Water Balance and the Influence of Temporal Factors on Final Covers for Landfill Closure

Melissa Salt
Bachelor of Science in Agriculture (Hons)

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School of Civil, Environmental and Mining Engineering
The University of Adelaide

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Abstract

Final covers for landfill have consisted of engineered barriers to prevent contact with the underlying waste, limit the generation of leachate and emission of landfill gas. The theory for cover design has predominantly relied on attempting to prevent moisture from draining into the waste by placing an impermeable or low conductivity barrier, often as compacted clay or more recently as geotextile or geocomposite layers (GCL). However, studies overseas over the last 10 – 15 years have shown that these barrier layers, particularly compacted clay barriers, may not perform as expected. Increasingly, interest has been focussed on designing covers that maximise evapotranspiration as this release to the atmosphere does not have other detrimental implications.

In 2006, the Waste Management Association of Australia and the Australian Research Council co-funded collaborative research between 5 Australian Universities to research the performance of compacted clay barriers and the emerging technology of phytocaps (also known as ET (evapotranspiration), alternate or store-and-release covers). This PhD is part of this collaborative research and aimed to: quantify drainage from phytocaps and conventional caps; compare water balance performance of conventional caps, including a compacted clay barrier, and phytocaps under a range of climatic, soil and vegetation conditions; and assess the temporal changes in the covers.

The trial methodology was based on field-scale lysimetry with phytocaps trialled in 5 Australian States. All test sections were constructed on previously landfilled cells and included a 10 m x 20 m lysimeter instrumented to measure weather, runoff, lateral flow (compacted clay sections only), drainage and soil moisture content. An adjacent control section without a liner to bound the area was also instrumented to provide an assessment of the impact of the lysimeter liner on the water balance. At 3 trial sites, the research included side-by-side comparison of a conventional compacted clay barrier cap and a phytocap. Data collection at the sites has been undertaken for 3 – 4 years.

The climate at the trial sites varies from summer-dominant rainfall in a tropical climate to sub-tropical and temperate climates with all-year rainfall and to temperate climates with hot, dry summers. The soil varied from alluvial loam and basaltic-derived clayey loam to coarse loamy sand. At one site, municipal waste compost was added to the available sandy loam. The vegetation has also varied between the sites from dominantly tree-based vegetation to only native grasses.

The research has found that phytocaps have the potential to reduce drainage to the same extent as conventional caps. Also, the short term data collected indicate that phytocaps are likely to be more sustainable in the longer term as the changes in the soil moisture content range over the trial timeframe tended to be beneficial in the phytocap, with increased soil storage as the plant roots developed, and detrimental in the conventional cap, with cracking and preferential flow paths developed in the compacted clay barrier. The phytocap also has greater potential for its performance to be easily improved (e.g. increasing plant density, changing plant species, adding soil ameliorants) when compared with compacted clay barriers. The drainage measured in both the phytocap and conventional caps was strongly influenced by the seasonal precipitation and the seasonality of precipitation. Long-term research is needed to confirm the findings herein and provide a better understanding of the impact of structural changes in the phytocap and improve the prediction of phytocaps in a wider range of Australian climates.

Declaration

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“Only a person who risks is truly free”

1. Introduction

1.1 Background

Final cover of landfills or waste disposal depots comprises a barrier designed to minimise the potential for human contact and environmental impact of the underlying waste. The physical presence of soil layers provides a barrier to contact with the waste by humans and disease vectors and other nuisances. The cover needs to be designed to limit emission of greenhouse gases and odour to the atmosphere and generation of leachate, i.e. water that has come into contact with the waste and is potentially contaminated with nutrients, salts, metals, etc. (SA EPA, 2007). An aesthetic requirement of the final cover is to enable other end uses of the site at the point of closure and into the future.

Guidelines for final cover of landfills have been developed in each state of Australia by the relevant state authority, i.e. the state department for environmental issues. A summary of the guideline requirements for final cover of landfills as at the commencement of this project (i.e. 2007) is shown in Table 1.1. It should be noted that the Queensland Department of Environment and Resource Management and the Victorian Environment Protection Authority have updated their guidelines since this project commenced.

The final cover designs all use compacted clay barriers to minimise drainage from the cover into the waste and generating excess leachate and prevent gas escaping to the atmosphere. The inherent assumption is that the clay barrier remains "as placed" and does not crack, deform or shear due to wetting and drying or differential landfill settlement. Vic EPA (2001) notes that the landfill surface may settle by 10 – 30% depending on the type of waste buried, suggesting that for landfills greater than 5 metres depth, differential settlement could result in discontinuity of the compacted clay barrier.

The various states' guidelines are defined in terms of qualitative objectives with suggested capping methodologies which may meet these objectives. Vic EPA (2001) and WA DEC (2006) also define quantitative cap performance objectives of ≤ 75% of the expected seepage through the liner, which equates to drainage ≤ 7.5 L/ha/day or approximately 2.7 mm/yr. However, there is no proof that the recommended capping methodology meets the required cap performance in the longer term. Each states' guideline document allows for alternative covers and measures to be used where they can be shown to meet the objectives stated in the guidelines.

Table 1.1 Recommended Final Cover Designs for Various Australian States as at 2007

Material or Layer	Aspect	Guideline requirement for final cover materials in different Australian states [a]			
		NSW	Qld	SA	Vic & WA
Topsoil	Thickness (mm)	1,000 (including subsoil)	150	100	1,000 (including subsoil)
	Other	Topsoil thickness not specified only total plant growing medium	Should reflect the type and depth of topsoil normally found in the local area and is able to support adequate vegetation	Silty sand, sandy silt, clayey sand or sandy clay with organic matter (either naturally occurring, mulch or compost)	May include mulch. Should reflect the type and depth of topsoil normally found in the local area and is able to support adequate vegetation
Subsoil	Thickness (mm)	1,000 (including topsoil)	200 – 300	800	1,000 (including topsoil)
	Other	Subsoil thickness not specified only total	Sufficient thickness to ensure roots do not penetrate cap		Sufficient thickness to ensure roots do not penetrate cap
Drainage Layer		300 mm of K > 1×10^{-5} m/s	No details	Only if required	Optional – 300 mm surrounded by geotextile and with geomembrane base
Clay Barrier	Thickness (mm)	500	500	600	> 600
	Permeability (m/s)	1×10^{-8}	1×10^{-8}	1×10^{-9}	To limit seepage to < 75% anticipated seepage through liner
	Other			Min 3 layers of 200 mm compacted thickness each. Compacted by padfoot roller	
Other Layers		300 mm gas drainage layer <10% $CaCO_3$	200 – 300 interim cover over waste	300 mm interim cover over waste	Gas collection layer over 300 mm interim cover over waste

[a] Guideline references are NSW EPA (1996), Qld EPA (2001), Vic EPA (2001), WA DEC (2006), SA EPA (2007)

Final covers minimise drainage (also termed seepage and percolation) by altering the natural water balance (as shown in Equation 1.1) through diversion, storage and/or utilisation of the rainfall that infiltrates into the soil to prevent percolation or drainage. Studies of natural systems in Australia have suggested that the proportion of rainfall lost in the long term as evapotranspiration (ET) is 78 – 89%, drainage 10 – 17%, runoff 1 – 4% and change in soil moisture as 0 – 2% (Rab *et al.*, 2002). Interception is sometimes included in ET as the moisture intercepted and not becoming throughflow is usually evaporated.

$$P = I + ET + R + L + D + \Delta S \quad \text{.......... Equation 1.1}$$

where:

P – precipitation, including rain, snow, irrigation, etc.
I – interception
ET – actual evapotranspiration
R – runoff
L – lateral flow
D – drainage
ΔS – change in soil moisture content

Conventional clay barrier covers, as defined in Table 1.1, rely on increased runoff and lateral flow on the surface of the clay barrier. However, as noted by Rab *et al.* (2002) evapotranspiration is the largest loss in the water balance equation with runoff and lateral flow a much smaller component. As a result, slight increases in ET from careful plant selection can result in a major reduction in drainage. Also, on a short-term basis the soil moisture storage in a 1 metre profile can be over 200 mm and hence increases in soil moisture storage can also result in significant decreases in drainage. Final covers that rely on increasing ET and ΔS are known as phytocaps, phytocovers, ET covers, store-and-release covers and alternative covers, as well as many other names. The term used herein is phytocap.

Research into phytocaps is important for the waste industry to provide alternative, and perhaps more sustainable and economical, options for the final cover of a finished landfill area with greater resource efficiency. These alternative options have been shown overseas to be as protective of human health as conventional covers and the Interstate Technology and Regulatory Council (ITRC, 2003) has identified the advantages of alternatives over conventional covers as: use of readily available construction materials; ease of construction; less complex quality assurance and quality control; greater cost effectiveness; and increased long-term sustainability with decreased maintenance.

Overseas researchers have investigated the use of phytocaps. In the US, the Alternative Cover Assessment Program (ACAP), established in 1998 by the US Environmental Protection Agency, compared their conventional covers, known as prescriptive covers, with alternative covers (Albright and Benson, 2002). Albright *et al.* (2004) reported results from the 12 ACAP sites, which showed that phytocaps can achieve at least equivalent performance to conventional covers, especially those utilising compacted clay, and are most suited to arid, semi-arid and sub-humid climatic regimes. They concluded that greater care in designing phytocaps is required in humid areas to minimise drainage, as at two ACAP sites the drainage was higher in alternative covers than the conventional covers. However, the phytocap in one humid site was reported to have performed better than the compacted clay cover, showing that equivalence is possible in humid regions where the impermeable clay barrier becomes cracked allowing preferential flow of water through the barrier (Albright *et al.*, 2006).

Other investigations into the potential performance of a compacted clay barrier were undertaken by Albrecht and Benson (2001). Their laboratory trials testing the affect of successive wetting and drying cycles on compacted clay found that the magnitude of the changes recorded was related to the soil properties and compaction conditions. For samples with higher plasticity index and clay content, increased volumetric shrinkage was recorded compared to less plastic and clayey samples. For samples which recorded shrinkage strain, the hydraulic conductivity was reported to increase by up to 3 orders of magnitude. Extended hydration of cracked samples did not result in return to original compacted hydraulic conductivity measurements.

Not reported in the field or laboratory trials are the potential changes in the phytocap which should occur due to root penetration and faunal activity, particularly meso-fauna such as earthworms and insects. Soil structural development in anthropogenic soil, such as a final landfill cover, is aided by plant and faunal activity as well as chemical changes, particularly the decomposition of organic matter which helps to bind the soil particles into discrete structural units, known as peds. The timeframe for the development of structure has been well studied for highly compacted areas, such as high traffic areas created during forest felling and cultivation in agriculture, but is not well recorded for anthropogenic soil used for landfill covers.

Overseas research has been undertaken in less variable climatic conditions and with less weathered soil than is found in Australia and hence the results of overseas trials may not be valid in the Australian context. In addition, many trials have noted altered drainage patterns over time with few correlating this to the soil hydraulic properties changing over time. Most studies have focussed on the hydraulic changes in the compacted clay barrier and have not investigated changes in the phytocap soil materials.

1.2 Australian Alternative Cover Assessment Program (A-ACAP)

In 2006, the Australian Research Council sponsored the Australian Alternative Cover Assessment Program (A-ACAP), a collaborative research programme between University of Melbourne, Waste Management Association of Australia (WMAA), Griffith University, Central Queensland University, Murdoch University, University of Adelaide, CSIRO Division of Land and Water and University of Western Australia. The aim of A-ACAP was to determine whether phytocaps can meet performance criteria for landfills more cost effectively and sustainably than conventional covers (A-ACAP, 2007). The performance criteria nominated were reduction of leachate generated and atmospheric emission of methane and other greenhouse gases.

This PhD research is part of the A-ACAP and focuses on the water balance issues related to final covers. Two other projects are being undertaken concurrently which focus on plant species performance and gas generation. Results from all 3 projects have been used by WMAA to establish guidelines for industry and regulatory agencies for the design, installation and monitoring of alternative covers (WMAA, 2011).

1.3 Research Aims

The aims of this PhD research project are to:

1. Quantify the drainage through phytocaps and conventional covers in a range of Australian climatic conditions using field scale trials;
2. Compare the performance, in terms of drainage, of the phytocap and conventional covers;
3. Determine if changes in the water balance, with particular reference to drainage, may be attributed to temporal changes in soil properties, e.g. changes in maximum or minimum profile moisture content or soil hydraulic conductivity over time.

1.4 Layout of Thesis

This introduction to the thesis has provided a brief background to this research project's inception. Context to the research is provided by discussion and review of the available literature, as presented in Chapter 2. As a predominantly field-based research project, the general methodology used at all the field sites is presented in Chapter 3 with specific design and construction details for each trial site discussed in Chapter 4. The trial sites were monitored for between 3 and 4 years and the water balance data collected from each of the instrumented field sites are presented and interpreted in Chapter 5, which also includes a summary of the data quality. The field data from one trial site were used in Chapter 6, to assess the accuracy of the design modelling, described in Chapter 3, and to calibrate the selected water balance model. Laboratory and small plot trials were undertaken to investigate temporal changes in a more controlled environment, with results presented in Chapter 7. Finally, Chapter 8 provides a summary of the major findings and conclusions from the research on the potential for phytocaps to outperform conventional compacted clay barrier and provides suggestions for further research.

2. Review of Literature

A review of literature on the soil water balance, landfill final covers and water balance modelling software suitable for use in landfills has been undertaken to explore the current knowledge relating to phytocaps and conventional covers for landfill sites. This exploration has aided the identification of gaps in the knowledge and focussed the aims and objectives of this research.

2.1 Soil Water Balance

For the purposes of this research and in consideration of the monitoring to be undertaken, the soil water balance equation used is a simplification of Equation 1.1. Interception has been removed as a separate term as intercepted precipitation is stored in the plant canopy where it is then evaporated from the leaf surface. Precipitation which has been intercepted can also be transmitted to the soil and roots down the stem or off the leaf surfaces. The simplified equation is thus:

$$P = ET + R + L + D + \Delta S$$ ....Equation 2.1

where,

P precipitation and includes any irrigation, if applied
ET evapotranspiration from the soil and plants and includes interception by default
R surface runoff
L lateral flow
D drainage through the cover that may become leachate. Drainage is used in preference to percolation or seepage to prevent confusion with abbreviations
S soil moisture storage as calculated for the entire final cover

A schematic of the soil water balance is shown in Figure 2.1.

The soil water balance has been variously described by several researchers, with each author including or excluding various terms relevant to their research. The basic equation is the balance between precipitation input and the losses due to evapotranspiration, runoff, drainage and change in soil moisture storage. Inputs can also include irrigation, while other losses can include interception by plants and lateral flow.

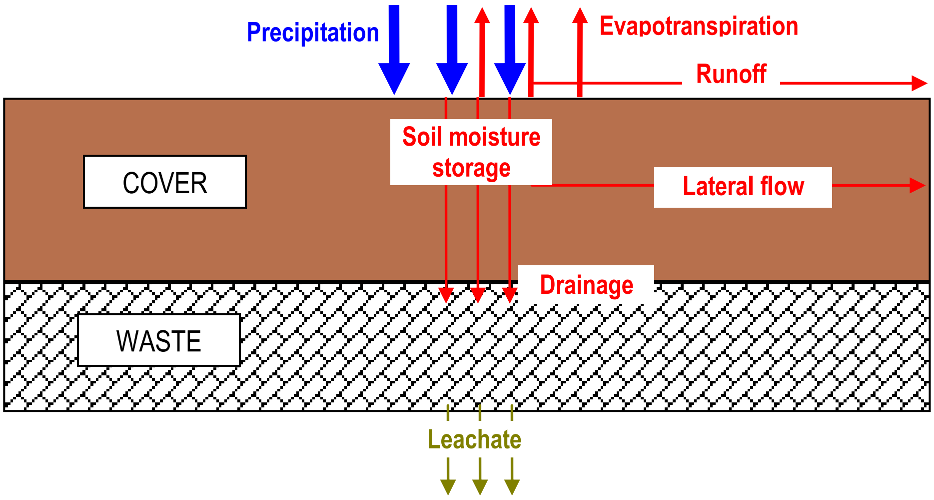

Figure 2.1 Schematic of Water Balance Flows, showing inputs (blue) and losses (red)

2.1.1 Precipitation

Raupach *et al.* (2001) note that Australia receives less water than the global average, i.e. Australia receives 465 mm compared to the global average annual rainfall of 777 mm. They also note that Australia's annual rainfall is highly variable by global standards and is linked with changing currents and water temperatures in the Pacific, Indian and Southern oceans. Daily rainfall for 5 sites proposed to be used in this project at Henderson (WA), Lismore (NSW), Lyndhurst (VIC), McLaren Vale (SA) and Townsville (Qld) were obtained from the Bureau of Meteorology's SILO database (2006). The rainfall varies markedly from year to year (Table 2.1). Townsville has the greatest variation from a minimum of 379 mm to a maximum of 2419 mm, while the southern sites (Lyndhurst, Henderson and McLaren Vale) have the least variation. McLaren Vale receives the lowest annual rainfall.

Table 2.1 Annual Rainfall Statistics for 5 Sites in WA, NSW, Vic, SA and Qld

Site location	Annual rainfall statistic for each site				
	Minimum	10th percentile	Average	90th percentile	Maximum
Henderson, WA	597.6	643.2	790.8	940.8	1037.1
Lismore, NSW	753.4	901.5	1321.1	1922.1	2091.9
Lyndhurst, Vic	488.9	602.8	762.2	941.2	1045.0
McLaren Vale, SA	316.2	374.7	517.8	633.1	801.9
Townsville, Qld	378.9	542.0	985.8	1494.9	2418.7

2.1.2 Evapotranspiration

Evapotranspiration (ET) is the combination of evaporation, the volume of water lost due to direct vaporisation of water from the soil and other surfaces, and transpiration, the indirect transportation of water from the soil, through the plants where it is then released to the atmosphere from plants' leaves via their stomata. Under dry conditions, evapotranspiration is affected by plant available water (a function of plant rooting depth as well as soil type) and canopy resistance from stomata (Zhang *et al.*, 1999). Under wet conditions, advection, net radiation, leaf area and wind are the main influences on evapotranspiration. Thus, to increase ET for a specific location, the choice of plants needs to consider the rooting depth, soil type, canopy resistance and leaf area.

ET is divided into potential ET (PET) and actual ET (AET or ET). PET is the volume of water that would be returned to the atmosphere if water was not limiting. Under dry conditions some plants may exert physiological controls of stomata that have the result of reducing water losses and hence the AET is less than PET. Plant stomata respond to surface temperature, incident radiation levels, ambient CO_2 concentrations, water stress and chemical signals. The rate of ET is controlled by energy available, humidity gradient, wind speed and water available.

It is generally accepted that evapotranspiration from a community of trees is higher than for a grassland community. However, Zhang *et al.* (2001) calculated a relationship between average annual ET and average annual rainfall based on observed data and showed that the evapotranspiration from grasslands was similar to treed communities in rainfall areas < 500 mm/yr, approximately. The difference between ET from grass and trees increases with increasing annual rainfall above 500 mm/yr. Hence in semi-arid and arid climates there would be little difference in ET between grasses and trees due to the limitation imposed by soil moisture.

Differences in ET may also occur between forest types. Dunin *et al.* (2001) measured ET in moist soil conditions of 3.25 mm/day from a mallee community at Hincks National Park in SA (dry site) and 4.28 mm/day from a white spotted gum eucalypt forest at Kioloa State Forest in NSW (humid coastal environment). As the soil dried out, the ET coefficient (i.e. AET/PET) in the mallee community began decreasing when the actual moisture content was 95% of the maximum moisture content. The ET coefficient from the wet eucalypt forest did not begin to decline until the actual moisture content was 30% of the maximum moisture content. This shows that the mallee community is a more conservative water user than the wet eucalypt forest. Under dry conditions, Dunin *et al.* (2001) reported a similar ET of about 1 mm/day was measured for both areas, though the leaf area index (LAI, which is m^2 leaf area per m^2 ground area) was 0.25 for the mallee community and 3.0 for the wet eucalypt forest. Dunin *et al.* (2001) suggested this showed a compensating effect of soil evaporation under the mallee community is occurring and that under dry conditions the LAI becomes exponentially less important.

Evapotranspiration estimates for perennial and annual pastures vary depending on the weather. At Rutherglen, Ridley *et al.* (1997) found annual ryegrass had the highest annual ET in the wettest years, while phalaris and cocksfoot had the highest annual ET in the drier years with the lowest annual ET reported for the fallow plot. However, McLeod *et al.* (1998) did not measure any difference in daily ET between annual ryegrass, phalaris and phalaris-clover. They theorised that this was due to atmospheric demand limiting evapotranspiration rather than canopy conductance and that the differences were too small to measure due to the low ET rates over the 6 days, i.e. 5.5 to 6.2 mm/day.

