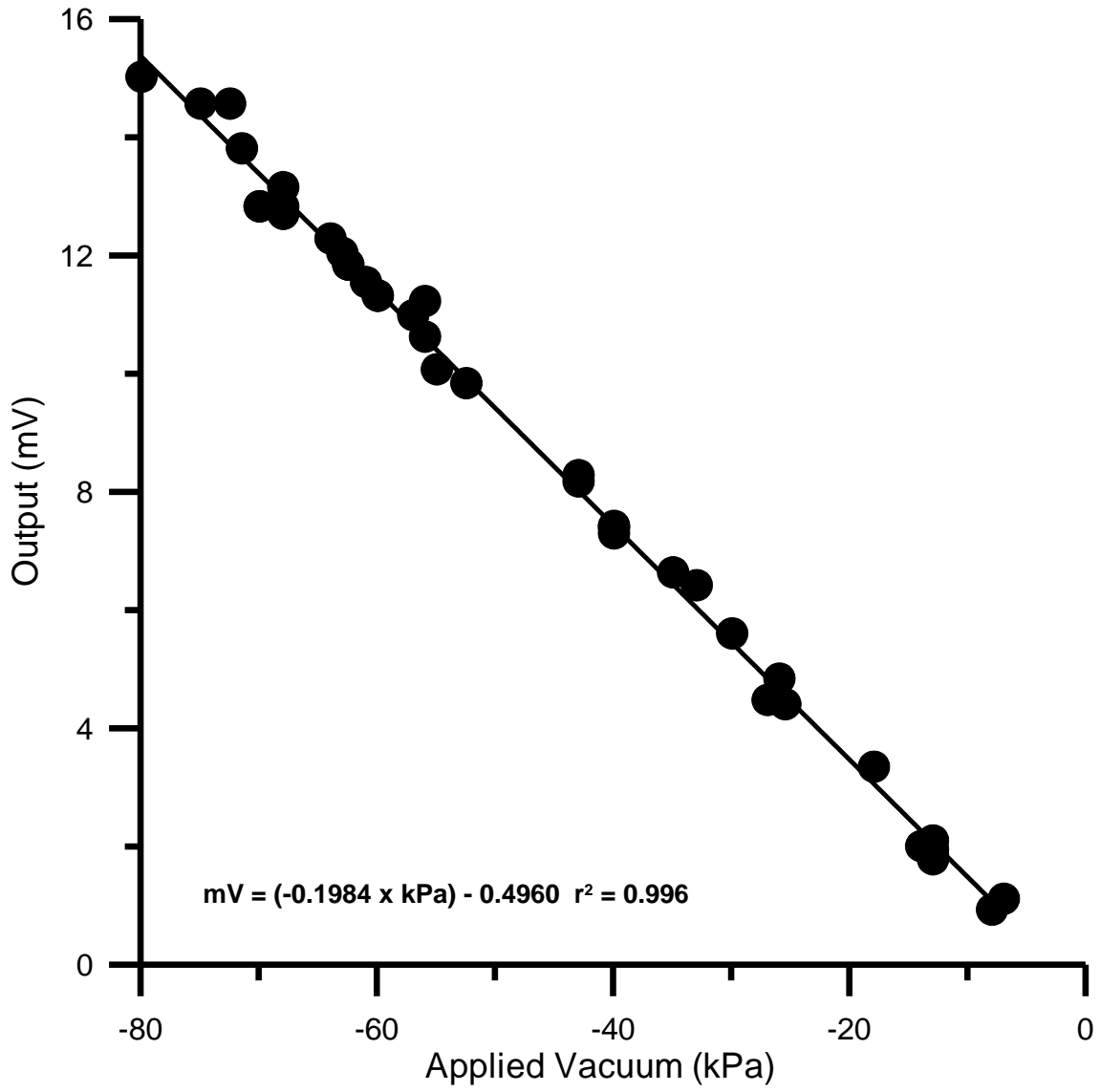


Figure 35. Calibration curve for jet-fill tensiometer transducer

Appendix A

Estimation of Upward Movement of Water by Capillary Flow

Introduction

A laboratory experiment was undertaken to determine the extent of upward movement of water in BRS in response to contrasting water content. The findings of this study will provide information on the extent of upward water movement due to capillary flow in response to decreasing water content in the surface layer due to bare soil evaporation and plant transpiration.