Influences on ET at five sites through south east Australia were investigated by Rab *et al.* (2002) by applying fertiliser (superphosphate) to kangaroo grass communities and oversowing with clover. Daily ET varied from 0 to 3.9 mm/day for the community, with mean daily evaporation of 1.1 – 1.3 mm/day for 1998/1999. Application of superphosphate increased the ET above unfertilised treatments but there was no significant difference between the clover sown treatment with 100 kg/ha or 250 kg/ha of superphosphate. Sowing clover into plots with 100 kg/ha applied superphosphate increased ET over plots without clover.

Plant density and mulch can also affect ET rates. Murphy and Lodge (2001) found that ET rates from a planted wallaby grass stand (*Austrodanthonia linkii*) were increased by increasing the planting density and that the application of mulch (native grass litter) to the soil surface increased the evaporation during wet periods but decreased evaporation during dry periods.

As modelled by Zhang *et al.* (2001) there is little difference in ET between plant species of similar habit during wet years. However, during dry years, deep-rooted perennials, like phalaris, have reported higher annual ET than annual pastures or fallow ground. ET can be increased by the addition of fertiliser or increasing plant density to increasing plant yields and thus plant water use requirements. The application of mulch or the formation of litter on the soil surface over time will aid in increasing evaporation during wet periods and decreasing evaporation during dry periods, which will aid in plant survival during dry periods.

2.1.3 Runoff

Runoff is the flow of water over the surface of the soil and occurs when the supply of water is greater than the soil's ability to accept it. This can occur during heavy rainfall events, if the soil has a low hydraulic conductivity (as can be caused by surface sealing or hydrophobicity) or when the soil is nearly saturated. The amount of runoff has been reported as varying from 0 – 10% of precipitation

(Costin, 1980; Rab *et al.*, 2002; Albright *et al.*, 2004) and is related to the rainfall intensity (Costin, 1980), soil permeability (Carroll *et al.*, 2000), surface roughness (Carroll *et al.*, 2000) and plant cover (Carroll *et al.*, 2000; Murphy and Lodge, 2001). Slope is also often mentioned as a factor in runoff; however, Albright *et al.* (2004) found runoff from their trials was not strongly related to slope or climate. Carroll *et al.* (2000) also found runoff was not strongly correlated to slope, especially once pasture grasses were established.

The major problem with excessive runoff is resultant soil erosion. On a landfill site, severe erosion can potentially expose buried wastes and the repair of erosion rills and gullies forms a large part of on-going maintenance requirements. Carroll *et al.* (2000) compared pasture grasses with trees on mine spoil in Queensland and found the pasture plots had less erosion (as measured by sediment loss) than the tree plots.

2.1.4 Lateral Flow

Lateral flow is the horizontal flow within the soil profile which is caused by slope and a change in soil materials. It is also referred to as through flow. In a landfill, the compacted clay barrier has significantly reduced permeability compared to the overlying layers and hence infiltrated water will tend to pond on the surface until sufficient pressure head is achieved to infiltrate into the pores. If this clay barrier is sloped, then gravity will result in the water moving downslope rather than ponding, thus resulting in lateral flow. Roesler *et al.* (2002) reported lateral flow on compacted clay barriers and geocomposite barriers (i.e. those that contain a geosynthetic membrane) between 0 – 3% of precipitation at arid, semi-arid and humid sites in the US. When measured, the lateral flow above the barrier (constructed 0.15 – 0.6 m below the surface depending on the site) was delayed by a few hours from runoff events.

2.1.5 Drainage

Drainage is the water which has moved through the soil profile and is no longer available to plants, or in the case of landfills, is the water which can move into the waste. Drainage can occur when the soil storage capacity has been exceeded or when gravity and moisture potential pull the moisture downwards.

Simpson *et al.* (1998) found in Australian conditions that drainage was higher in winter dominant rainfall areas and under permanent pasture compared to a eucalypt plantation. However, these results were all for higher rainfall areas and it can be expected that as for ET, the differences would be reduced in rainfall areas <500 mm (Zhang *et al.*, 2001). The drainage under permanent pasture can vary depending on the dominant species, with Ridley *et al.* (2001) reporting drainage as a percentage of rainfall over all years was 9% below phalaris, 10% below cocksfoot, 12% below annual ryegrass and 13% below the fallow plot, which is similar to the drainage percentage defined by Rab *et al.* (2002) of 10 – 17%.

In semi-arid regions, the drainage from phytocaps has been reported from 0 – 8.5 mm/yr (Albright and Benson, 2002; USEPA, 2003; McGuire *et al.*, 2004). The error for rainfall measurement has been estimated at 5% and ET as 6 – 20% (Ward *et al.*, 1998; Zhang *et al.*, 2001). Drainage has been estimated as 10 – 17% of precipitation, which is equal to the error in ET measurements and hence makes accurate drainage estimates from models difficult.

2.1.6 Soil Water Storage

The soil water storage is a factor of the texture and structure of the soil. The soil water characteristic curve defines the moisture content in the soil at different suctions. Once a soil has been saturated, the water drains freely under gravity until the suction of the soil is greater than the pull of gravity. At this point the soil is at field capacity. The soil continues to dry due to evapotranspiration, with the largest pores, usually those between the soil aggregates which are part of the structure, draining first. As the soil continues to dry, the soil water characteristic is controlled more by the texture than the structure as only the smallest pores between the soil grains still hold water. At a certain point, known as the permanent wilting point, the soil's ability to hold water is greater than the plant's ability to extract it and drier still is air-dry which is when the soil's ability to hold the water is greater than the evaporative demand.

Drying is facilitated by evaporation and transpiration. Evaporative losses occur at the soil's surface while plants (using transpiration) are able to extract moisture from depth. Plants vary in their ability to access and utilise soil moisture, while those with deeper roots are more able to access moisture stored deeper in the profile. Ridley *et al.* (1997) found profiles under perennial grasses growing at Rutherglen were 50 mm drier at end of summer than annuals but profile moisture contents were similar within 4 – 6 weeks of commencement of autumn rains. In addition, the soil moisture content at which plants reduce transpiration and senesce varies between species.

Tree roots may exploit moisture tens of metres below ground surface. Grasses and forbs may exhibit deep rooting through the soil profile. Kangaroo grass can reduce moisture content to 1.25 m depth (Rab *et al.*, 2002), while lucerne roots have been found to 1.5 m and influenced the moisture content in the profile to over 1.9 m depth (Ridley *et al.*, 2001; Ward *et al.*, 2001; Ward *et al.*, 2002).

Clover roots were shallower, growing to approximately 0.5 m, and had an influence on the moisture content to 0.6 m (Ward *et al.*, 2001; Ward *et al.*, 2002).

Most plants utilise water in the upper soil profile preferentially to water deeper in the profile. Little difference was found between the soil moisture content of the A horizon where lucerne was growing compared to clover at Katanning in WA (Ward *et al.*, 2001). The differences observed were in the B horizon, where lucerne accessed water up to 1.9 m below the surface while clover only accessed water to 0.6 m depth. During the growing season both crops used water at near PET rates, therefore total water use under the lucerne was increased by its greater use of moisture stored in the B horizon.

A comparison of continuous cropping, continuous lucerne, annual pasture and various lucerne crop rotations was undertaken in Rutherglen, Victoria by Ridley *et al.* (2001). The soil under lucerne was drier in the summer months and often during the winter months, depending on the season, with lucerne drying the profile to approximately 3.5 m depth compared to continuous cropping which only affected soil moisture content to 1 m depth. Three years of continuous lucerne resulted in decreased moisture throughout the profile for three to four years after a return to continuous cropping. Ridley *et al.* (2001) hypothesized that this was due to the crops being able to exploit the root channels left by the lucerne for a number of years until natural shrink-swell processes closed the channels.

Plants response to drying conditions varies between species. Successful plants for a phytocap need to have a high water use but also tolerate dry conditions to ensure maximum profile drying during summer. A pot trial conducted for eight perennial pasture species (5 Australian natives and 3 introduced species) found varying drought tolerance or avoidance responses by plants (Rivelli *et al.*, 2001). Plant responses to increasing dry conditions included:

- *Eragrostis curvula*, *Themeda australis* and *Austrodanthonia racemosa* reduced their transpiration rates at higher soil moisture contents than other species resulting in a longer leaf survival time compared to other species.
- *Microlaena stipoides* was able to tolerate dry conditions with low leaf water content but was not conservative and hence had only a short survival time.
- *Dactylis glomerata* and *A. caespitosa* lasted many days and retained high leaf moisture content by folding or rolling leaves and hence did not utilise soil moisture as much as the first three species.

- *Phalaris aquatica* and *Bothriochloa macra* are classified as dehydration avoider/tolerators; however, they did not avoid dehydration in this trial and were reported with the highest final soil water content of all species. Rivelli *et al.* (2001) suggested that this might be due to the deep roots of these species maximising potential water uptake rather than minimising water loss.

The tolerance strategy of *E. curvula*, *T. australis* and *A. racemosa* will allow the longest growth during an extended dry season. However, for short dry periods, the unconservative approach and tolerance of dry soil moisture conditions shown by *M. stipoides* would be advantageous in reducing potential drainage.

For a phytocap, perennial, deep rooting species are advantageous to maximise the use of stored soil moisture throughout the depth of the cover. Combining a mixture of species will enable maximum exploitation of the soil moisture by achieving maximum soil moisture reduction during shorter and longer dry periods and extending the growing season. This will ensure the soil profile is completely dried during the dry season to allow maximum moisture storage during the wet season.

2.2 Final Landfill Covers

2.2.1 Types of Covers

Final cover for landfill is placed once the landfill or landfill cell has been filled. The objectives of the final cover (NSW EPA, 1996; Qld EPA, 2001; Vic EPA, 2001; ITRC, 2003; US EPA, 2003; WA DEC, 2006; SA EPA, 2007) are to:

- Isolate waste material from human and ecological receptors;
- Reduce or control infiltration and percolation through the waste to reduce the potential for contaminants to leach to groundwater;
- Prevent direct exposure to the waste;
- Control gas emissions and odours;
- Prevent occurrence of disease vectors and other nuisances;
- Meet aesthetic and other end uses of the site now and in the future;
- Remain in place and maintain function for an extended period of time.

In Australia, the typically recommended practice for covering a landfill is to place a compacted, low permeability clay barrier over the site at the completion of landfilling, as shown in Table 1.1. Landfill covers are not always prescribed and the cover designer accepts the risk for their performance. Similar practices are recommended in other countries. In the United States, the Resource Conservation Recovery Act prescribes landfill covers for Subtitle C (hazardous waste) and Subtitle D (municipal solid waste) landfills (Table 2.2). The final covers in the US have substantially thinner layers overlying the compacted clay barrier than is recommended in Australia.

Table 2.2 United States Prescriptive Cover Designs for RCRA Subtitle D (Solid Waste) Landfills

Existing Base Liner Design	Prescriptive Cover Design
No liner	0.15 m erosion protection layer 0.45 m barrier layer with $K_{sat} \leq 10^{-7}$ m/s or $\leq K_{sat}$ of underlying soils, whichever is less
Soil liner with $K_{sat} \leq 10^{-8}$ m/s	0.15 m erosion protection layer 0.45 m barrier layer with $K_{sat} \leq 10^{-8}$ m/s
Soil liner with $K_{sat} \leq 10^{-9}$ m/s	0.15 m erosion protection layer 0.45 m barrier layer with $K_{sat} \leq 10^{-9}$ m/s
Composite Liner: Soil layer with $K_{sat} \leq 10^{-9}$ m/s overlain by geomembrane	0.15 m erosion protection layer Geomembrane 0.45 m barrier layer with $K_{sat} \leq 10^{-7}$ m/s

In both the United States and Australia, there are no regulatory barriers to alternative cover designs as long as the alternative cover can be proven to be equivalent or better than the recommended or prescribed cover or to meet the objectives stated for a final cover. This “equivalence” is often measured by comparison of the quantity of drainage or percolation leaving the landfill cover, which may enter the underlying waste but can also be assessed in terms of maintenance requirements and gas generation.

Alternative cover designs have been gaining interest from landfill operators, especially in areas where suitable clay materials that are capable of meeting the required permeability are not readily available. Alternative designs have focussed on mechanisms by which precipitation received at a site can be diverted, stored and/or utilised to minimise the potential for drainage through the cover and into the waste material. Evapotranspiration is a natural process by which water is removed from the soil and hence interest focussed on utilising this natural process to remove water from landfill covers. Schematic representations of a conventional compacted clay cover and 2 types of phytocap, monolithic cover and capillary break cover, are shown in Figure 2.2.

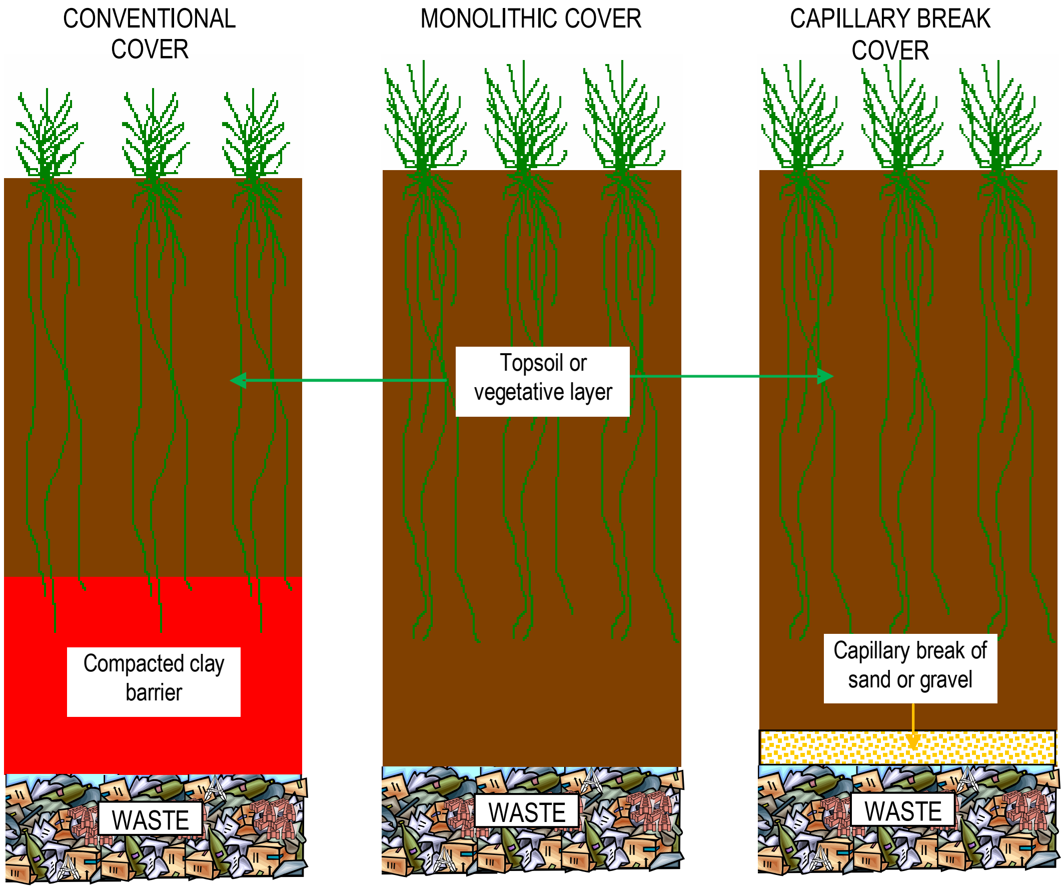

Figure 2.2 Schematic Representation of Three Final Covers. Note: Cover Thickness Varies

A conventional compacted clay cover is typically comprised of a topsoil/vegetative layer overlying an impermeable, compacted clay barrier. Conventional covers may also incorporate a geomembrane rather than, or as well as, a clay barrier and are referred to herein as composite covers. Conventional covers aim to achieve the objectives of final cover by preventing drainage from moving through the clay barrier or geomembrane and into the waste and preventing gas and odour movement upwards through the barrier. The moisture moving through the profile is diverted as lateral flow along the top of the clay barrier, which has potential to then move into the waste through cracks and deformations in the clay or to accumulate at the toe of the batter slopes. The topsoil layer is to support plant growth thereby improving the visual amenity of the site and reducing erosion. The limited profile depth and need to prevent root intrusion into the barrier layer limits the type of vegetation grown.

The phytocap is comprised of a suitable soil medium to store moisture and support plant growth. The phytocap is based on the natural system and sometimes referred to as the “store and release” cover as the soil stores the moisture and evapotranspiration releases the moisture back into the atmosphere. The simplest cover is comprised of a monolith, i.e. one layer of soil material. It may also be comprised of a number of layers of various textures; however, all layers are placed with minimal compaction and as near to the natural state as possible to maximise plant growth and therefore water use.

A more complex phytocap includes a capillary break created by placing a coarse sand or gravel layer within the cover. At the interface between the overlying soil and the coarser layer, the soil moisture needs to reach near saturation before drainage into the lower layer occurs. Once drainage occurs into the coarser layer, the water will rapidly drain to the lowest contoured point.

2.2.2 ACAP Evapotranspiration Cover Experience

Since the early 1990s, alternative covers have been trialled on solid and hazardous waste landfills across the United States. In 1998, the US Environmental Protection Agency (US EPA) initiated the Alternative Cover Assessment Program (ACAP) with research conducted by Desert Research Institute, Battelle Memorial Institute (Pacific Northwest Division), the University of Wisconsin-Madison and Science Applications International Corporation (SAIC). The program comprised four phases:

- Phase I: Review current data collection efforts and numerical modelling capabilities relative to landfill cover design. Phase I was completed in 1999 and has been reported by Albright *et al.* (2002).
- Phase II: Design, construct and operate (for 5 years) a network of alternative cover testing facilities. Design and construction of Phase II was completed in 2000 with test sections constructed at 12 facilities, with conventional and alternative cover designs being evaluated in a side-by-side comparison at seven of the test sites. Detailed design of covers is reported in the Phase II report (Albright and Benson, 2002) and presented on the Desert Research Institute website (http://www.acap.dri.edu/acapusa.html).
- Phase III: Analyse field results with improved numerical models to predict long-term performance of alternative cover systems at the selected testing sites.
- Phase IV: Develop a comprehensive guidance document for alternative cover systems.

Albright and Benson (2002) reported preliminary results for the sites constructed as part of ACAP. For the twelve sites across US, rainfall ranges from 221 mm/yr to 1280 mm/yr with snow fall a significant contributor to precipitation at many sites. While under snow the soil is frozen and has a lowered permeability, hence snow fall is not equivalent to rainfall in the context of infiltration into a final cover. The conventional covers tested were all significantly shallower than recommended in Australia.

Lysimeters are devices installed to collect water moving through the soil. Large pan lysimeters were installed, as described by Benson *et al.* (1999), on the phytocap and conventional cover at 10 of 12 sites and constructed to prevent run on and collect runoff and drainage. Weather stations were installed at all sites to measure rainfall, temperature, solar radiation, wind speed and direction and relative humidity.

In summary, the results from the ACAP sites constructed with lysimeters were:

- Livermore, California has cool wet winters and warm, dry summers. Summer temperatures range from 21 °C to 41 °C and winter temperatures range from 1 °C to 12 °C. Average rainfall is 340 mm and the average annual potential evaporation is 2000 mm. Percolation of 1.4 mm was measured through the phytocap after a large rainfall event. Albright and Benson (2002) suggested this was due to preferential flow as moisture probes did not register change. No drainage was measured from the conventional cover.
- Marion/Cedar Rapids, Iowa has hot and humid summer with sub-freezing winter weather. The average annual precipitation is 925 mm/yr. The average potential evapotranspiration (PET) is 1077 mm and it exceeds precipitation in eight months of the year. The trial site was comprised of a composite barrier cover (i.e. one that included a geomembrane), a compacted clay cover and a phytocap of sandy clay amended with compost in the upper 0.9 m of the 1.5 m cap. Drainage was recorded through all covers with the total measured over 21 months of 6.1 mm measured below the composite barrier, 18.1 mm below the compacted clay and 190.5 mm below the phytocap.
- Monticello, Utah has an arid climate with 384 mm/yr of precipitation. Average snowfall is 1500 mm with an average snow depth of 50 mm. Temperatures range from −10 °C to 2 °C in January to 12 °C to 29 °C in July. The final cover consisted of topsoil and 1.5 m fine-grained soil over a capillary break followed by an HDPE (high-density polyethylene) geomembrane and a compacted clay layer. ACAP monitored the cover above the geomembrane. Cumulative drainage below the capillary break was measured as < 0.1 mm.
- Bennington/Omaha, Nebraska experiences warm summers, cold winters and moderate rainfall of 711 mm/yr and snowfall of 813 mm/yr. Two capillary break alternative covers were compared to a conventional composite cover. The phytocaps comprised 0.15 m topsoil then 0.45 or 0.75 m silty soil underlain by 0.15 m sand acting as a capillary break.

Measured drainage was higher in the phytocap with capillary break (>50 mm) than the composite barrier cover (5.5 mm).

- Boardman, Oregon is a semi-arid climate with cool, dry winters and warm, dry summers. The average annual precipitation is 220 mm/yr and temperatures range from −2 °C in January to 32 °C in July. The trial site consisted of two phytocaps (1.2 m and 1.83 m sandy silt loam) and a composite cover. Drainage of < 1 mm was measured in the conventional cover and in both phytocaps.
- Sacramento, California receives approximately 440 mm/yr rainfall and occasional snowfall in winter. The climate is generally comprised of cool, wet winters and hot, dry summers. The trial site consisted of two phytocaps, a 1.2 m deep clay loam and 2.4 m deep clay loam cover. Drainage was less through the deeper cover, where 8.5 mm was measured, compared to 132 mm drainage through the 1.2 m cover.
- Polson, Montana experiences cold winters, hot summers and a short growing season. Precipitation is 382 mm/yr. Covers for the trial included a phytocap of 0.15 m silty sand then 0.46 m silt overlying 0.61 m silty sand and finally a capillary barrier comprised of 0.46 m sandy gravel. The conventional cover was a composite barrier cover. Drainage was < 0.5 mm in both the conventional and phytocaps. Drainage occurred during snow melt and other rainfall events; however, the water storage capacity of the profile was never exceeded and hence preferential flow is the likely cause of drainage.
- Helena, Montana experiences cold winters and hot summers, with 308 mm/yr precipitation predominantly falling in summer. A phytocap was trialled consisting of three layers: 0.15 m sandy clay topsoil, 1.2 m sandy clay and 0.3 m gravel capillary break. Albright and Benson (2002) report no drainage has been measured below this cover.
- Albany, Georgia is in a humid climate with hot, humid summers and cool winters. The average annual precipitation is 1280 mm/yr. Two covers were constructed as part of the trial: a conventional compacted clay barrier and a phytocap of 0.61 m sandy clay mixed with compost, over 0.7 m soil from on-site excavation (sandy clay) over 0.3 m "interim" soil (sandy clay) which covers the underlying waste. A root barrier was placed between the on-site soil layer and the "interim" soil layer.

  Over the two years of the trial, less drainage was measured on the phytocap (185 mm) compared to conventional cover (683 mm). The phytocap was irrigated to maintain poplar trees and drainage was predominantly recorded prior to and during tree establishment. After tree establishment, the drainage did not follow the rainfall pattern and lower soil water storage has been maintained in the cap.

On the compacted clay conventional cover, grass was planted but established poorly in the first year and so the cover was resown with native grasses. The drainage was < 100 mm from March to December 2000 and did not follow the rainfall pattern. However, after an extended dry period from September to December 2000, the drainage increased to approximately 480 mm/yr and followed the rainfall pattern. The storage capacity of the conventional cover has not been exceeded and hence Albright and Benson (2002) and Albright *et al.* (2006a) suggested that the drainage was due to preferential flow through desiccation cracks.

- Marina/Monterey, California experiences maritime weather conditions comprising cold wet winters and cool, foggy summers. The annual rainfall varies from 250 mm/yr to 1103 mm/yr with an average of 412 mm/yr. The trial site comprised a composite barrier conventional cover and a phytocap comprised of 1.20 m fine-grained soil over 0.30 m sand. Over the 25-month monitoring period, total drainage through the conventional cover was measured as 34.5 mm but this was likely to be an underestimate and is believed to be due to liner puncture. The heavy winter rains resulted in 119 mm total drainage over the monitoring period below the phytocap.

The most recent data from measurements at the ACAP sites were presented by Albright *et al.* (2004) and show that:

- Surface runoff from the covers accounts for 0 – 10% of precipitation, with an average runoff of 4%, and was nearly insensitive to cover slope, barrier type or climate.
- Lateral drainage within the soil layers only accounted for 0 – 5% of precipitation, with an average of 2%. Lateral drainage was typically a large proportion at humid sites, such as Georgia. Lateral drainage is often ignored in water balance modelling as the simple models are one-dimensional and hence do not account for internal lateral drainage.
- Drainage or percolation as a percentage of precipitation was:
  - For conventional covers with a composite barrier: <1.4% (12 mm/yr) in humid areas and < 0.4% (1.5 mm/yr) in arid, semi-arid and sub-humid locations;
  - For conventional covers with a compacted clay layer: 6 – 17% (52 – 195 mm/yr). The high rates of flow were attributed to preferential flow through desiccation cracks and other imperfections in the soil barrier;
  - For phytocaps: 6 – 18% (33 – 160 mm/yr) in humid locations and < 0.4% (2.2 mm/yr) in arid, semi-arid and sub-humid climates. Two phytocaps performed below expectations due to insufficient soil moisture storage in the profile or lower transpiration than estimated.

Overall, the ACAP sites have shown that phytocaps can achieve equivalent performance to conventional caps, especially those utilising compacted clay as the infiltration barrier. Phytocaps appear to be suitable in arid, semi-arid and sub-humid climatic regimes. Greater care in designing phytocaps is required in humid areas to minimise drainage, as at the ACAP sites in Ohio and Nebraska the drainage was higher in alternative covers than the conventional covers. However, the phytocap in Georgia (another humid site) performed better than the conventional compacted clay cover, showing that equivalence is possible in humid regions.

2.2.3 Hanson's Wollert Landfill, Victoria

Hanson Landfill Services operates the Wollert Landfill, approximately 50 km north-east of Melbourne, Victoria Australia, which is adjacent to a basalt quarry, also operated by Hanson. The quarry produces a waste rock by-product which was identified as having potential for use in the landfill cover. In 2003, Hanson and the University of Melbourne commenced extensive research of the ≤ 20 mm waste rock for use as a phytocap. This work has been reported by Michael (2010) and a summary of her research is presented.

Michael (2010) undertook preliminary plant trials to determine potential species and also optimum placement and growing conditions when using the waste rock. A small-scale, replicated, field trial showed that the waste rock was able to support native plant growth but that the addition of mulch was detrimental to the growth of all plant species, which included a range of trees, shrubs and grasses, which was attributed to nitrogen draw-down (exacerbated by the low nutrient status of the waste rock) and soil temperature differences. However, it was noted that the ambient conditions during the trial were wetter than the seasonal averages which may have limited the advantage afforded from reduced moisture loss from the mulched surface. The laboratory trial was used to investigate the influence of dry density on water use and plant root growth of 2 native grasses (*Themeda australis* and *Microlaena stipoides*), 2 native shrubs (*Acacia mearnsii* and *Allocasuarina verticillata*) and 2 native trees (*Eucalyptus camaldulensis* and *Eucalyptus cladocalyx*). The dry densities used were 1.45, 1.55, 1.65 and 1.75 t/m^3, which as a percentage of standard compaction maximum dry density were 72%, 77%, 82% and 87% respectively. Michael (2010) reported the optimum bulk density to maximise plant water use was 1.5 – 1.65 t/m^3 (74 – 82% MDD) and that total root length decreased at the highest dry bulk density.

Field trials commenced in 2005 were used to measure the water balance of a 1.5 m thick waste rock phytocap with and without a capillary break using lysimetry (10 m x 10 m) and also included unlined test section placed directly over waste. Michael (2010) reported the following findings from the field trial:

- Bulk density increased by 0.05 t/m^3 after 3 years, i.e. from placement dry density of 1.39 – 1.46 t/m^3 to 1.44 – 1.50 t/m^3 and was reflected in a 50 mm decrease in phytocap depth. A significant increase was reported in the surface soil and a non-significant increase was reported toward the base of the profile;
- Gas extraction commenced in June 2006 and, prior to that, CO_2 concentrations in capillary break should have had a fatal effects on plants while the concentrations in the monolithic cover (i.e. without the capillary break) would have been detrimental to plant growth. Adverse gas concentrations existed for up to 11 months in monolith and up to 17 months in capillary break. However, although these concentrations resulted in plant growth differences, there was no difference in plant mortality related to gas and after 3 years, the plants appeared to have recovered from any gas effects. It should be noted that these high gas concentrations were created by the unlined test sections being excavated into a clay cap resulting in funnelling of the gas through the more permeable phytocap;
- The soil temperature was over 5 °C higher in unlined sections than the lysimeters and increasing temperature with depth and higher temperatures were reported for the capillary break cover. The higher temperature in the unlined sections was attributed to leachate recirculation, which increases refuse moisture content resulting in more active degradation of the waste mass, which in turn results in higher temperatures;
- The soil moisture content was 13 – 17% higher, on average, in the capillary break cover than the monolithic cover and unlined sections reported higher moisture content than the lysimeters. Higher moisture on unlined sections were attributed to either reduced plant evapotranspiration (resulting from detrimental gas and temperature effects) or oxidation of methane producing water;
- With rainfall of 419 mm and 438 mm in two successive years of measurement (which was below average of 542 mm), water balance measurements from the lysimeters showed both cover designs resulted in <<1% drainage, <1% runoff and > 95% ET, as a percentage of total precipitation. Michael (2010) does note that runoff was underestimated in the first year due to use of magflow meters but tipping buckets used in the second year still recorded < 1% of precipitation as runoff.

Overall, Michael (2010) showed that native vegetation is able to survive and grow in the adverse environmental conditions which can be present on a landfill and their water use requirements were sufficient to utilise almost all of the soil moisture. Michael (2010) also reported no difference in the water balance measured in the lysimeter between capillary break and monolith. However, when landfill factors were included, particularly the effect of gas, the capillary barrier design remained wetter and resulted in poorer plant growth than the monolithic design. This finding is significant as other studies (Albright *et al.*, 2004; Fayer and Gee 2006; Khire *et al.*, 2000), where landfill effects have not been accounted for, have suggested lower drainage when a capillary break is included due to increased profile moisture content.

2.2.4 Phytocap Experience at Other Sites

US EPA (2011) presents a database of phytocaps with 33 full-scale monolithic phytocaps listed and a further 25 sites noted as demonstration sites (which includes the ACAP trial sites). Twenty-one sites include capillary barriers, either full-scale or demonstration. The status of the projects varies as does their path to approval. Some sites have commenced as full-scale projects without first requiring demonstration trials. The Lopez Canyon Sanitary Landfill received conditional approval in 1998 to construct a phytocap on the landfill to allow two years of field performance data to be recorded to validate the preliminary modelling (USEPA, 2003). The cover was fully approved in October 2002 after a calibrated model (UNSAT-H; Fayer, 2000) predicted 500 mm of drainage from a phytocap and 950 mm drainage from a conventional cover over the 10 year modelling period, i.e. an average 50 mm/yr for the phytocap and 95 mm/yr from the conventional cover.

Other trial and full-scale sites have found similar results to the ACAP sites, with varying success of phytocaps. The drainage from phytocaps has been measured in field trials as equivalent to or less than that from conventional covers, especially in semi-arid and arid environments. Dwyer *et al.* (2000) reported drainage through various covers constructed in Albuquerque New Mexico, with similar percolation of < 0.2 mm/yr through the phytocap and conventional cover. The phytocap including a capillary break was slightly higher, with drainage of 0.87 mm/yr. McGuire *et al.* (2004) measured no drainage through a 1.22 m deep clay loam phytocap through winter from August 2000 to April 2001. UNSAT-H predicted less than 0.1 mm/yr drainage based on four years of rainfall at 530 mm/yr.

An arid site in Idaho, the Protective Cap/Biobarrier Experiment was used to compare phytocaps (with and without a capillary break) and a conventional cover with data collected from 1993 to 2000 (Anderson and Forman, 2002) and again from 2002 to 2006 (Janzen *et al.*, 2007). It should be noted that drainage was not explicitly measured but was inferred from moisture accumulation at the base of the profile. The phytocaps returned all moisture received back into the atmosphere via evapotranspiration, i.e. no drainage was evident for the initial seven-year period. Drainage was occasionally measured from the conventional cap and is believed to be caused by water infiltrating to the flexible membrane layer and running off. During the subsequent 5 year period, based on moisture content at the base of the profile, Janzen *et al.* (2007) suggest that drainage was unlikely from plots containing mixed native vegetation and under ambient rainfall or summer irrigation. However, drainage was more likely to have occurred from the monolithic phytocap than the capillary barrier cover (where the capillary barrier was approximately 1 m below the surface) or the prescribed cap (1 m soil over a flexible membrane and 0.6 m compacted clay).

Experience in Melbourne, Australia has also shown precipitation may move through compacted layers. Hancock *et al.* (2004) tested two covers comprised of 300 mm topsoil/mulch overlying a 1200 mm barrier compacted to 98 – 103% standard compaction, one comprised of local on-site clay and the other from a clayey non-descript crushed rock. The highest moisture content was measured at the lowest depth above waste and it was hypothesised that this was due to methane degradation in the soil. However, closer inspection of moisture profiles shows that the moisture content changes mimic the changes in the surface layers due to precipitation and hence it is more likely that this accumulation is due to moisture moving through the profile and accumulating above the waste due to limitation to deeper leaching, such as capillary barrier effect over waste. The potential error in the measuring equipment was not assessed as part of this study and hence the apparent increase in moisture content may be an artefact of the calibration.

In Hawaii, Colorado State University and Naval Facilities Engineering Services Center (undated) investigated covers for areas where precipitation exceeds evapotranspiration in all months of the year. The site was located at the Marine Corp Base in Hawaii where the annual rainfall average is 970 mm/yr. In these environments, the cover needs to be designed to divert a proportion of the precipitation to reduce infiltration into the soil and then use evapotranspiration to remove the precipitation which has infiltrated.

Initial modelling for the Base suggested runoff structures on 20 and 40% of the surface should reduce drainage to very low levels (*ibid*). Runoff structures were constructed from 120 mm wide metal rain gutter placed parallel to slope. The cover was 0.6 m depth and placed at 95% density at optimum moisture, which is more compact than would occur naturally. Side-by-side plots were constructed without runoff structures, i.e. a phytocap without runoff structures and phytocaps with either 20 or 40% infiltration control. Runoff, drainage, soil moisture and precipitation were measured on the trial site. For comparison, a conventional cover consisting 0.6 m soil overlying 0.3 m sand drainage layer and then a 0.3 m compacted clay (1×10^{-9} m/s), was modelled using HELP (Hydrologic Evaluation of Landfill Performance; Schroeder *et al*., 1994) .

The site received 1203 mm rainfall over the 14 month trial, which is equivalent to 1196 mm/yr (*ibid*). There were no significant differences between using 40% infiltration control cover over 20% infiltration control cover but both increased runoff by 2 to 5 times in any month compared to the phytocap with no runoff structures. The drainage measured from the covers was 31 – 95 mm from the phytocap, 8 – 43 mm for the 20% infiltration cover and 7 – 15 mm for the 40% infiltration cover. HELP predicted that the drainage on the conventional cover would be 7 mm over the period; however, this appeared to have been based on average rainfall and not actual rainfall for the period and hence actual drainage is likely to have been greater. The drainage between covers was not statistically significant but the data indicate that a two to three times reduction in drainage may occur with infiltration control covers compared to a phytocap without runoff structures.

Hauser and Gimon (2001) assessed the water balance at 60 US Air Force bases to determine the potential for phytocaps to be successful. The EPIC model (Environmental Policy Integrated Climate; Mitchell *et al*., 1998) was used to estimate the potential evapotranspiration (PET) and actual evapotranspiration (AET). A simple model was used as climatic data were limited at most sites which limited the use of more complex and realistic models. Based on a monoculture of warm-season grasses with 2 m rooting depth growing in a 2 m deep silty clay loam (14% sand, 42% silt and 44% clay), Hauser and Gimon (*ibid.*) divided the bases into good, fair and marginal opportunity for using phytocaps based on the PET:precipitation ratio, such that:

- Good = ratio > 1.5;
- Fair = 1.2 < ratio <1.5;
- Marginal < 1.2.

Using this division, 42 bases had good opportunity for phytocaps to work and only 4 bases in the eastern US (Tennessee, Mississippi, Maine and New Jersey) had marginal opportunity. Hauser and Gimon (2001) also note that using both cool and warm season grasses and forbs, rather than a monoculture of warm-season grasses, would substantially increase the AET and therefore increase the potential for a phytocap to operate adequately in many areas.

2.3 Landfill Water Balance Models

Modelling the water balance for a phytocap is usually undertaken in the US to prove equivalence, though ITRC (2003) suggest that in some cases a risk-based approach may be more appropriate or that natural analogues will provide sufficient validation. Water balance models may be one-, two- or three-dimensional in the flows they assume. A one-dimensional model accounts for vertical water movement through the soil profile, while a two-dimensional model includes lateral movement within the soil profile and a three-dimensional model accounts for water movement in all directions. An increasing level of knowledge is required for each additional dimension, so where insufficient information is available, simpler one-dimensional models are more suitable.

Water balance models may also be divided into storage routing models or enhanced water balance models and Richards' equation-based models. Storage routing models do not account for upward movement of water, drainage under moisture conditions less than field capacity or the capillary impact of layers (ITRC, 2003). CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems; Kinsel, 1980), EPIC (Environmental Policy Integrated Climate; Mitchell *et al.*, 1998) and HELP (Hydrologic Evaluation of Landfill Performance; Schroeder *et al.*, 1994) are such models. HELP is currently one of the main models used to predict drainage through Australian landfills. In storage routing models, each soil layer is presumed to hold all water entering up to field capacity and then water begins to drain to the lower layer at the rate dictated by the hydraulic conductivity. This does not account for water movement under unsaturated conditions where water moves due to a hydraulic gradient. The redistribution of moisture once rainfall has ceased is therefore not accounted for in these storage-routing models, though it is a critical factor when attempting to calculate drainage to millimetre accuracy.

Models based on Richards' equation are considered more "physically correct" as they can predict flux for soil moisture less than field capacity and capture the dynamics of varying soil type and their potential impact on flux. Overall water balance models based on Richards' equation, allow a more realistic response to design changes and hence allow design sensitivity analysis (ITRC, 2003).

Comparison of models and evaluation of their ability to predict field results has been undertaken by many authors. The most extensive comparison was undertaken by Scanlon *et al.* (2002) where a comparison and evaluation of seven models was undertaken using measured field data from trial sites in Texas (12 months of data) and Idaho (26 months of data).

The models compared were HELP, HYDRUS 1-D (Simunek *et al.*, 1998), SoilCover (GEO2000, 1997), SHAW (Simulation of Heat and Water; Flerchinger and Saxton, 1989), SWIM (Soil Water Infiltration and Movement; Verburg *et al.*, 1996), UNSAT-H (Fayer, 2000) and VS2DT1 (Variably Saturated 2 Dimensional Transport Interface; Healy, 1990) in a non-vegetated cold (Idaho) or warm (Texas) desert situation. All models are based on Richards' equation except HELP which is storage routing. HELP uses the runoff versus precipitation curve developed by US soil conservation service while others assume runoff occurs when precipitation intensity exceeds infiltration rate. All models average the input data over the time period, e.g. an input of daily rainfall is assumed to occur over the whole day and hence often does not reflect the actual intensity of the rainfall event. This tends to underestimate runoff.

At the Texas site, all models under-predicted runoff. The measured runoff was 6 mm while all models predicted 0 mm except HELP (1.5 mm) and SoilCover (0.9 mm). Decreasing hydraulic conductivity of the surface by an order of magnitude resulted in the models more accurately predicting runoff. Scanlon *et al.* (2002) also tried using hourly rainfall data rather than daily rainfall; however, this only produced more accurate results from one model. The drainage estimated at the site was measured as 0 mm and most models predicted 0 mm, with the exception of HELP, SHAW and UNSAT-H. Overall, HELP and VS2D were most out of step compared to the measured values as they underestimated evaporation and overestimated changes in soil moisture which was reflected in an overestimate of drainage by HELP.