Procedure

The study was undertaken under laboratory conditions using undisturbed cores of BRS collected from the PJ Residue Storage Area.

1. A 1180 mm "undisturbed" core of residue sand (BRS) was collected from RSA4 north (from J Anderson's 3% Carbonated Mud buffer strip) by hammering a PVC tube (50 mm i.d. by 1500 mm long) into the BRS embankment.
2. After removing the core (by manual excavation), the two ends were sealed with PVC end caps and transported to the Huntly environmental laboratory.
3. The end caps were removed and the base re-sealed by wrapping a section of chux cloth around the bottom of the core. This allowed free movement of water into the BRS core and eliminated the loss of BRS out of the core.
4. The PVC tube was placed vertically into a plastic bucket containing a 100 mm depth of 1.5 M hydrochloric acid (HCl). The base of the tube was placed on top of a 25 mm spacer to ensure easy movement of water into the BRS core (i.e. the base was 25 mm above the bottom of the bucket). This produced a watertable about 75 mm into the BRS core. An acid solution with a high electrical conductivity (EC) solution ensured a distinct contrast between the highly alkaline BRS and highly acid HCl solution to be made. Thus the upward movement of water into the BRS core would be accompanied by a change in pH and EC relative to the initial BRS conditions.

5. A loose layer of Gladwrap was placed on top of the PVC tube to maintain exposure of the BRS core to atmospheric conditions.
6. The BRS core was allowed to stand vertically in the 1.5 M HCl solution for 7 days under a relatively constant temperature of $23\pm 3^{\circ}\text{C}$.
7. After 7 days, the core was removed from the HCl solution and segmented in 25 or 50 mm lengths (Note: segments of 25 mm lengths were collected close to ponded water interface).
8. The gravimetric water content (θ_g), pH (1:5 BRS to water) and EC (1:5 BRS to water) were measured on each segment.
9. The effective pore diameter was calculated from the capillary rise data as outlined by Rowell (1994) and Jury et al. (1991). This was done using the following equations:

$$h \approx 3000 \div d \quad (\text{A.1})$$

where d = pore diameter (μm) and h = applied soil-water tension (cm).

$$\text{Capillary Rise (m)} = (2\sigma \cos\gamma) / (\rho g R) \quad (\text{A.2})$$

where σ = surface tension of water = 0.0728 N/m @ 20°C ; γ = water contact angle and assumed to = 0 , so $\cos 0 = 1$; ρ = density of solution and assumed 1000 kg/m^3 ; g = acceleration due to gravity = 9.8 m/s^2 ; R = effective pore radius (m)

Results & Conclusions

Capillary rise was observed to a height of 85 mm (i.e. 0.085 m) above the watertable surface (Eqn A.2). This is consistent with pH, EC and θ_g distributions measured after a 7-day reaction period (Fig. A.1). This resulted in the BRS having an effective pore diameter of 0.35 mm (Rowell 1994). Using Eqn A.1, then these pores are expected to drain at applied soil-water tensions (h) of 9 cm (or a $\text{pF} = 0.95$). This information is consistent with the very low water retention properties of BRS, and represents a loss of 15% of the volumetric water content (θ_v) at saturated water content ($\theta_s = 0.48 \text{ m}^3/\text{m}^3$) to $\theta_v = 0.40 \text{ m}^3/\text{m}^3$ at $h = 9 \text{ cm}$ (Eqn A.1). Transmission pores have an effective diameter $> 50 \mu\text{m}$, and are responsible for much of water flow in soils (Rowell 1994). Since the effective

diameter of BRS was found to be 0.315 mm (or 315 μm), then BRS would be expected to display a high hydraulic conductivity near saturated water contents, which would decrease dramatically with decreasing water content. This behaviour is in fact observed in the field.

Based on these findings, it is concluded that upward movement of water via capillary flow is negligible in BRS, and that water moving below the plant root zone would not move back to the surface of BRS profiles in response to decreasing θ_v due to bare soil evaporation and transpiration. Field monitoring demonstrates that $\theta_v = \theta_s$ rarely occurs and that the high K_s of 20 m/d would not allow this condition to be maintained if it did occur. Since this study involved maintaining a watertable in the BRS profile for a period of 7 days, then the opportunity for sustained upward water flow must also be considered negligible.