At the Idaho site, a capillary barrier was included in the design and it was necessary to force models with no account for seepage face to model one by including a 100 mm gravel layer at the base of the model and predicting drainage into this layer. SHAW predicted runoff from this site even though runoff was prevented and hence underestimated drainage. A ponding depth of 100 mm was required to correct this and prevent SHAW from modelling runoff. HELP overestimated drainage and underestimated the soil moisture change. Most models simulated drainage earlier than actually occurred, which was believed to be due to soil freezing effects preventing infiltration early during snow melt. Overall, the modelling accuracy was improved for models with a "seepage face" lower boundary, while the HELP model (which only models gravitational movement and not matric movement) produced markedly different results from the other models.

Scanlon *et al.* (2002) concluded that it was preferable to use models that are based on Richards' equation, allow evaporation and precipitation to occur on the one day, use hourly precipitation and use appropriate lower boundary conditions. Scanlon *et al.* (2002) also suggest that it is important for the modeller to understand implications of models which do not include the above and to ensure good understanding of accumulation of errors as these will greatly affect small terms such as drainage.

In a later study, Scanlon *et al.* (2005) noted that vegetation is the most critical parameter in phytocaps and models which simulate vegetation by externally prescribing time series in vegetative growth, such as those discussed above, fail to simulate the two-way interaction between vegetation and water balance. Young *et al.* (2006) used a Monte Carlo analysis with Hydrus-2D and showed that in shallow soil profiles the presence or absence of plants did not affect drainage as the moisture moved too quickly through the profile and that in deep soil profiles increasing soil depth did not reduce drainage. However, without plants, their modelling showed that soil alone could only reduce drainage to a certain volume and plants were required to gain further decreases.

Roesler *et al.* (2002) also reported that models based on Richards' equation provide more realistic output than storage routing models. It was noted that HELP tended to show unrealistic responses and relative insensitivity to design changes. HELP under-predicted percolation from composite covers in humid sites and over predicted lateral flow for covers that incorporated a drainage layer and under-predicted for covers that did not. This indicates that the output from HELP can be erratic and is not conservative. It also suggests limited ability for HELP to be used for comparing phytocap designs for a selected site.

Comparison of two storage routing models was undertaken by Hauser and Gimon (2004) and showed that EPIC underestimated ET by 2% of measured, overestimated runoff by 395% which resulted in underestimating drainage by 14% and change in moisture storage by 30%. HELP underestimated ET by 29% of measured, overestimated runoff by 961%, overestimated drainage by 34% and underestimated change in moisture storage by 78%. The very large errors in estimating runoff and drainage were probably caused by their low relative values compared to runoff and ET. However, it is evident that EPIC predicted ET and drainage with some degree of accuracy while HELP did not predict any parameter with accuracy.

Hauser and Gimon (2004) suggested a number of reasons for errors in runoff including use of the SCS Curve number which was developed for estimating runoff from large or extreme storm events from data collected at sites south-east of the Rocky Mountains and hence is of limited use for daily water balance models. In addition, Penman Monteith method for determining PET (as used by HELP) has been suggested in other literature as not as accurate as the modified Penman (as used by EPIC). An overall difference between the models was their proposed use as EPIC was designed to model natural systems while HELP was designed to evaluate hydrology of complete barrier-type landfill covers and not natural systems. They concluded that the HELP model has limited usefulness in design or evaluation of ET landfill covers and failed to meet criteria established for maximum monthly drainage on any of the four lysimeter datasets used.

With the HELP model, even where it may more accurately predict the water balance volumes, researchers have noted that there are still errors. Colorado State University and Naval Facilities Engineering Services Center (undated) found that on 2 control plots, total runoff was 60 mm and 145 mm over the 14-month period. HELP modelling estimated 90 mm from RCRA cover, which is similar. However, on the control plots, runoff occurred in 9 months over the 14-month period, while HELP predicted runoff would occur in all months except June. A similar trend was found for drainage with drainage being measured in 7 – 9 months depending on treatment, while HELP predicted drainage to occur in all months except July and September. The HELP model did not accurately predict drainage from a phytocap and the authors found that adjusting input parameters was not able to overcome the inherent limitations in the model when modelling natural systems.

Bohnoff *et al.* (2009) compared field data from the ACAP trial site in Altamont, California with predictions from UNSAT-H, HYDRUS, VADOSE/W (Krahn, 2004) and LEACHM (Hutson and Wagenet (1992). The soil hydraulic inputs to the model were varied depending on whether they were based on average laboratory results, field results or ± 2 standard deviations from the laboratory mean. The latter was to represent variants of “higher moisture retention-lower permeability” and “lower moisture retention-higher permeability”. Vegetation inputs, being LAI or root density were also varied but little effect on the predicted waste balance was found.

Overall, Bohnoff *et al.* (2009) reported the models predicted less runoff, with the exception of UNSAT-H, and drainage than was measured in the field and soil moisture storage and evapotranspiration were poorly predicted by most models, though tended to be better predicted when average laboratory values were used rather than field values. Runoff prediction was improved when precipitation was applied uniformly across the day, the surface layer had higher saturated hydraulic conductivity (which is in contrast to Scanlon, 2002, findings) or the Brooks-Corey model (Brooks and Corey, 1964) was used to describe the soil hydraulic properties. The soil moisture storage and evapotranspiration were better predicted when runoff was more accurate, average laboratory values for soil hydraulic properties were used and the vegetation followed a cyclic seasonal pattern. However, even then, predicted drainage was still less than field measured. Unit gradient at lower boundary and increasing the profile saturated hydraulic conductivity tended to improve drainage prediction.

Based upon the review of published literature, as summarised above, it was concluded that for the assessment of the design and performance of phytocaps, the following model features are required to address these limitations:

- based on the Richards' equation to account for unsaturated flow;
- designed for Australian conditions, and not based on US standard curves;
- inclusive of rainfall duration in the input parameters to allow runoff to be more accurately estimated;
- responsive to soil and climatic conditions in estimating plant growth.

The model that has not been tested for phytocap design is the WAVES (Water, Atmosphere, Vegetation, Energy, Solute) model created by CSIRO (Zhang and Dawes, 1998). WAVES is a one-dimensional, daily time step model, which not only simulates the interaction between the climate and vegetation with the soil, it also simulates the interactions and feedbacks between the atmosphere, vegetation and soil, which most other water balance models do not. The energy balance partitions available energy (from the sun) into canopy and soil for plant growth and evapotranspiration using Beer's law. The water balance includes simulation of infiltration, runoff, evapotranspiration (based on Penman-Monteith equation), soil moisture redistribution (based on Richards equation), drainage and water table interactions. For plant growth, a carbon balance is performed to calculate carbon assimilation using integrated rate methodology (Wu *et al.*, 1994) and dynamically allocates carbon to leaves, stems and roots, and to estimate canopy resistance for plant transpiration. WAVES also undertakes a solute balance to estimate solute transport within the soil column and the impact of salinity on plants.

The WAVES model was originally developed for catchment-scale modelling (Zhang and Dawes, 1998) and has been tested in a number of catchments. Zhang and Dawes (1998) report on the application of WAVES for modelling: water and salt movement on the Chowilla Floodplain, South Australia; growth of irrigated lucerne over a shallow saline water table; episodic recharge under crop rotations; water use efficiency of irrigated crops in the North China Plain. Slavich *et al.* (1998) technically reviewed the canopy growth and transpiration model of WAVES plant growth and found that WAVES modelled the interactions consistently with current understanding of plant responses to soil and climatic effects and found good correlation between modelled and measured results.

The limitation of all the models is the inability to account for temporal changes in the soil hydrology and vegetation community and the effect of events such as pest infestation, cyclones and tornadoes, fire and other such events. In addition, modelling of long-term performance of compacted clay is difficult with any model without increasing permeability over time to account for preferential flow through desiccation cracks (Roesler *et al.*, 2002).

2.4 Temporal Changes

Changes in compacted clay barriers have now been reported widely in the literature. One of the first notable experiments was reported in a German study on conventional compacted barriers. Melchior (1997) measured increasing drainage from conventional compacted barriers (comprised of 750 mm cover soil over a 600 mm compacted soil) over an eight year period. Dye tracer studies and excavation of the covers was reported to show small fissures from desiccation initially but were followed by penetration of roots into and through the compacted layer. The permeability of the compacted layer increased from 1×10^{-10} m/s at construction to 2×10^{-9} m/s two years later and after five years had increased to a maximum of 1×10^{-7} m/s. The increases in permeability and drainage followed dry summers in 1989, 1992 and 1995. Albright *et al.* (2006) also reported a change in saturated hydraulic conductivity after a drought at the ACAP test section in Georgia. Large cores taken from the site after a drought showed the saturated hydraulic conductivity had increased from 1×10^{-9} m/s to 1×10^{-6} m/s. Albright *et al.* (2006) also conducted dye tracer experiments in the field which revealed the presence of large cracks in the compacted clay.

Joshi and Maulé (1999) found evidence of macropores in a heavy textured soil to 1.5 m depth, suggesting that cracking can occur to significant depth in heavy clay and increasing the thickness of a compacted clay barrier may not improve longer term hydraulic performance. Montgomery and Parsons (1990) reported that the desiccation cracks observed in a compacted clay barrier in Wisconsin after a drought were not observable 1½ years later, though they noted that the drainage did not return to pre-drought values and that the drainage was not correlated with precipitation events, suggesting drainage occurred predominantly via porous media rather than preferential flow paths.

Albrecht and Benson (2001) conducted laboratory trials with compacted soil cores of various clay sources and subjected these cores to wetting and drying cycles. They found that the hydraulic conductivity increased by as much as 500 times and that the shrinkage cracks and largest increases in hydraulic conductivity appeared after the first drying cycle. Upon rewetting for 350 days, the desiccation cracks did not close unless over 60 kPa of effective stress was applied to the clay. As this stress is unlikely to occur in conventional covers, they concluded that the desiccation damage is likely to be permanent.

The changes in soil properties over time do not appear to be limited to the compacted clay barrier. Benson *et al.* (2007) compared the hydraulic properties of phytocaps at construction with their values 1 – 4 years after construction in the ACAP test sections. Overall, they reported similar changes in saturated hydraulic conductivity for all sites over a similar timeframe, suggesting that these changes are irrespective of climate. After 1 – 4 years, the saturated hydraulic conductivity had increased by a factor of up to 1×10^{-4}, saturated moisture content increased by a factor of 2 and the shape of the moisture retention curve also changed. The magnitude of the change was greatest for denser or more plastic clayey soil. Benson *et al.* (2007) also reported that most of the phytocap soil tended to a narrow range of values, such that the saturated hydraulic conductivity was 10^{-7} – 10^{-5} m/s, saturated moisture content was 0.36 – 0.40 and van Genuchten's parameters (van Genuchten, 1980) of α between 0.002 kPa^{-1} and 0.2 kPa^{-1} and n of 1.2 – 1.5. Kelln *et al.* (2007) also found changes in uncompacted covers in a subhumid continental climate, with saturated hydraulic conductivity increasing by 1 to 2 orders of magnitude in the first year and then stabilising for the subsequent 4 years.

An increase in dry bulk density has also been reported for phytocaps. McGuire *et al.* (2009) reported an increase in dry bulk density of a clay loam phytocap from < 1.3 t/m^3 at construction to 1.44 t/m^3 after 2 months and after 3 years the dry bulk density had increased marginally to 1.46 t/m^3. Michael (2010) also noted an increase of approximately 0.1 t/m^3 in the topsoil and the base of the profile, though it should be noted only the topsoil increase was statistically significant.

More complex development of structure was not found by Breshears *et al.* (2005) 10 years after the installation of 2 landfill covers. They noted that horizonation was not evident and although macropores were present there was no clearly defined structure and bulk density was highly variable but showed no trend over time. Dye tracer infiltration studies showed that the dye stained the matrix for the upper 5 – 10 cm but then stains followed macropores created by burrowing animals, ants and roots.

Breshears *et al.* (2005) also reported the vegetation changes over 10 years. The vegetation's total biomass increased over time and colonisation by other species (i.e. not those planted in the cover at installation) attributed to approximately 10 – 40% of the total biomass. Roots, as expected, were mainly in the upper 10 – 20 cm but extended to > 0.9 m in the phytocap and had formed a dense mat on top of the geotextile placed at 71 cm depth in the other cover.

As a result of their findings, Breshears *et al.* (2005) hypothesised that the sustainability of the cover over time is more influenced by environmental factors (such as plant succession, soil profile development, erosion and intrusion by plant roots and animals) than the engineering factors (such as soil thickness and texture) or the initial ground cover or vegetation.

2.5 Summary, Conclusions and Data Gaps

The water balance defines the factors that influence the amount of drainage which may occur in any environment. In natural environments, as well as in landfill environments, evapotranspiration is the dominant loss in the water balance and maximising this through selection of deep rooted plants with moderate to high water use requirements can aid in minimising drainage.

Final covers for landfill play an important role in minimising the potential for environmental impact into the longer term. Research into phytocaps has shown that they are able to perform equivalently to a compacted clay barrier in many climatic settings; however, most of the research has been undertaken in the northern hemisphere in climates which include snow. In addition, northern hemisphere soil has been enriched through more recent glacial and seismic activity than the more ancient soil in Australia. Further to this, many studies have shown the importance of native vegetation in the performance of the phytocaps and, with the exception of the Wollert trial, the impact of Australia native species on the water balance of a landfill cover has not been extensively researched.

Modelling of the water balance is often used for the design of a phytocap but has also been used to compare with field monitoring data. These simulations have shown that models can simulate the water balance of a final cover but that there are some discrepancies between the timing and magnitude of the predicted water balance and the field measured parameters. Most models used do not simulate feedback between the atmosphere, vegetation and soil and hence the WAVES model, which includes this simulation but has not been tested for landfill covers, may provide a more accurate tool for water balance predictions.

The research conducted to date has shown that the compacted clay barriers which have been used to minimise drainage into the landfill's waste are not an effective barrier as drought, frost and time tend to result in drying and cracking and that even at depth and after rewetting, their hydraulic conductivity is permanently affected. Phytocaps are also affected by changes over time but the research conducted appears to suggest that these changes are not as drastic; the phytocap is not reliant on a barrier effect to control. However, given the climatic and pedological differences between Australia and many other countries, the importance and magnitude of these changes may be different in the Australian context.

The Australia Alternative Cover Assessment Program, as documented in this thesis, will investigate the potential for phytocaps to perform hydraulically in the Australian environment and also to assess the potential for temporal changes to impact on the longer term water balance of both compacted clay barrier and phytocaps.

3. General Methodology

The same general methodology was used on all sites. Variations between the sites related to available machinery and materials. This chapter details the general methodology with site specific information and construction details provided in Chapter 4.

3.1 Methodological Framework

Five trial sites (Table 3.1) were selected in different climatic regimes of Australia (Figure 3.1). The climatic regimes shown are based on vegetation, as defined by Köppen, and as described and mapped by Bureau of Meteorology (BoM, 2005). The trial sites ranged from the summer-dominant, high rainfall around Townsville to the winter-dominant, low rainfall around Perth and Adelaide and included warmer (subtropical) and cooler (temperate) sites with rainfall all year around Lismore and Melbourne, respectively.

Table 3.1 Field Trial Sites Location Details

Landfill Name	Location	Operator	Climate Zone
Vantassel Street Landfill	Vantassel St, Stuart. 10 km south Townsville Queensland	Townsville City Council	Tropical rainforest (monsoonal)
Lismore Waste Facility	Wyrallah Rd, East Lismore, New South Wales	Lismore City Council	Subtropical, no dry season
Taylors Road Landfill	Taylors Rd, Lyndhurst. 40 km south-east of Melbourne, Victoria	SITA Environmental Solutions	Temperate, no dry season (warm summer)
Southern Waste Depot	South Road, McLaren Vale. 35 km south of Adelaide, South Australia	Lucas Earthmovers	Temperate, distinctly dry (and warm) summer
Henderson Waste Recovery Park	Rockingham Road, Henderson. 30 km south of Perth, Western Australia	City of Cockburn	Temperate, distinctly dry (and hot) summer)

The basic methodological framework for the five trial sites at Townsville, Lismore, Melbourne, Adelaide and Perth was:

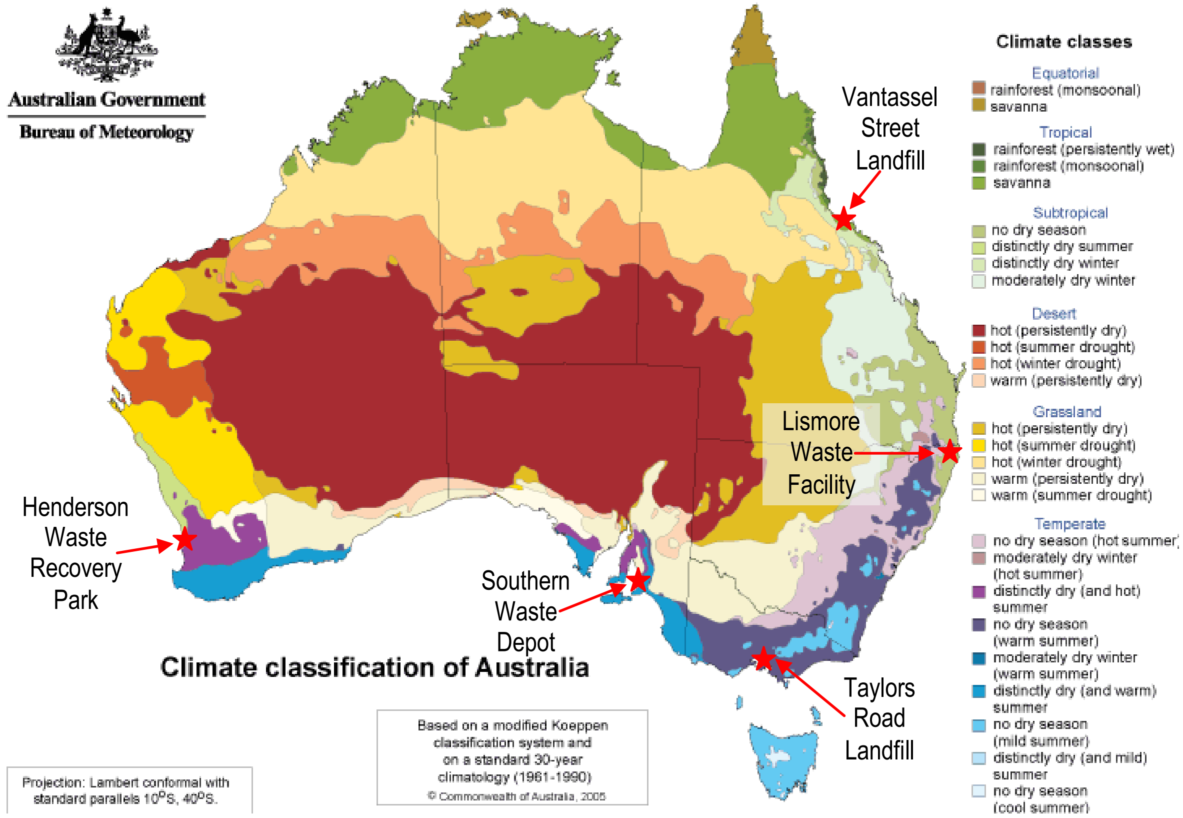

Figure 3.1 Trial Site Locations shown on Climate Classification of Australia Map (Source of base plan: BoM, 2005)

1. Characterise the climate, soil and vegetation for the site. Soil characterisation included identifying and characterising available and suitable soil for phytocap and conventional cover;
2. Undertake preliminary design using water balance methods;
3. Construct field trials using lysimetry and install soil moisture and suction instrumentation;
4. Monitor water balance parameters;
5. Compare water balance performance of the phytocap compared to the conventional cover.

As part of the A-ACAP, the trial sites were also used for gas monitoring and plant growth analysis.

3.2 Site Characterisation

3.2.1 Climate

Long-term climate data are recorded by the Australian Bureau of Meteorology (BoM, 2011). The number of parameters measured at each recording station varies, from rainfall and/or temperature only to complete weather records. A summary of these data for the closest recording station to each trial site is shown in Table 3.2. Using Hauser and Gimon's phytocap potential ratio (PET/P), Southern Waste Depot and Henderson Waste Recovery Park have a good opportunity, Vantassel St Landfill and Taylors Rd Landfill are likely to have a fair opportunity to use a phytocap with Lismore Waste Facility in the marginal group.