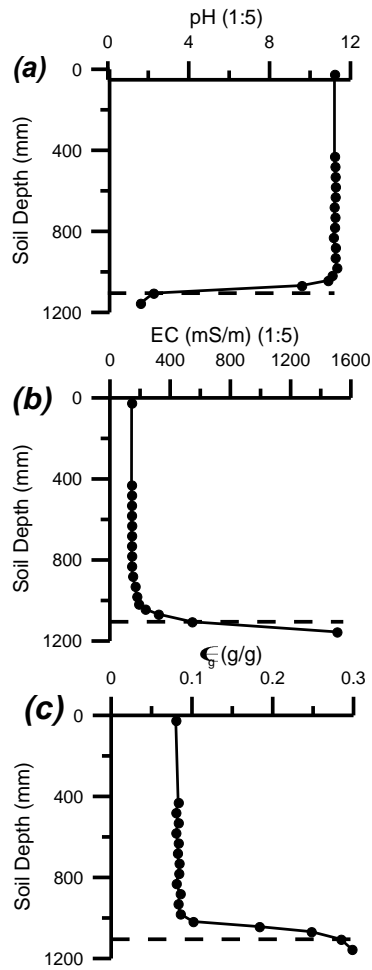


Figure A.1. Capillary rise as indicated by pH, EC and θ_g profiles in a "undisturbed" core of residue sand. Symbols refer to measured data and dashed line refers to position of watertable surface in core

Appendix B

Calculation For Amounts of Gypsum and Fertiliser to Apply to Lysimeter

B.1 Gypsum

Rate of addition (% w/w) =	1
Pad area (25 x 25 m ²) =	625
Lysimeter volume (m ³) =	1875
Volume of unamended sand (m ³) =	937.5
Volume of gypsum-amended sand (m ³) =	937.5
Bulk density of sand (t/m ³) =	1.54
Mass of sand per 1.5 m depth (tons) =	1443.8
Mass of gypsum per 1.5 m depth (tons) =	14.4
Number of lifts =	5.0
Mass of gypsum per 0.3 m lift (tons) =	2.9

1. Prepare a pad of fresh, unamended BRS at a suitable location to allow for a minimum workable area of 25m by 25 m.
2. Source gypsum from most recent stockpile, and remove the surface crust (approx. 10 cm) to obtain clean, white material.
3. Crush the gypsum prior to incorporation into BRS to remove as much as possible the large lumps and to obtain material as fine as possible.
4. Place a minimum depth of 0.3 m of fresh, unamended BRS across the 25 by 25 m pad. Ensure that this BRS does not contain any bitumen, mulch or other contaminants that may have been added for dust control.
5. Evenly spread 2.9 t of gypsum across the surface of the (0.3 m) BRS layer and incorporate into the sand using a rotary hoe.
6. As soon as possible after mixing, transport gypsum-amended sand to lysimeter.
7. Repeat this process another 4 times to achieve a total depth of gypsum-amended sand in the lysimeter of 1.5 m.

B.2 DAP Fertiliser

Rate of addition (t/ha) =	2.71
Lysimeter volume (m ³) =	1875
Volume of unfertilised sand (m ³) =	1687.5
Volume of fertiliser-amended sand (m ³) =	187.5
Bulk density of sand (t/m ³) =	1.54
Mass of sand per 0.3 m depth (tons) =	288.8
Area of application (m ²) =	625.0
Fertiliser required per lysimeter area (kg) =	169.4

Procedure

1. Spread the fertiliser across the lysimeter surface area as evenly as possible.
2. Incorporate fertiliser into residue sand to depth of 0.3 m using a rotary hoe (manually-driven).
3. Cover with woodmulch as soon as possible after incorporation.

Appendix C

Composition of Di-ammonium Phosphate Fertiliser and Fertiliser Tablet

B.1 DAP Fertiliser

Fertiliser specification	%	Rate (kg/ha)	Active element (kg/ha)	P kg/ha	N kg/ha
DAP	54.1	1500.00		300	265
K ₂ SO ₄ (granulated)	30.4	843.37	350.00		
CuSO ₄	1.7	48.00	12.00		
ZnSO ₄ (granulated)	1.6	45.71	16.00		
MnSO ₄ (granulated)	1.7	46.88	15.00		
NaMo	0.0	0.66	0.25		
MgSO ₄	9.6	266.67	40.00		
Boron (granulated)	0.7	20.00	2.00		

B.2 Tablet

Chemical Composition	Specification
Total Nitrogen (N)	14.4%
Total Phosphorous (P)	16.0%
Total Potassium (K)	6.3%
Sulphur (S)	1.1%
Calcium (Ca)	0.01%
Chloride (Cl)	5.7%
Iron (Fe)	0.01%
Manganese (Mn)	1.3%
Copper (Cu)	0.64%
Zinc (Zn)	0.34%
<u>Physical Test</u>	
Drop Test	Conforms

Appendix D

Species List Applied in Seed Mix and as Tubestock to Lysimeter

B.1 Seed Mix Species

- *Acacia cochlearis*
- *Acacia cyclops*
- *Acacia huegleii*
- *Acacia lasiocarpa*
- *Acacia pulchella*
- *Acacia rostellifera*
- *Acacia saligna*
- *Acacia truncate*
- *Acacia huegelii*
- *Acacia xanthina*
- *Acacia cochlearis*
- *Agonis flexuosa*
- *Allocasuarina fraseriana*
- *Allocasuarina humilis*
- *Brachyscome iberidifolia*
- *Callitris preissii*
- *Calothamnus quadrifidus*
- *Calothamnus villosus*
- *Carpobrotus virescens*
- *Clematis microphylla*
- *Conostylis aculeate*
- *Conostylis candicans*
- *Daviesia divaricata*
- *Daviesia nudiflora*
- *Dianella revolute*
- *Dodonaea aptera*
- *Dodonaea hackettiana*

- *Dryandra lindleyana*
- *Dryandra sessilis*
- *Eucalyptus decipiens*
- *Eucalyptus gomphocephala*
- *Gompholobium tomentosum*
- *Hakea lissocarpha*
- *Hakea prostrate*
- *Hardenbergia comptoniana*
- *Hovea pungens*
- *Isolepis nodosa*
- *Jacksonia furcellata*
- *Jacksonia sternbergia*
- *Kennedia prostrate*
- *Lepidosperma gladiatum*
- *Macrozamia riedlei*
- *Melaleuca acerosa*
- *Melaleuca huegelii*
- *Melaleuca incana*
- *Melaleuca lanceolata*
- *Melaleuca nesophylla*
- *Melaleuca viminea*
- *Nuytsia floribunda*
- *Olearia axillaris*
- *Olearia rudis*
- *Oxylobium capitatum*
- *Petrophile linearis*
- *Petrophile serruriae*
- *Phyllanthus calycinus*
- *Podotrochea gnaphalioides*
- *Rhagodia baccata*

- *Santalum accuminatum*
- *Scaevola crassifolia*
- *Sollya heterophylla*
- *Spyridium globulosum*
- *Templetonia retusa*
- *Trachymene coerulea*
- *Trymalium ledifolium*
- *Viminaria juncea*
- *Xanthorrhoea preissii*

B.2 Tubestock Species

- *Agonis flexuosa*
- *Callitris preissii*
- *Calocephalus brownie*
- *Conostylis candicans*
- *Daviesia divaricata*
- *Dianella revolute*
- *Diplolaena dampiera*
- *Dryandra sessilis*
- *Eremophila glabra*
- *Eucalyptus decipiens*
- *Eucalyptus foecunda*
- *Gompholobium tomentosum*
- *Grevillea crithmifolia*
- *Grevillea thelmanniana*
- *Guichenotia ledifolia*
- *Hakea lissocapra*
- *Hakea trifurcate*
- *Hardenbergia comptoniana*

- *Hemiandra pungens*
- *Hibbertia cuneata*
- *Hibbertia cuneiformis*
- *Hibbertia cuneiformis*
- *Hibbertia racemosa*
- *Jacksonia furcellata*
- *Jacksonia sternbergiana*
- *Lepidosperma gladiatum*
- *Leucophyta brownii*
- *Melaleuca heugellii*
- *Melaleuca lanceolata*
- *Myoporum insulare*
- *Olearia axillaris*
- *Scaevola crassifolia*
- *Sollya heterophylla*
- *Thomasia triphylla*