Table 3.2 Climate Summary for Nearest BoM Recording Stations and PET:P Ratio

Landfill	Recording Station (Site number)	Mean Annual (mm/yr) Precipitation	PET*	PET/P
Vantassel St Landfill, Qld	Townsville Aero (032040)	1,113.1	1,604	1.4
Lismore Waste Facility, NSW	Lismore (Centre St) (058037)	1,343.1	1,269	0.9
Taylors Road Landfill, VIC	Cranbourne Botanic Gardens (086375)	811.7	1,022	1.3
Southern Waste Depot, SA	Old Noarlunga PO (023740) & Noarlunga (023885)	521.6	1,163	2.2
Henderson Waste Recovery Park, WA	Medina Research Centre (009194)	767.2	1,353	1.8

Water balance models require long-term, daily climate data which are not readily available from BoM. DERM (2011) use BoM recording stations to create long-term records using either patched point or direct drill daily datasets for particular sites. Patched point datasets use measurements from a BoM meteorological stations but “patch” missing data by interpolation. Direct drill datasets use gridded, interpolated data to create meteorological data for a specific location. Patched point data are appropriate where a recording station is located near to the proposed site, while data drill datasets are used for sites where appropriate recording data are not available. These datasets were created for each trial site for use in water balance modelling.

3.2.2 Soil

Soil borrow sources were identified by the site owners at each landfill. Selected materials were sampled from stockpiles and then analysed for soil physical and chemical properties using Australian Standards (Standards Australia, 1995; 2001a; 2001b; 2003a; 2003b) or the Australian Soil and Land Survey Handbook series (McKenzie *et al.*, 2002; Rayment and Higginson, 1992). The number of analytes measured and the timing of analysis varied between sites, with some analyses undertaken prior to construction and other on samples taken during construction. The soil physical properties measured on soil at all sites were:

- Particle size analysis;
- Saturated hydraulic conductivity;
- Standard compaction;

- Soil moisture characteristic curve also known as the soil moisture retention curve.

Soil chemical testing was undertaken by CSBP, a commercial soil and plant analysis laboratory in Perth, WA, and included:

- pH;
- Electrical Conductivity;
- Exchangeable Cations (sodium, potassium, calcium, magnesium);
- Extractable Phosphorus (Colwell);
- Extractable Potassium (Colwell);
- Extractable Sulfur ($KCl_{4}0$);
- DTPA - Extractable Iron;
- Total Nitrogen;
- Total Organic Carbon (Walkley-Black).

The results of these tests are detailed in Chapter 4, which describes the trial for each site in detail.

3.2.3 Vegetation

Suitable vegetation for the trial was selected from endemic species for each area and also on species which potentially grow in many areas. Variations exist between the vegetation types (i.e. trees, shrubs, herbs and/or grasses) and the species planted at each site but a variety of species were planted at each site and all vegetation was native and endemic to the area to maximise the potential for growth and survival.

Vegetation was established from tubestock to enable control of the mix and placement of species within the trial area and to maximise vegetative coverage. Over the short timeframe of the trials, tubestock will establish faster than seed. It should be noted that direct seeding establishes healthier plants (Florabank, 2008) which are more tolerant of site conditions than tubestock, which often requires irrigation to aid establishment.

3.3 Phytocap Design for Trials

For all trial sites, the main design objectives were to provide a minimum soil depth for plant root development and to allow drainage through the profile to ensure valid drainage data could be collected for each site. Two methods were used to develop the designs for the phytocaps used in the trials.

At Taylors Rd Landfill, a simple net water balance was used to determine an approximate profile depth. Benson and Chen (2003) recommend a method to estimate the required phytocap thickness based on the minimum drainage requirement. Michael (2010) found that this method over estimated profile thickness as plant transpiration is not included in the calculation. So for the Taylors Rd Landfill a simple net water balance approach was based on average long-term monthly rainfall and potential evapotranspiration. The nett rainfall was calculated, i.e. gross rainfall – potential evapotranspiration, and then the aggregate of months with positive nett rainfall defined the profile soil water storage required. To provide a more conservative estimate, the profile soil water storage was based on the available water content and not the total profile water. The available water content is the difference between the field capacity and the permanent wilting point.

For the remaining 4 trial sites, water balance modelling was used to design the phytocap profile. A number of water balance models have been used by authors to predict the water balance from landfills. A summary of these models is provided in Table 3.3 and is based on a comprehensive comparison presented by Gross (2005) and Dawes *et al.* (1998). This comparison shows that the WAVES model is similar to HYDRUS, LEACHM and UNSAT-H in terms of the water balance assumptions but that it internally simulates vegetative growth and has feedback loops between the atmosphere, soil and vegetation, which are only present in EPIC and HELP. As the WAVES model was developed in Australia and local support for using the model was available, this model was selected for designing the phytocap test cells. Details of the design modelling are presented in the site specific methodology in the following chapter.

3.4 Field Trials

Large scale field trials were established to maximise the potential for water balance measurements to be representative of full-scale landfill cover conditions. Non-weighing lysimeters were chosen to facilitate water balance measurements as a number of authors have compared measurement methodologies and lysimetry has been shown to provide the most accurate method of measuring drainage (Benson *et al.*, 1999; Gee, 2004; Abichou *et al.*, 2006). It is also important to understand the limitations of lysimetry, which include:

- lower boundary conditions not reflecting landfill conditions (Abichou *et al.*, 2006);
- underestimation of drainage (Abichou *et al.*, 2006; Scanlon *et al.*, 2005);

Table 3.3 Comparison Summary of Common Water Balance Models for Phytocaps and WAVES

Model	Full Name	Reference	Development Application	Dimension	Runoff	Soil Moisture Movement	Transpiration
EPIC	Environmental Policy Integration Climate	Mitchell *et al.* (1998)	Evaluate the effects of wind and water erosion on plant growth and food production	1D with lateral flow	SCS Curve Number	Storage routing	LAI function of biomass considering water, nutrient, temperature and radiation stress. Root growth modelled. Positive feedback between growth and stresses
HELP	Hydrologic Evaluation of Landfill Performance	Schroeder *et al.* (1994)	Planning tool for evaluating barrier-type landfill covers and movement through waste and bottom liner	Quasi 2D	SCS Curve Number	Storage routing	LAI function of biomass considering water and temperature stress. Root growth modelled. Positive feedback between growth and stresses
HYDRUS		Simunek *et al.* (1998 and 1999)	Estimate water flow in unsaturated soil that support plant growth	1D and 2D versions	Precipitation > infiltrate rate	Richard's equation	Exponential root distribution, above ground biomass not considered
LEACHM	Leaching Estimation and Chemistry Model	Hutson and Wagenet (1992)	Groundwater recharge including solutes	1D	Precipitation > infiltrate rate	Storage routing and Richard's equation	Constant plant cover and root distribution
UNSAT-H	Unsaturated soil water and heat flow	Fayer (2000)	Estimate recharge fluxes for waste disposal facilities in arid sites	1D	Precipitation > infiltrate rate	Richard's equation	User specified LAI and root density
WAVES	Water Atmosphere Vegetation Energy and Solutes	Dawes *et al.* (1998)	Catchment scale water and salinity modelling	1D with lateral flow	Precipitation > infiltrate rate	Richard's equation	LAI function of carbon balance and considers water, temperature, light and nutrient stress. Feedback loops between growth, soil and climate

- isolation of soil from potential moisture and temperature effects of the underlying waste. Michael (2010) found this to be significant at Wollert landfill, though it should be noted that leachate recirculation is practiced at Wollert and this is not the case at any of the proposed trial sites.

Abichou *et al.* (2006) modelled lysimeter design and suggested that lysimeters should be at least 2.5 times larger than the soil thickness, at least 7 m wide and at least twice as long as wide; have side walls at least 0.35 m high (to minimise lateral diversion) and an end wall to the surface.

For the A-ACAP test sites, side-by-side comparison of a phytocap and a conventional cover prescribed for that site was established over waste-filled areas at 3 of the 5 test sites, with Lismore and Perth sites only establishing a phytocap test section. Adjacent to the lysimeter test sections are unlined "control" sections, constructed in a similar manner to the lysimeters but able to interact with the decomposing waste mass. An approximate design in plan view is shown in Figure 3.2.

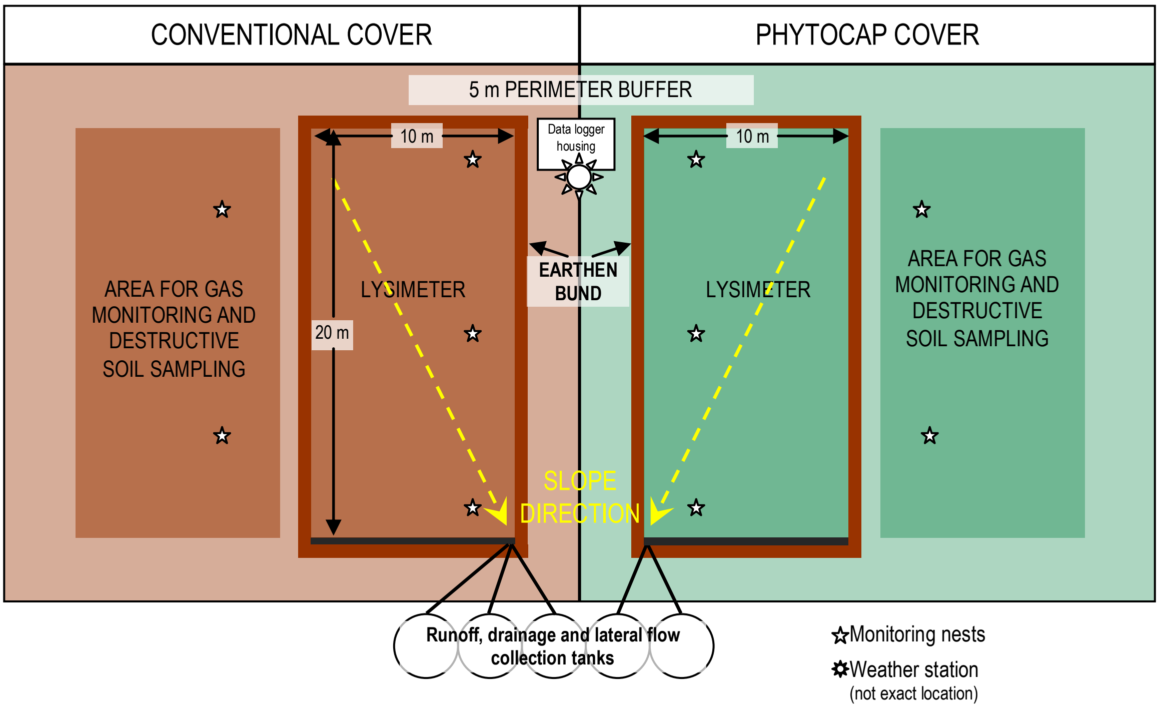

Figure 3.2 Conceptualised Plan View of Test Section Layout

3.4.1 Lysimeter Design

Lysimeters were used to measure the water balance parameters (rainfall, runoff, lateral flow, soil moisture and drainage) within a controlled profile depth. Large-scale lysimeters (10 m × 20 m) were constructed in each test cell in a similar manner to those used in the ACAP trials and as described by Benson *et al.* (1999). The lysimeters were made from HDPE welded to form a bath tub with walls to the surface (Figure 3.3). HDPE was welded by a trained technician and proof testing of welds was undertaken to ensure integrity of the liner, i.e. there were no holes.

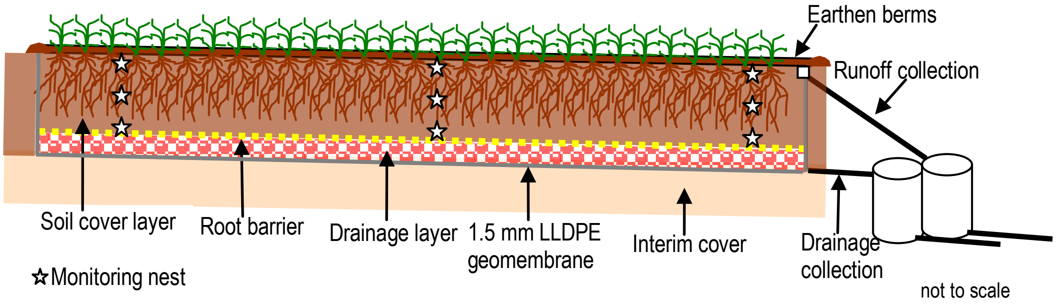

Figure 3.3 Conceptualised Cross-Section of Lysimeter. Phytocap design shown; conventional cover would also require lateral drainage collection

The features of the lysimeter from the surface to the base were:

- Earthen bunds were formed to prevent run-on, direct runoff and minimise preferential vertical flow on lysimeter walls. All test sections were constructed with slope and cross fall to direct flows to one corner. HDPE guttering was used to collect runoff at the surface with a Bidim™ geotextile flap trenched into the soil to ensure contact was maintained between the soil and prevent erosion at the leading edge.
- An HDPE flap was welded on the side wall at the interface of the soil and the compacted clay barrier in the conventional cover lysimeters to facilitate collection of lateral flow (Figure 3.4). Bentonite was placed beneath the flap to force lateral flow onto the flap. An HDPE pipe (Figure 3.4) was welded into the lowest corner to collect lateral flow.
- Below the cover soil, a root barrier was created by spraying Trifluralin™ (2.5 ml/m^2) on to the surface of the underlying soil layer, with the exception of Melbourne where Trifluralin™ was sprayed between A24 Bidim™ geotextile sheets.
- A separation layer was created to prevent plant roots accessing moisture which may collect on the base of the lysimeter. This separation layer was formed from soil material similar to that used for interim cover or subgrade, with the exception of Melbourne where aggregate was used (see Section 4.2.6 for specific details).
- Beneath the drainage layer, Flownet™ (a biaxial drainage net) was used to direct drainage to the collection corner. The Flownet™ was placed between two A24 Bidim™ geotextile layers to prevent soil infill and damage to the HDPE base.

Figure 3.4 Lateral Flow Collection Flap and Collection Pipe

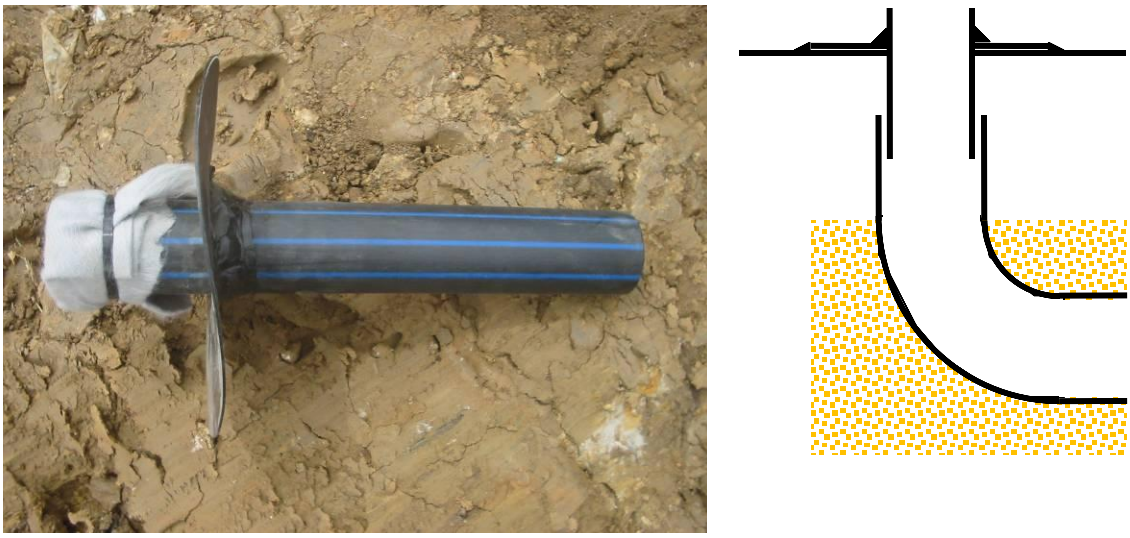

Figure 3.5 Welded Drainage Pipe (left) and Schematic Cross Section of Placement (right)

- At the base of the lysimeters, a drainage pipe was welded to the lowest corner to collect drainage (Figure 3.5, left). The pipe was sleeved into a larger diameter pipe to allow for preferential settlement and packed with sand to provide support (Figure 3.5, right).

3.4.2 Control Area

An unlined area, called the “Control”, was established adjacent to the lysimeters. The control areas were constructed in a similar manner to the lysimeters but were not bounded by an HDPE liner. The control areas were instrumented (as detailed below) to allow comparison of the soil moisture conditions and allow assessment of the impact of the lysimeter pan on the moisture regime, in particular the potential effects of methane oxidation, which releases water as part of the reaction. The control areas are able to interact with the underlying waste mass and hence the impact of moisture and gas on the water balance, the vegetation and the atmosphere can be assessed. Vegetation effects and gas emission do not form part of this thesis and were the subject of concurrent research by Benaud (2011) and Sun *et al.* (2011).

3.4.3 Monitoring Equipment

Monitoring equipment was used to measure weather, water balance flows and soil moisture and suction as listed in Table 3.4. All equipment, with the exception of flow meters and soil suction sensors, were purchased from ICT International.

Table 3.4 Monitoring Equipment Used at A-ACAP Field Trial Sites

Type	Parameter	Sensor/probe
Datalogger		ICT SL5 EnviroStation (ICT International, undated_b)
Weather	Rainfall	Tipping bucket
	Temperature	Temperature probe (screened)
	Wind Speed	Anemometer
	Wind Direction	Wind vain
	Solar radiation	ICT electronic sensor
	Barometric pressure	ICT electronic sensor (screened)
	Relative humidity	ICT electronic sensor (screened)
Water Balance Flows	Runoff	Electromagnetic flow meter – Aquamaster F (ABB, undated) Dosing siphon
	Lateral Flow	Tipping bucket
	Drainage	Tipping bucket and dosing siphon
Soil Storage	Soil volumetric moisture	MP406 frequency domain reflectometer (ICT International, undated_a)
	Soil suction	CS229 heat dissipation matric potential sensor (Campbell Scientific, 2006)

The location of the weather station and data logger varied depending on the site configuration. Water balance flow sensors were always located downslope of the test sections. The electronic flow meters reported erroneous readings, e.g. a few litres of runoff recorded even when rainfall had not been received in the preceding hours (sometimes days). The flow meters at the Adelaide site were subjected to frequent inspections and extensive testing, including in the laboratory by University of Adelaide instrument technicians (Figure 3.6). Although this testing reduced the random recordings, the flow meters proved to have too high resolution to be effective in measuring low flow runoff events. Michael (2010) also noted that flow meters did not record slow flow rates and substituted flow meters for tipping bucket devices to measuring runoff.

Figure 3.6 Laboratory Testing of Electronic Flow Meters at University of Adelaide

Dosing siphons were installed in 2008 as backup sensors for the tipping buckets (see Chapter 4 for specific details), with the exception of Adelaide where the drainage was low and the tipping buckets proved adequate. Additional dosing siphons were installed at the Perth and Townsville sites to measure runoff. Each dosing siphon was calibrated prior to installation by measuring the volume ejected for each siphon event over a number of events and averaging the volume.

Soil storage monitoring nests were placed in the landfill covers, with three nests placed in each lysimeter (upslope, centre and downslope) and 2 nests (upslope and downslope) in control areas. Each nest comprised one volumetric soil moisture sensor and one soil suction sensor placed together at three depths, top (150 mm below the soil surface), middle (mid way through the phytocap or at the clay barrier interface in the conventional cap) and bottom (150 mm above the base of the profile). The horizontal and vertical placement of the monitoring nests is shown in Figures 3.2 and 3.3. Both the volumetric moisture sensors and the soil suction sensors required calibration.

3.4.4 Soil Moisture Sensor (MP406) Calibration

Soil moisture sensors required calibration for each soil type. Individual sensors do not require calibration as there is unlikely to be variation between sensors. The calibration for soil type and temperature has been reported for the major soil materials by Sun *et al.* (2010). The calibration curve used for each soil type is shown in Table 3.5. The calibration undertaken on the Adelaide topsoil was also used for the Melbourne conventional cap topsoil, which was a similar texture and colour. The "average" calibration for all soil was used for compacted clay.

Table 3.5 Soil Moisture Sensor (MP406) Calibration Curve Used for Each Soil Type

Site	Soil Description	Corrected Moisture Content
Adelaide	Topsoil	= 0.9235 × [reading] – 0.0182
	Subsoil	= 0.8095 × [reading] + 0.0338
	Compacted clay	= 0.8591× [reading] +0.0112
Melbourne	Sand + Compost	= 0.9467 × [reading] +0.0242
	Topsoil	As for Adelaide topsoil
	Compacted Clay	= 0.8591 × [reading] +0.0112
Townsville	All soil (except clay)	RAW DATA USED
	Compacted Clay	= 0.8591 × [reading] +0.0112
Lismore	All soil	= 0.8448 × [reading] -0.0019
Perth	All soil	= 0.7896 × [reading] -0.0026

The calibration curve for the Townsville soil did not show a similar distribution to the other calibration curves and was highly non-linear. Correction of the field readings of moisture content with the calibration curve resulted in unrealistic corrected moisture contents when compared to the laboratory results for the moisture retention curve. As a result, the calibration curve was not used and values were left uncorrected. As the water balance analysis focuses on changes in moisture content rather than the absolute values, this omission is unlikely to be significant in the context of this thesis.

3.4.5 Soil Suction Sensor (CS229) Calibration

The soil suction sensors require individual calibration but do not require calibration for each soil type. Differences in the pore size distribution and hence moisture retention of the ceramic outer of the suction sensor makes individual calibration a requirement. A detailed discussion of the theory and calibration of the CS229 heat dissipation matric potential sensors is provided by Flint *et al.* (2002) and is not repeated herein.

The CS229 sensor contains a thermocouple surrounded by a ceramic cylinder which was then cabled to an ICT proprietary interface so it could communicate with the logger. The sensor reports temperature difference (ΔT) which is related to the soil's matric potential. The ΔT reported by each sensor needs to be calibrated against a known matric suction. As the calibration is curvilinear, it is necessary to undertake the calibration at various suctions. Campbell (2006) recommends measuring the ΔT at air dry, saturation and 5 data points, 4 points between 20 kPa and 500 kPa and one point at > 1,000 kPa.

Calibration methods reported by Flint *et al*. (2002) and Campbell (2006) used modified moisture retention apparatus to achieve the desired soil suction on 3-6 probes at a time. Due to the large number of sensors requiring calibration, i.e. 120 sensors, a bulk method of calibration was developed. A summary of the methodology is provided here with further details given in Appendix A.

CS229 sensors were calibrated in batches of 30 sensors using large plastic containers filled with warm, deaerated water or soil compacted to the approximate density and conditioned to the moisture content equivalent to the required suction. While equilibrating, the sensors were placed in a constant temperature room and plastic sheeting used to prevent moisture loss. Soil moisture content was determined at each sensor location once the sensor had equilibrated. To achieve air-dry, the sensors were hung from racks in an oven set at 35-40 °C. The oven was sealed with plastic bags to assist in maintaining temperature. Sensors were equilibrated until constant ΔT for 24 hours was recorded. For wetter suctions and air-drying, this process took 2-7 days, while the drier suctions, equilibration required weeks.

The field data reported higher and lower ΔT readings than were measured in the laboratory and calibrated data did not conform with moisture content traces, e.g. at moisture contents nearing saturation, CS229 suction was markedly less than saturation. The calibration method and the field validation are discussed in Appendix A.

The CS229 sensors also record soil temperature. Data thought erroneous was removed from the soil temperature traces (and thus appear as gaps in all soil temperature vs time figures in Chapter 5). The longevity of the CS229 sensors was also limited, in most cases to just over 12 months.

3.5 As Constructed Soil Sampling

Bulk soil samples were taken from the soil placement layers during construction. On average, 2 – 3 large undisturbed core samples were taken from each soil material and in some cases from each lift.

The cores were collected in thick-walled PVC pipes by excavating a circular trench larger than the core diameter, carefully trimming soil material and gradually sliding the pipe over the soil to provide support and protection during removal and transport (Figure 3.7). While taking the undisturbed sample, a bulk disturbed sample was also collected for analysis. Selected samples were used to determine the particle size distribution by hydrometer, dry bulk density and moisture retention at 1 kPa, 10 kPa and 30 kPa by ceramic plate hanging column. For the compacted clay, the plastic limit and linear shrinkage were also determined on the bulk sample.

Figure 3.7 Trenching for Undisturbed Soil Sample Collection (left) and Pipe Slid Over Core Sample (right)

3.6 Data Validation and Replacement

Data were recorded on the data loggers on an hourly basis for all sensors. Data have been validated where possible by comparison with other sensors and/or comparison with data collected at the site or at a nearby BoM weather station. Data were downloaded either weekly or fortnightly when possible to minimise data losses. Regardless, missing data are present in all datasets due to low battery voltage, sensors malfunctioning, which in some cases prevented the data logger from recording any data, and occasionally intermittent faults which were difficult to solve in the short term. Where realistic, missing data have been substituted or interpolated. The data validation and missing data protocol for each sensor type is shown in Table 3.6.

3.7 Summary and Conclusions

The proposed trial sites cover 5 major climatic regions in Australia with the trial designs accounting for the variation in climate, vegetation, soil type and regulatory requirements. It should be noted that the profiles were generally under-designed to ensure drainage would occur so that useful research data could be obtained.

Table 3.6 Data Validation and Missing Data Protocol Used for Sensors

Sensor	Data Validation	Missing Data Protocol
Rain gauge	BoM weather station or site data	
Other weather sensors	BoM weather station	None
Runoff	Rainfall received at the same time or in the preceding hour; runoff volume does not exceed rainfall	None
Lateral flow and drainage	Soil moisture increase at relevant depth and/or rainfall preceding event. Correlation between primary and secondary measurement devices, where present	Each event was reviewed. When logging event skipped usually reported at next logging event. Where this did not occur and flow was recorded before and after missing data, data were interpolated for up to 24 hours
Soil moisture	Moisture content within range of saturated and air dry measurements	Missing data interpolated for up to 24 hours. For the shallowest recording depth, data were not interpolated if rainfall was received during the period of missing data
Soil temperature	Soil temperature within 10 °C of ambient temperature	Missing data interpolated for 1 hour only

The trials were designed based on overseas research and experience to ensure that the research would provide comparable, justifiable and precise data. Lysimetry was used to provide accurate measurement of the water balance parameters. Many other research trials, such as the ACAP trials in the US, did not place the test sections over landfill cells. This research was conducted over completed landfill cells and hence the designs included unlined test sections to include the potential effects from temperature, moisture and gas from the decomposing waste. Placement over waste cells resulted in a potential for differential settlement of the underlying waste mass so the lysimeter design was slightly modified where possible to allow some movement in HDPE liner and pipework. The following chapter provides details of the site-specific design for each of the field trial sites.

Instrumentation used at the A-ACAP trial sites covered a range of water balance parameters. Redundancy in soil moisture/suction sensors and back up instruments, particularly for drainage, provided confidence in the data collected (with the exception of runoff data) and resulted in only short periods where data substitution was required and only a few occasions where data gaps are present. The data quality at each site is discussed in Chapter 5 prior to the discussion of results.

4. Site Specific Field Designs

The general methodology for trial design was consistent between the 5 trial sites, as discussed in Chapter 3. Site specific aspects varied depending on the climatic regime, available construction materials and machinery and the proposed vegetation. This chapter describes the site specific design and construction details.

4.1 Adelaide Site

4.1.1 Landfill Location and Characteristics

Southern Waste Depot (SWD) is a landfill operated by Lucas Earthmovers at McLaren Vale, 30 km south of Adelaide (35.22° S; 138.49° E), shown in Figure 4.1. SWD is licensed by SA Environment Protection Authority as a landfill able to receive low level contaminated waste. The site covers 37 ha and receives approximately 80,000 – 100,000 tonnes waste annually, with over 3 million cubic metres total capacity. The waste streams include construction and demolition waste, commercial and industrial waste, low level contaminated waste and listed waste (asbestos, sewage treatment residues, etc.). The landfill incorporates gas and leachate collection systems.

Figure 4.1 Southern Waste Depot and Trial Area (Source of base plan: Google, 2011)

The trial area, shown in Figure 4.1, was positioned over Cell 1 which was completed in 2003. The prescribed final cover for this cell was a 0.6 m low permeability (< 1×10^{-9} m/s) compacted soil overlain by 0.9 m growing medium, including 0.1 m topsoil as the upper portion, that will sustain the approved vegetative cover (Tonkin Consulting, 2004). The compactive effort required to achieve the low permeability layer is large, resulting in high construction costs. In addition, the maintenance costs are often high as the growing medium is not high quality.

4.1.2 Climate

The McLaren Vale climate consists of cool, wet winter and distinctly dry and warm summers, consistent with a Temperate/Mediterranean climate (BoM, 2005). The closest Bureau of Meteorology recording station is at McLaren Vale, with rainfall records from 1938 to present. Stations at Noarlunga (Station No. 23885; 7 km N), Kuitpo (Station No. 23887 and 23818; 18 km E) and Myponga (19 km S) also record temperature, while Adelaide Airport (Station No. 23034; 30 km N) is the closest station recording all weather data. A SILO dataset was created from 1 January 1957 to 5 September 2006 using a data drill method (i.e. where data are interpolated from the nearest BoM weather stations) for the site co-ordinates.

The mean annual rainfall calculated from the dataset for Southern Waste Depot is 515 mm and ranges from ≤ 23 mm/month in summer (December to February) to 62 – 73 mm/month in winter (June to August), as shown in Figure 4.2. Summer rainfall has varied from 0 – 140 mm/month while winter rainfall is also highly variable ranging from 7 – 193 mm/month. Mean pan evaporation is 1,588 mm/yr and exceeds rainfall for 10 months of the year. Annual evaporation is three times greater than rainfall, suggesting that plant transpiration will be limited by moisture availability.

The mean daily temperatures range from 15 – 27 °C in summer to 7 – 16 °C in winter (Figure 4.2). On average, summer maximum daily temperatures can exceed 35 °C for 1 week every year while winter minimum daily temperatures can be below 2 °C for 1 day/year. These ranges show that temperature stress will limit plant growth in summer and winter, though frost is unlikely.

4.1.3 Soil Characterisation

Initial soil characterisation was undertaken pre-construction with disturbed soil samples collected from potentially suitable soil stockpiles at Southern Waste Depot, i.e. silty loam topsoil, clayey sand subsoil and purple-grey silty clay (created by crushing highly weathered shale). Small diameter,

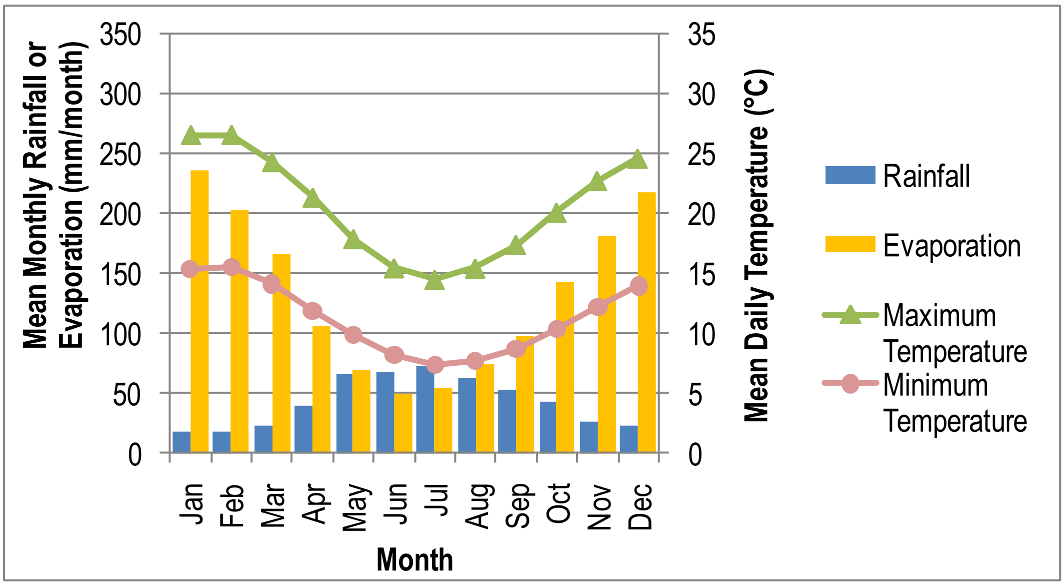

Figure 4.2 Mean Climate Data for Southern Waste Depot

undisturbed cores were collected from the topsoil and subsoil stockpiles for determining moisture retention. The physical and chemical parameters determined are shown in Table 4.1. Soil chemical properties were not determined for the clay as this is not standard practice and due to the depth and density of material, it chemical properties are unlikely to have a significant impact on plant growth.

The topsoil is a sandy loam soil with available moisture holding capacity of 200 mm/m and moderately permeable. The soil is slightly alkaline, non-saline and slightly sodic with low organic matter content and low nutrient status. The subsoil is sandier and has lower available moisture holding capacity than the topsoil. Sandier soil generally has higher saturated hydraulic conductivity; however, the subsoil is sodic which is likely to be the cause of the lower saturated hydraulic conductivity. The subsoil is alkaline and slightly saline and has very low organic matter and nutrient status.

The clay used for the compacted clay barrier is predominantly silt rather than clay and is derived from crushing weathered shale. This material has the largest moisture holding capacity and when placed at near maximum dry density has an extremely low saturated hydraulic conductivity. The high silt content results in a very low plasticity and the linear shrinkage indicates that the material is non-expansive but has a medium potential to show volume change (Hazelton and Murphy, 2007). Overall, the clay material is considered to have a low potential to develop preferential flow paths from desiccation cracking.

Table 4.1 Soil Physical and Chemical Properties for Adelaide Final Covers

Property (units)	Average value for soil material		
	Topsoil	Subsoil	Clay[a]
Particle size distribution[b] (%)			
Gravel (>2 mm)	0.2	7.4	3.7
Sand (0.02 – 2 mm)	84.7	84.4	11.1
Silt (0.02 – 0.002 mm)	5.1	5.1	70.9
Clay (<0.002 mm)	10.0	3.1	14.3
Texture[b]	Sandy loam	Loamy sand	Silty loam
Soil water characteristic			
Permanent wilting point (volumetric moisture content @ 1500 kPa)	0.09	0.08	0.24
Field capacity (volumetric moisture content @ 100 kPa)	0.29	0.24	0.50
Saturated hydraulic conductivity (m/s)[c]	1.9×10^{-6}	1.3×10^{-6}	$<1.4 \times 10^{-11}$
Compaction			
Maximum dry density (t/m^3)	1.77	1.83	1.78
Optimum moisture content (g/g)	0.13	0.11	0.18
As constructed Dry Density (t/m^3)	1.41	1.39	1.72
Plastic Limit (g/g)	▨	▨	0.20
Linear Shrinkage (%)			7.5
pH ($CaCl_2$)	7.7	8.1	▨
Electrical conductivity (dS/m)	0.261	0.437	
Exchangeable cations (mEq/100 g)			
Sodium	0.95	2.27	
Potassium	0.42	0.32	
Calcium	9.6	8.41	
Magnesium	1.67	3.55	
∑(exch. cats)	12.64	14.55	
ESP	7.5	15.6	
Ca:Mg	5.7	2.4	
Total Organic Carbon (%)	0.561	0.153	
Total Nitrogen (%)	0.05	0.02	
Colwell Extractable Phosphorus (mg/kg)	11	2	
Extractable Potassium (mg/kg)	166	116	

▨ Not tested

[a] Clay permeability and standard compaction conducted by Adelaide Geotechnics

[b] Particle size distribution and texture based on Australian soil textural classifications (Marshall, 1947)

[c] Saturated hydraulic conductivity for topsoil and subsoil at 85% maximum dry density while for clay at > 95% maximum dry density.

4.1.4 Vegetation

The vegetation proposed for the Adelaide trial site was based upon native grasses. This site was selected for a grass only vegetation as grasses only were likely to provide a worst case scenario, given grasses potentially use less water than trees and shrubs. The use of grasses also reflected current practice and the potential end use of the site for grazing. Native grasses included cool season (C3) grasses as well as warm season (C4) grasses.

Approximately 2 months prior to planting, a non-selective, non-residual herbicide was used to kill all volunteer plants on the trial site. Observations suggested that the more weeds had established on the conventional cover than the phytocap. Planting was completed in late July 2007 using 8 perennial native grasses, as shown in Table 4.2. The availability of tubestock controlled the density of each species. *Themeda australis*, also known as *Themeda triandra*, set seed poorly in the summer of 2006/07 and hence available tubestock were limited. *Bothriochloa macra* and some *Austrodanthonia spp* tubestock were kept in the glasshouse for 3 months prior to planting due to timing and availability of tubestock material and this may have affected the survival of these species once planted.

Table 4.2 Species Planting List and Density for Southern Waste Depot, Adelaide

Photosynthetic Pathway	**Native Grass Species**	**Common Name**	**Planting density (plants/m^2)**
C3 – cool season	*Austrodanthonia linkii* *Austrodanthonia racemosa*	Wallaby grass Clustered wallaby grass	2.5
C3 – cool season	*Austrodanthonia geniculata*	Kneed wallaby grass	1.5
C3 – cool season	*Austrodanthonia caespitosa*	Ringed wallaby grass	2
C3 – cool season	*Elymus scaber*	Common wheat grass	3
C4 – warm season	*Themeda australis*	Kangaroo grass	0.5
C4 – warm season	*Bothriochloa macra*	Red grass	4
C4 – warm season	*Aristida behriana*	Bunch wiregrass	0.5
C4 – warm season	*Dichanthium sericeum*	Queensland bluegrass	2
		Total	**16**

4.1.5 Cover Design

The phytocap was designed based on preliminary modelling using WAVES (Water, Atmosphere, Vegetation, Energy and Soil; Zhang and Dawes, 1998). WAVES was used to estimate the required depth of cover for the phytocap to limit drainage into the waste and was based on 50 years of historical weather data from the closest Bureau of Meteorology station and soil physical parameters measured (where available) or estimated from the borrow source material. Plant input parameters were sourced from available literature or professional judgement where necessary.

Three phytocaps were modelled with varying thickness from 1 to 2 m. For comparison, water balance modelling was also undertaken for the conventional cover for the Adelaide site, which is comprised of 0.9 m of soil (including a minimum of 0.1 m topsoil) over a 0.6 m compacted clay barrier with a permeability ≤ 1×10^{-9} m/s. Preliminary modelling of the conventional cover showed that the moisture content decreased within the clay barrier from near saturation at the commencement of the modelling tending to permanent wilting point, as shown in Figure 4.3. The drying of the clay barrier from 40% to 26% volumetric moisture content suggests cracking through the barrier is likely, creating preferential pathways for moisture movement.

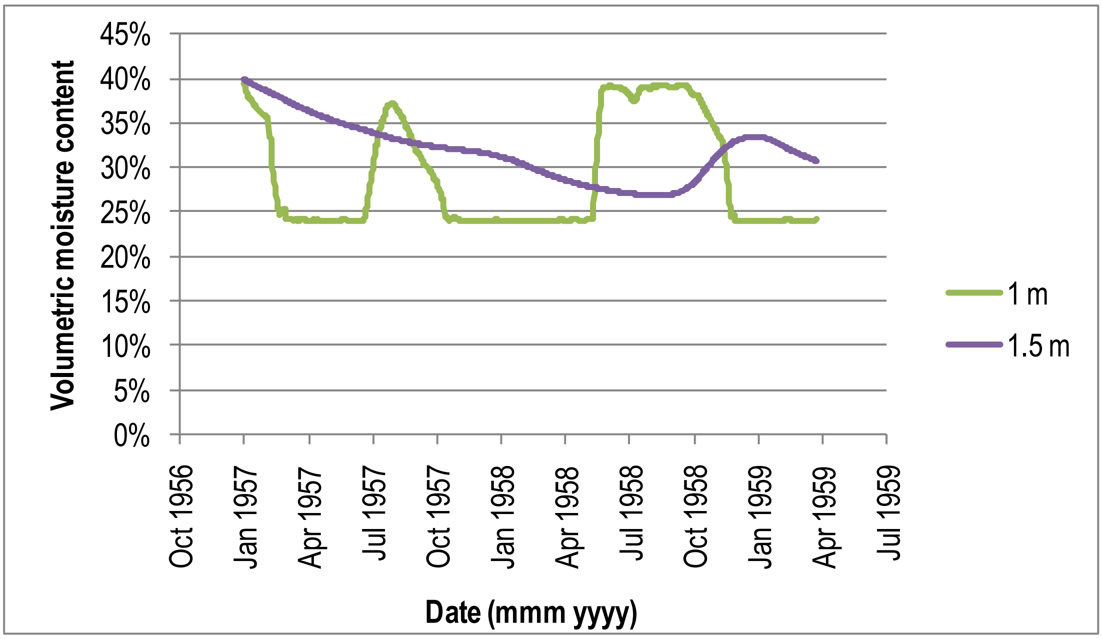

Figure 4.3 Modelled Soil Moisture Content within Compacted Clay Barrier over First 27 Months (January 1957 to March 1959)

Most water balance models can not model preferential pathways. To overcome this, Sadek *et al.* (2007) used a staged modelling approach with Hydrus-2D (Simunek *et al.*, 1999) where they introduced a "cracked" soil model with altered soil moisture characteristic curve and hydraulic conductivity once the clay had dried to below the plastic limit. Sadek *et al.* (2007) reported that modelling predicted that the clay dried in the first year, as did the Adelaide design modelling shown in Figure 4.3. Rather than use this more complex approach for the design modelling for Southern Waste Depot, instead a modelling scenario was used where the clay hydraulic input parameters were altered based on laboratory values and values recommended by Dawes *et al.* (1998). The input parameters for each soil type, i.e. topsoil, subsoil, compacted clay and uncompacted clay, are shown in Table 4.3. These input parameters were used in the Broadbridge and White (1988) hydraulic function to create moisture retention and hydraulic conductivity data for the WAVES model.