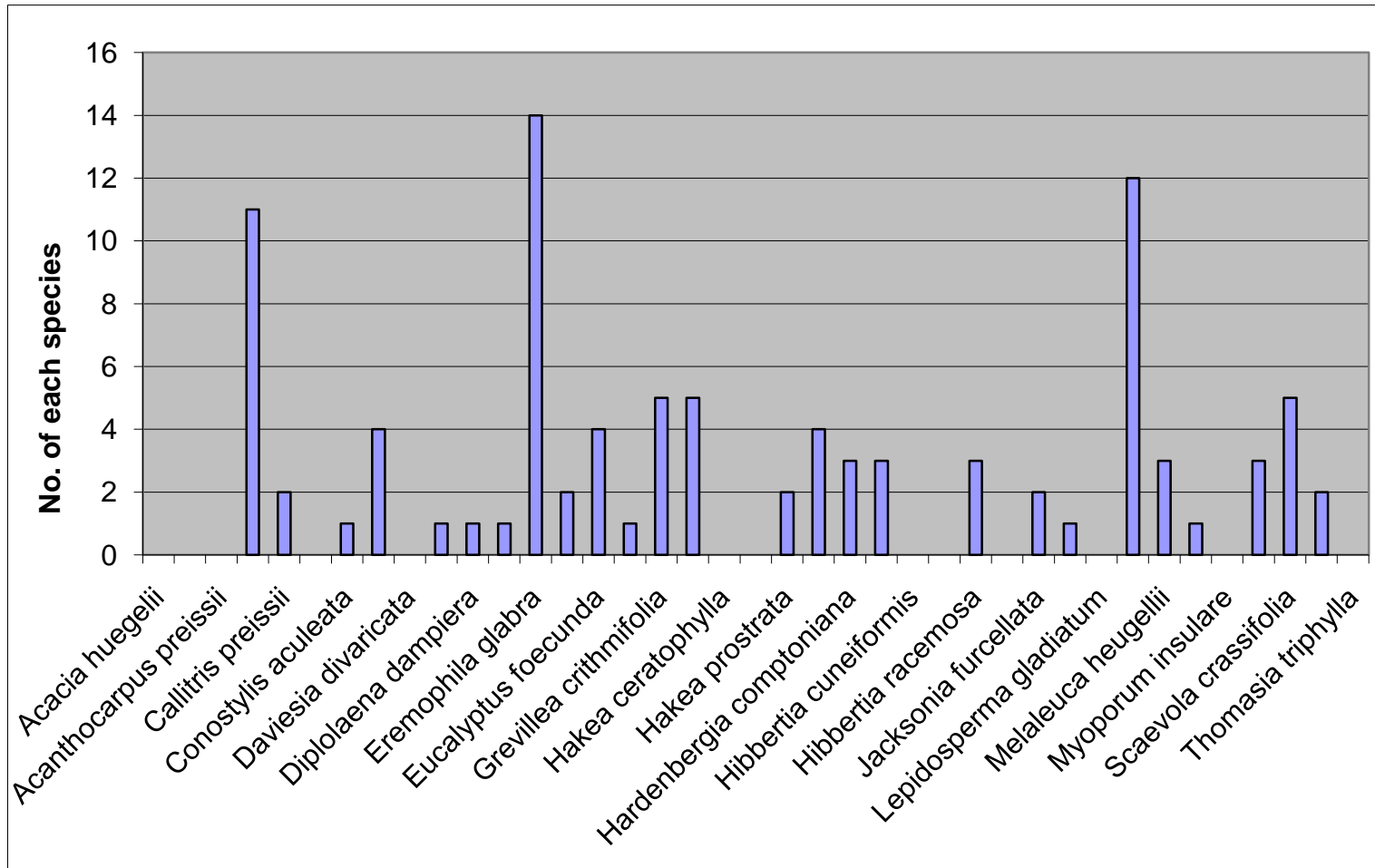


Figure D.1. Tubestock species identified within 4 weeks of planting