Table 4.3 Soil Hydraulic Input Parameters for Southern Waste Depot

Hydraulic Input	Input Value for Each Soil Material			
	Topsoil	Subsoil	Compacted Clay	“Cracked” Clay
Saturated hydraulic conductivity (m/s)	2×10^{-6}	1.3×10^{-6}	1×10^{-9}	1×10^{-7}
Saturated moisture content (v/v)	0.429	0.352	0.40	0.56
Dry moisture content (v/v)	0.09	0.09	0.24	0.24
Macroscopic capillary length (m)	0.3	0.3	2	2
C factor	10	1	1.05	2

WAVES modelling suggested the phytocovers can perform equivalently to the conventional cover, assuming desiccation and cracking of the clay occurs (Table 4.4). Plant growth appears similar between the phytocovers and conventional covers, with similar interception and transpiration suggested from modelling. Increasing the thickness of the cover decreases the drainage and increases the ET through plants accessing the extra stored moisture through the drier summer (Table 4.4). Also as expected, the change in the permeability of the compacted clay barrier increases the drainage and decreases lateral flow.

Table 4.4 Water Balance Summary from Phytocaps and Conventional Covers Modelled for Southern Waste Depot

Parameter	Modelled average annual water balance (mm and % of rainfall in brackets)				
	Phytocover 1 m	Phytocover 1.5 m	Phytocover 2 m	Conventional 1.5 m as placed	Conventional 1.5 m after drying
Precipitation	515	515	515	515	515
Interception	117 (23)	123 (24)	123 (24)	103 (20)	125 (24)
Evapotranspiration	349 (68)	357 (69)	364 (71)	412 (80)	369 (72)
Runoff	0.7 (0.1)	0.7 (0.1)	0.7 (0.1)	0.8 (0.1)	0.8 (0.1)
Lateral flow	0 (0)	0 (0)	0 (0)	0.5 (0.1)	0 (0)
Drainage	48 (9)	34 (7)	28 (5)	0.2 (0)	23 (4)

The drainage from the 1.5 m phytocover is greater than the conventional cover after drying but this is not significant as the ranges of annual drainage over the 49 years of modelling were similar with 0.6 – 174 mm/yr and 0.4 – 141 mm/yr for the phytocover and conventional cover, respectively. The predicted drainage is 6% of precipitation in the phytocover which is greater than measured in semi-arid sites in the US (Albright *et al.*, 2004). Conversely, the predicted drainage in the conventional cover is 4% of precipitation, which is less than that measured at the US sites.

The correlation between the annual drainage for the two covers is high (R=0.96). Drainage from the 1.5 m phytocover and conventional cover after drying is correlated to soil water storage (R=0.8), slightly correlated to rainfall (R=0.47 or 0.41) but shows no correlation to plant growth. It is likely that the lower drainage from the conventional cover is due to the presence of the clay layer which increases the soil moisture holding capacity of the profile. However, preferential flow paths would "short-circuit" moisture directly to the underlying layers and it would appear that the model is not adequately predicting this phenomenon.

WAVES predicted very small volumes of runoff occurred from both the phytocap and conventional cover. Runoff of 33 mm and 41 mm for the phytocovers and conventional covers respectively occurred once in February 1969 after 117 mm of rain, even though the site has a 12° slope. Many authors have noted that many models do not accurately predict runoff, particularly under extreme events, and have suggested that this is caused by the inability to incorporate rainfall intensity and/or near surface soil hydraulic changes, e.g. surface crusting (Roesler *et al.*, 2002; Scanlon *et al.*, 2002; Bohnhoff *et al.*, 2009). For the Southern Waste Depot trial site, reducing the surface 0.1 m permeability by an order of magnitude resulted in increased surface runoff volume (16 – 17 mm/yr on average) and frequency (94 – 98 times over 49 years) from the 1.5 m phytocover and the conventional cover after drying (Figure 4.4). This technique increased runoff to approximately 3% of precipitation and appeared to result in more realistic runoff patterns. The runoff from the phytocover is less than the conventional cover, in terms of volume and frequency.

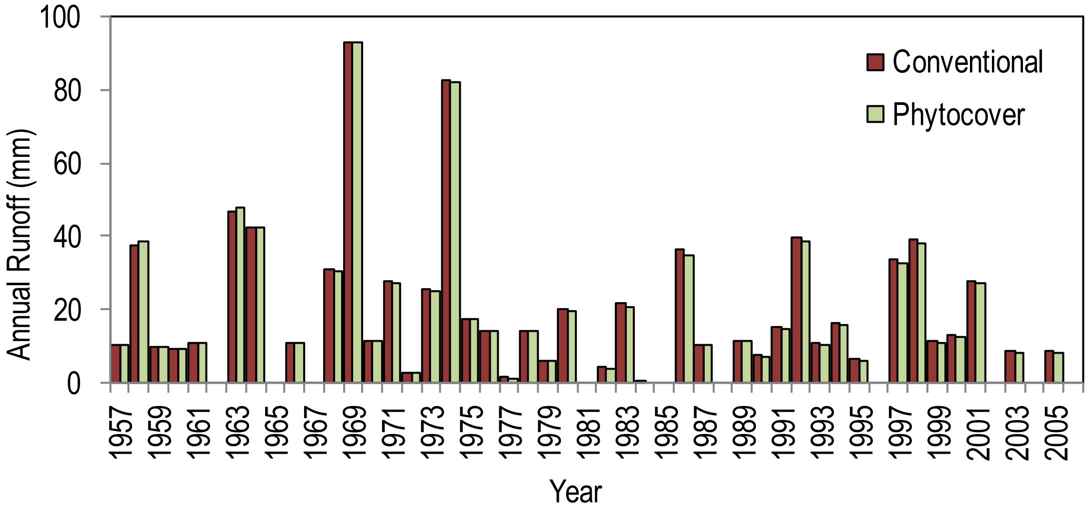

Figure 4.4 Predicted Annual Runoff Volumes when Surface Soil Permeability is Reduced by One Order of Magnitude.

Preliminary water balance modelling suggested that a 2 m phytocap would perform equivalently to the 1.5 m conventional cover, with modelling suggesting drainage would occur from all covers, unless the compacted clay does not crack. To facilitate ease of construction and to maximise the potential for drainage to occur, a 1.5 m phytocap was proposed for the Southern Waste Depot trial site.

4.1.6 Construction

The phytocap and conventional cover were constructed in March 2007. A report detailing the construction techniques for this site was prepared by Tonkin Consulting (2007) and a summary is presented following. The trial site was located on Cell 3 (Figure 4.1) and the plan of the trial layout and instrumentation placement is shown in Figure 4.5. The trial site has a northerly aspect and an average slope of 12°.

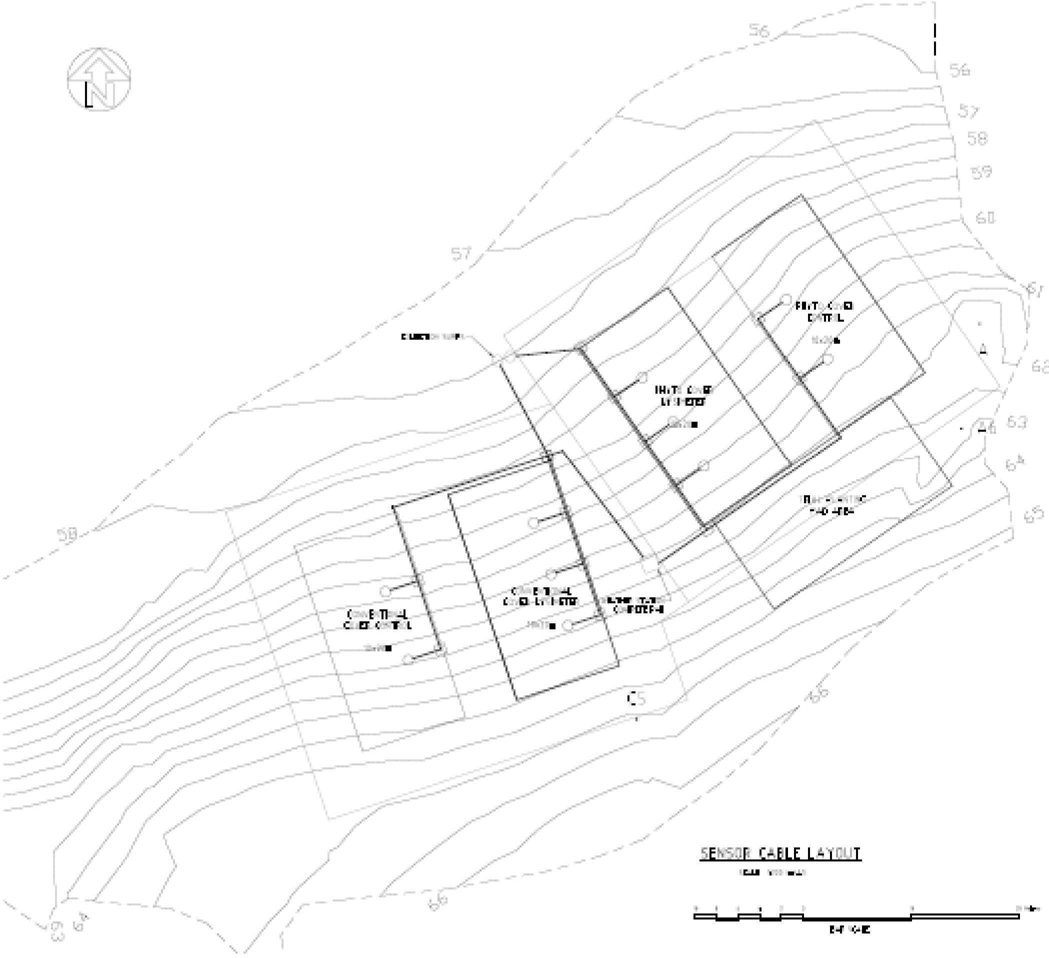

Figure 4.5 Site Layout and Instrumentation Placement (Tonkin Consulting, 2007)

The existing interim cover over Cell 1 was augmented by placement of additional material, which was compacted to provide a suitable construction surface. Lysimeters were constructed from 2 mm textured HDPE which were supported during material placement by large concrete blocks (Figure 4.6). The blocks remained in place with material backfilled around the blocks. Once the HDPE was welded in place, the Flownet™ sandwiched between Bidim™ was placed in the base and a 300 mm silty sand layer placed over the top (Figure 4.7).

Figure 4.6 Concrete Blocks Used to Support Lysimeter Walls During Construction at SWD

Figure 4.7 Silty Sand Base in Phytocap Lysimeter (left) and Purple Compacted Clay in Conventional Lysimeter (right)

Trifluralin™ was sprayed directly over the surface of the silty sand to reduce the potential for roots to grow to the Flownet™ and potentially access held moisture. Bidim™ was not used to retain the Trifluralin™ as this was likely to create a capillary break and increase the moisture holding capacity of the profile, which is not representative of the control cover conditions. The phytocap or conventional cap was then placed onto the Trifluralin™ layer. After each lift, a compaction plate was used around the walls of the lysimeter to ensure good contact and prevent preferential flow down lysimeter walls. In the compacted clay, bentonite was also spread around the edges of each lift within the lysimeter to further reduce the potential for preferential flow.

The phytocap was comprised of 0.3 m sandy loam topsoil over 1.2 m loamy sand subsoil. The subsoil was placed in three lifts with a final lift of topsoil. All lifts inside the lysimeter and in the control area were placed with an excavator and tracks were loosened with the toothed bucket prior to placement of the subsequent lifts. Traffic movement was not allowed on the placed layers with the exception of the excavator to limit compaction to < 85% maximum dry density.

The conventional cover required in South Australia is one of the most stringent conventional covers required, with a minimum 0.6 m compacted clay liner with a permeability of $< 1\times10^{-9}$ m/s which is constructed with a minimum of 3 lifts of a maximum 0.2 m compacted thickness compacted using a vibratory sheep's foot roller. Clay was conditioned to achieve near optimum moisture content for compaction prior to placement. Once the clay was placed and compacted (Figure 4.7), geotechnical testing of the compacted clay confirmed that it met placement specifications. The subsoil was placed on top of the compacted clay in 3 lifts with a final lift of topsoil. Material placement was undertaken as per standard practice with dozers and, due to the limited size of the trial area, a bob cat was used to level lifts as placed. Traffic was not controlled on the placed material.

Once all layers had been placed, the upslope end was excavated and the top flap welded to create the top wall. The HDPE walls were cut at the surface and berms placed around the lysimeter pan to prevent runon from outside the defined area and reduce the potential for preferential flow down the walls of the HDPE (Figure 4.8).

At the downslope end of the lysimeters, HDPE guttering (Figure 4.9) was placed to collect runoff and cross fall resulted in runoff flowing to a collection sump and then to the flow meter. Bidim™ was used to prevent erosion around the collection area. A conduit pipe was installed during construction to allow testing of the drainage collection after placement (Figure 4.9). A measured volume of water

Figure 4.8 Completed Material Placement and Berm Construction of SWD Trial Site

Figure 4.9 Runoff Collection Guttering and Drainage Check Pipe

was poured into the conduit and then collected from the drainage outflow pipe. This test failed for the lysimeters; however, an inspection camera showed no blockages.

After controlling the weeds, the trial site was planted in July 2007 with cool season and warm season native grasses including kangaroo grass, wallaby grass, weeping grass, red grass (Figure 4.10). Planting was facilitated by marking 2 m^2 areas and tubestock were planted using potti-putki (Figure 4.10). Further details on vegetation growth and survival are presented by Benaud (2011).

Figure 4.10 Native Grasses Tubestock (left) Planted Using Potti Putki (right)

Figure 4.11 SWD Trial Site with Phytocap in the Foreground and Conventional Cover in the Background (November, 2007)

After grasses were planted, a rabbit proof fence was constructed around the entire trial site, as shown in the foreground of Figure 4.11. The completed trial site as at November 2007 is shown in Figure 4.11, with the weather station and solar panel are located at the junction between the two cover types.

4.2 Melbourne Site

4.2.1 Landfill Description

Taylors Road Landfill, Lyndhurst, Victoria (38.04° S; 145.24° E) is operated by SITA Environmental Solutions and is located 40 km south east of Melbourne (Figure 4.12). Taylors Road Landfill is licensed by Vic Environment Protection Agency to receive municipal, commercial and industrial waste, including hazardous waste (or prescribed industrial waste). The site commenced operation in 1990 as the first fully engineered landfill in Australia with side and base liners and a gas and leachate collection system.

Figure 4.12 Taylors Road Landfill and Trial Area (Source of base plan: Google, 2011)

The trial site is located on completed cells in the east of the landfill (Figure 4.12). This area had already been capped with the approved design for the cell which consisted of 0.5 m compacted clay overlain by 0.5 m soil.

4.2.2 Climate

Lyndhurst experiences a temperate climate with no dry season and a warm summer (BoM, 2005). The closest recording stations to Taylors Road Landfill are at Dandenong (Station No 086224; 7 km north), which records rainfall and temperature and at Cranbourne (Station No 086375; 11 km south) which records all climate data. The patched point data for Dandenong station were created by SILO from January 1957 to May 2011.

The mean annual rainfall calculated from the dataset for Dandenong is 766 mm and varies from 533 mm/yr to 1,048 mm/yr. Rainfall is uniform throughout the year (Figure 4.13) but tends to be comprised of more intense events during summer compared to winter. Average monthly rainfall is > 49 mm but has ranged from 1 mm/month to over 200 mm/month, with both extremes occurring in summer (December to February). Average annual pan evaporation is 1,247 mm and exceeds rainfall for an average 8 months of the year (Figure 4.13). The moisture deficit suggests plants may become stressed during summer.

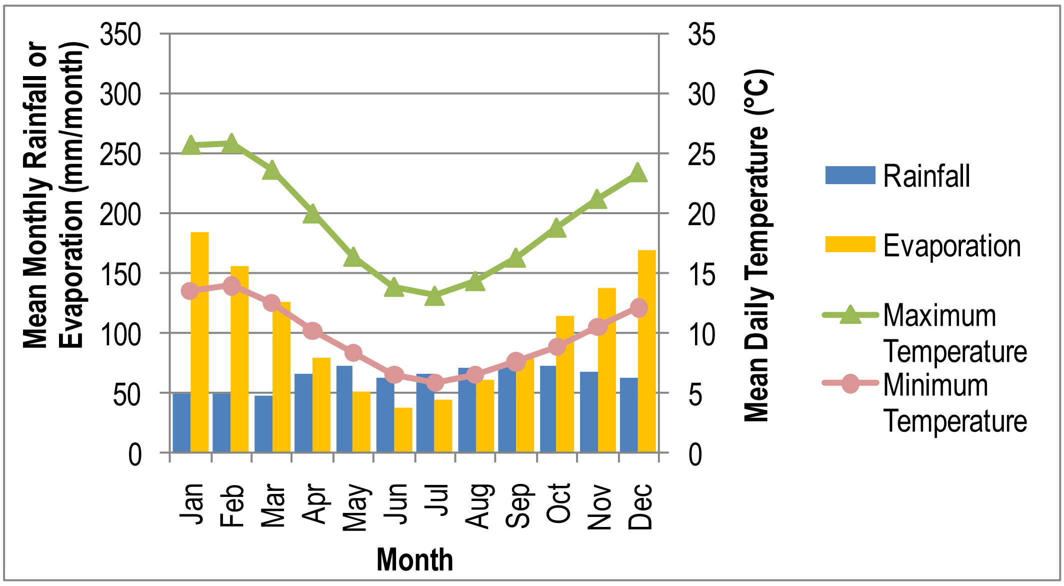

Figure 4.13 Mean Climate Data for Dandenong

The mean daily temperature ranges from 12 °C to 26 °C in summer and from 6 °C to 14 °C in winter (June to August), as shown in Figure 4.13. Summer temperatures are above 35 °C for an average 6 days/yr while frosts are likely in winter with an average 7 days below 2 °C. Plants may become stressed due to low temperatures in winter.

4.2.3 Soil Characterisation

The soil material for the phytocap was comprised of clayey sand from cell construction at SITA's Hallam Rd Landfill mixed with municipal compost, screened to < 19 mm, at a volumetric ratio of 2 parts sand: 1 part compost. The conventional cap was comprised of 0.5 m soil over 0.5 m compacted clay. The soil physical and chemical properties for the three soil types are shown in Table 4.5. Particle size distribution and soil moisture retention were measured in Adelaide for all soil

Table 4.5 Soil Physical and Chemical Properties for Taylors Road Landfill Final Covers

Property (units)	Average value for soil material		
	Sand:compost mix	Soil	Clay
Particle size distribution[a] (%)			
Gravel (>2 mm)	14.4	8.5	4.5
Sand (0.02 – 2 mm)	54.4	57.9	42
Silt (0.02 – 0.002 mm)	17.8	16.7	28.1
Clay (<0.002 mm)	13.4	16.9	25.4
Texture[b]	Loam	Loam	Silt clay loam
Soil water characteristic			
Permanent wilting point (volumetric moisture content @ 1500 kPa)	0.06	0.03	0.05
Field capacity (volumetric moisture content @ 100 kPa)	0.38	0.28	0.35
Saturated hydraulic conductivity (m/s)[b]	7.3×10^{-7}	▨	▨
Compaction		▨	▨
Maximum dry density (t/m^3)	1.52	▨	▨
Optimum moisture content (g/g)	0.23	▨	▨
As constructed Dry Density (t/m^3)	1.33	1.67	1.78
Linear Shrinkage (%)	▨	▨	6
pH (CaCl$_2$)	7.1	▨	▨
Electrical conductivity (dS/m)	1.2	▨	▨
Exchangeable cations (mEq/100 g)		▨	▨
Sodium	3.5	▨	▨
Potassium	2.45	▨	▨
Calcium	11.7	▨	▨
Magnesium	10.15	▨	▨
$\sum$(exch. cats)	27.8	▨	▨
ESP	12.6	▨	▨
Ca:Mg	1.2	▨	▨
Total Organic Carbon (%)	2.8	▨	▨
Total Nitrogen (%)	0.25	▨	▨
Total Phosphorus (mg/kg)	923	▨	▨

▨ Not tested

[a] Particle size distribution and texture based on Australian soil textural classifications (Marshall, 1947)

[b] Saturated hydraulic conductivity for topsoil and subsoil at 85% maximum dry density while for clay at maximum dry density.

types from as constructed material. The saturated hydraulic conductivity and standard compaction were undertaken at University of Melbourne and chemical analyses were undertaken by CSBP.

The sand:compost mixture has the largest moisture holding capacity, showing the improvement made to the sand by adding compost. The chemistry of the sand:compost mixture shows it has neutral pH and is non-saline though sodic. The sodicity would be counteracted by the physical stability of the compost.

Particle size distribution of the soil and clay used for the conventional cover indicate that the soil is likely to have good moisture holding capacity. The clay also contains silt which is less reactive and hence should be less likely to result in preferential cracking than material with a higher proportion of clay. This is shown by a linear shrinkage of 6% which indicates the clay is non-expansive and has a low-medium potential for volume change (Hazelton and Murphy, 2007).

4.2.4 Vegetation

A mixture of native trees, shrubs and grasses were planted on the phytocap in September 2007 with replanting of poorly established areas in April 2008 and September 2009 (Table 4.6). The planting density was 16 grasses/m^2, 1 shrub/3 m^2 and 1 tree/8 m^2.

Table 4.6 Species Planting List for Taylors Road Landfill Phytocap

Species	**Common Name**	**Notes**
Trees		
Eucalyptus tereticornis *Eucalyptus camaldulensis*	Forest red gum River red gum	*E. tereticornis* was not available for planting in September 2007 but was replanted in April 2008
Acacia mearnsii	Black wattle	Replanted in April 2008
Acacia melanoxylon	Blackwood	Planted in September 2009 as *A. mearnsii* not available
Acacia pycnantha	Golden wattle	Replanted in September 2009
Allocasuarina littoralis	Black she-oak	
Shrubs		
Acacia myrtifolia	Myrtle wattle	Replanted in April 2008
Bossiaea cinerea	Showy bossiaea	
Indigofera australis	Australian indigo	Replanted in April 2008
Melaleuca ericifolia	Swamp paperbark	Replanted in September 2009
Grasses		
Austrodanthonia spp.	Wallaby grass	Cool season. Replanted in April 2008
Microlaena stipoides	Weeping grass	Cool season
Bothriochloa macra	Red grass	Warm season. Replanted in April 2008
Dichanthium sericeum	Queensland blue grass	Warm season. Planted in April 2008
Themeda australis	Kangaroo grass	Warm season

Replanting in April 2008 consisted of 120 trees and shrubs and approximately 1,000 grass seedlings. It was noted during site inspections that windmill grass (*Chloris truncata*), a warm season grass, had colonised the trial site, and was left to grow as part of the native vegetation. Replanting in

September 2009 consisted of 20 tubestock seedlings of *M. ericifolia*, 20 potted seedlings of *A. pycnantha* and 10 potted seedling of *A. melanoxylon*. During this replanting, potting mix was placed under the seedlings with the aim of increasing moisture retention and hence plant survival.

Vegetation on the conventional cover, side slopes and buffer areas was a mixture of cool season and warm season native grasses, as used in the phytocap (see Table 4.6). These grasses were hydroseeded with a sterile ryecorn to provide immediate stability and cover while native grasses established. Hydroseeding was repeated in April 2008.

4.2.5 Cover Design

The phytocap cover design for Taylors Road Landfill was based on an approximate moisture balance method. The net monthly moisture deficit (i.e. P – PET) for this area shows that excess moisture usually occurs from May to August and based on data from 1970 to 2010 averages 116 mm/yr. The available moisture holding capacity of the sand:compost mixture was estimated as 83 mm/m. Using a conservative estimate that drainage may commence at approximately 80% available water content this approximation suggest that 1.7 m phytocap should be sufficient to minimise drainage in an average year. Using PET rather than AET (i.e. potential vs actual) is likely to overestimate moisture loss and hence adopting this thickness for phytocap design should still result in drainage.

The approved conventional cover for this area of the site consists of 0.5 m soil over 0.5 m compacted clay. This design was maintained for the conventional cover comparison.

4.2.6 Construction

The construction of the trial was detailed by SITA Environmental Solutions (2007). A summary of the construction is provided herein. Taylors Road Landfill was the first site constructed in October 2006. As discussed above, the phytocap used in this trial was a mixture of compost and clayey sand, planted with native trees, shrubs and grasses. The conventional cover for this site is comprised of 0.5 m of soil overlying 0.5 m of compacted clay liner planted with a mixture of pasture grasses. The trial layout, shown in Figure 4.14, includes an additional unlined phytocap section to allow destructive sampling of plants referred to as the Planting Pad.

The trial area had already been capped with the conventional cover in 2003. As a result, the conventional cover control area remained as placed. The trial area was graded to strip vegetation and provide 10% slope and 1.3% cross fall. Areas for the lysimeters and the phytocap control and

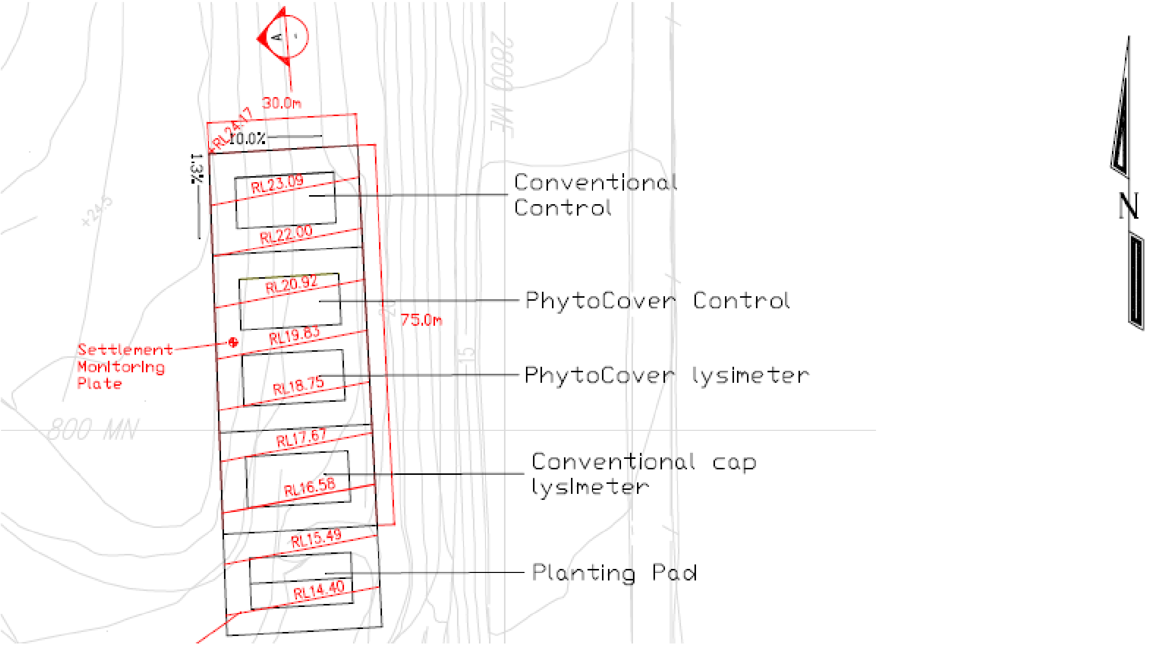

Figure 4.14 Trial Site Layout for Taylors Road Landfill (SITA Environmental Solutions, 2007)

Figure 4.15 Excavation of Existing Conventional Cover for Conventional Lysimeter Construction.

planting areas were excavated into the existing cap (Figure 4.15). The base was rolled and rocks picked from the surface prior to placement of the lysimeter pans.

The 2 mm HDPE was placed into the excavation and sides cut and welded. Star pickets were used to support the sides of the lysimeter during material placement (Figure 4.16). A geotextile cushion was placed on the base of the lysimeter to protect the HDPE and then 300 mm layer of 50:20 brick rubble was placed as a drainage layer and to prevent roots from accessing moisture held on the base of the lysimeter pan. Bidim™ was laid on top of the rubble and then sprayed with Trifluralin™ before covering with another layer of Bidim™. Covers were then constructed on the Bidim™. In the control area, slotted pipe was laid around the upslope and side perimeters of the excavation to ensure preferential flow did not result in increased moisture movement at the base of the profile.

Figure 4.16 Phytocap Lysimeter Pan Supported by Star Pickets with Rubble Base and Partly Covered by Bidim™. First Lift of Sand:Compost Placed Outside Lysimeter

Sand and compost were mixed on site using an excavator. Material was transported by tipper trucks to the edge of the trial area. The phytocap was placed by an excavator in 450 mm loose lifts and then compacted using a small bitumen roller. Each lift was scarified with a toothed excavator bucket prior to placement of the next lift, resulting in an as placed dry bulk density of 1.15 – 1.39 t/m^3. A total of 6 lifts were placed.

The compacted clay lysimeter was constructed with 2 × 250 mm compacted clay lifts. Material was placed with a dozer and compaction was obtained using a vibratory padfoot roller (Figure 4.17, left) and achieved a dry bulk density of 1.35 – 1.55 t/m^3 which was > 95% standard compaction. The topsoil was placed in 1 lift and compacted by track rolling with a dozer (Figure 4.17, right).

Vegetation was sown in September 2007. Grass tubestock was planted randomly within 1 m^2

Figure 4.17 Construction of Conventional Lysimeter with Compaction using a Vibratory Padfoot Roller (left) and Placement by Dozer (right)

Figure 4.18 Planting of Trees and Shrubs in Phytocap Lysimeter (left) and Hydroseeding of Batters and Conventional Cover Areas (right).

quadrats and consisted of 50 – 60% cool season grasses and 40 – 50% warm season grasses. Trees were then planted in 3 m rows with 2.7 m intra row spacing in the lysimeters, with large quadrats defined with spray paint (Figure 4.18, left). Three randomly selected shrub species were then planted around each tree, as shown by stakes in Figure 4.18 (left). Hydroseeding was undertaken by Australian Seed & Turf, as shown in Figure 4.18 (right). Further details on vegetation growth and survival are presented by Benaud (2011).

4.3 Townsville Site

4.3.1 Landfill Description

Vantassel Street Landfill, Stuart (near Townsville), Queensland (19.34° S; 146.87° E) is owned and operated by Townsville City Council (Figure 4.19). The landfill is currently licensed by Queensland Department of Environment and Resource Management (DERM) to receive solid hazardous waste and also receives municipal, commercial and industrial wastes as well as recyclables.

Figure 4.19 Vantassel Street Landfill and Trial Area (Source of base plan: Google, 2011)

4.3.2 Climate

Townsville experiences a tropical rainforest (monsoonal) to savannah climate (BoM, 2006) which has distinct wet and dry seasons but also experiences cyclones. The closest BoM weather stations are Oonoonba (Station No. 032057; 5.2 km north west) and Townsville Aero (Station No. 032040; 12 km north west). Rainfall data have been recorded at Oonoonba since 1959, while Townsville Aero has been in operation since 1940 and records all weather data including pan evaporation. The dataset for Vantassel Street Landfill was created using data drill from 1957 to 2006.

The average annual rainfall calculated from the dataset for the Landfill is 991 mm with average monthly rainfall varying from < 20 mm/month in winter (June to August) to > 200 mm/month in January and February (Figure 4.20). Due to summer cyclones, daily rainfall can reach 256 mm, with 6 days on record exceeding 200 mm and 57 days exceeding 100 mm. Annual pan evaporation is 2,214 mm and exceeds rainfall for 10 months of the year (Figure 4.20). Though rainfall is high, evaporation is also high and hence a moisture deficit is likely for most of the year.

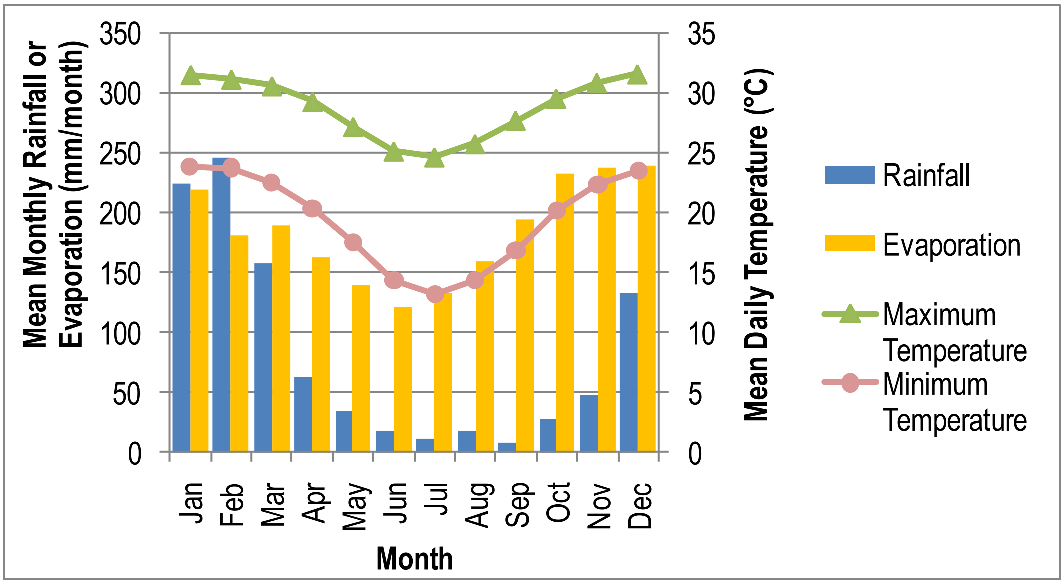

Figure 4.20 Mean Climate Data for Vantassel Street Landfill

The average temperature varies from 24 – 31 °C in summer to 13 – 25 °C in winter (Figure 4.20). The minimum daily temperature recorded was 4 °C, showing the Landfill does not experience frosts. The maximum daily temperature was 44 °C and on average 3 days/yr exceed 35 °C. Temperature stress can be a problem in summer due to the combination with high humidity and the few high temperature days each year.

4.3.3 Soil Characterisation

The soil material for the phytocap and conventional cap were both locally available. The phytocap soil was sourced from excavations within the site for a new landfill cell. The same material was used for the topsoil of the conventional cap and locally won clay used for the compacted clay barrier. The soil physical and chemical properties of the phytocap soil are shown in Table 4.7.

Table 4.7 Soil Physical and Chemical Properties for Vantassel Street Landfill Final Covers

Property (units)	Average Phytocap Soil Property	Average Clay Properties
Particle size distribution[a] (%)		
Gravel (>2 mm)	6	14
Sand (0.02 – 2 mm)	57	55
Silt (0.02 – 0.002 mm)	33	8
Clay (<0.002 mm)	4	23
Texture[b]	Silt loam	Clay loam
Soil water characteristic		
Permanent wilting point (volumetric moisture content @ 1500 kPa)	0.18	0.12
Field capacity (volumetric moisture content @ 100 kPa)	0.28	0.25
Saturated hydraulic conductivity (m/s)[b]	2×10^{-6}	▨
Compaction		
Maximum dry density (t/m^3)	1.69	▨
Optimum moisture content (g/g)	17.5	▨
As constructed dry density (t/m^3)	1.50	1.77
Linear shrinkage (%)	▨	12
pH ($CaCl_2$)	6.2	▨
Electrical conductivity (dS/m)	0.07	
Exchangeable cations (mEq/100 g)		
Sodium	0.96	
Potassium	0.26	
Calcium	9.0	
Magnesium	4.4	
$\sum$(exch. cats)	14.5	
ESP	6	
Ca:Mg	2.1	
Total Organic Carbon (%)	0.78	
Total Nitrogen (%)	0.07	
Extractable Phosphorus (mg/kg)	8	

▨ Not tested

[a] Particle size distribution and texture based on Australian soil textural classifications (Marshall, 1947)

[b] Saturated hydraulic conductivity for topsoil at 85% maximum dry density.

The phytocap material was sourced from excavation during diversion of a creek and hence the relatively high silt content would be expected for an alluvial material. The moisture holding capacity of alluvial loam soil would be expected to be large (200 – 250 mm/m) but the high moisture content at permanent wilting point limits the potential capacity. The slightly acidic pH and high organic matter content are typical for alluvial soil.

During saturation of the cores for moisture retention and subsequent drying, the bulk density of the phytocap soil and the compacted clay changed. For the phytocap soil, the bulk density of the as constructed material increased from an initial density of 1.50 t/m^3 to 1.59 t/m^3 after a slight suction (approximately 1 kPa) was placed on the core. Conversely, in the compacted clay, the core swelled and decreased in bulk density from the initial compaction of 1.77 t/m^3 to 1.54 t/m^3. Although the compacted clay layer in the field would have had a confining pressure exerted by the overlying soil, this is less than 1 kPa and the soil core remained swollen once this suction was applied. The linear shrinkage measured for the clay was 12%, which is considered to be non-expansive but is likely to have a medium potential for volume change, based on Townsville having a strongly seasonal climate (Hazelton and Murphy, 2007).

4.3.4 Vegetation

The vegetation for the phytocap was a combination of native trees, shrubs and grasses to maximise transpiration in this high rainfall environment. The species selected are shown in Table 4.8. It should be noted that some of the species listed as trees or shrubs can grow as either depending on site plant growth conditions. The planting density for trees and shrubs were 1 tree/3.8 m^2 and 1 shrub/3.9 m^2.

The conventional cover was vegetated with the dominant local species which is Rhodes grass (*Chloris guyana*).

4.3.5 Cover Design

Cover design was again undertaken prior to construction using the WAVES model. The modelling was undertaken to compare to potential performance of different phytocap thicknesses with the conventional cover but also included consideration of the likelihood that the compacted clay barrier would dry and crack. At the time of modelling the site location had not been finalised and hence consideration was also given to the potential impact of slope on the cover performance.

Parameters were varied for the phytocap and the conventional cap, as shown in Table 4.9. Soil hydraulic parameters were not completed for field conditions at the time of modelling. The saturated hydraulic conductivity of the topsoil (for both the phytocap and the conventional cap) was varied representing the possible texture range from sandy loam to loam (Dawes *et al.*, 1998). The saturated hydraulic conductivity and saturated volumetric moisture content were varied for the clay in the conventional cover to represent cracking of the compacted clay (Table 4.9).

Table 4.8 Species Planting List for Vantassel Street Landfill Phytocap

Species	Common Name
Trees	
Alphitonia excelsa	Red ash
Allocasuarina littoralis	Black she-oak
Araucaria cunninghamii	Hoop pine
Casuarina cunninghamiana	River she-oak
Casuarina equisetifolia	Coastal she-oak
Casuarina glauca	Swamp she-oak
Corymbia tessellaris	Carbeen, Moreton Bay Ash
Cupaniopsis anacardiodes	Tuckeroo
Eucalyptus creba	Narrow-leaved ironbark
Eucalyptus tereticornis	Forest red gum
Ficus racemosa	Cluster fig
Flindersia australis	Australian teak, Crows ash
Livistona decipiens	Palm
Lophostemon confertus	Brush box
Macaranga tanarius	Nasturtium tree
Mallotus philippensis	Red Kamala
Melaleuca alternifolia	Tea tree
Melaleuca bracteata	Black tea-tree
Melaleuca leucadendra	Weeping paperbark
Melaleuca viridiflora	Broad-leafed tea-tree
Melia azedarach	White cedar, Chinaberry Tree
Millettia pinnata	Pongamia, Indian Beech
Sterculia quadrifida	Red-fruited Kurrajong
Shrubs	
Acacia fimbriata	Fringed wattle
Acacia flavescens	Red wattle
Breynia oblongifolia	Coffee bush
Callistemon viminalis	Weeping bottlebrush
Clerodendrum sp.	Glorybower
Glochidion lobocarpum	Pin flower tree
Hibiscus tiliaceus	Cottonwood hibiscus
Leptospermum polygalifolium	Pink Cascade
Myoporum acuminatum	Boobialla
Westringia fruticosa	Wynnyabbie, Coastal rosemary
Grasses/Herbs	
Alloteropsis semialata	Cockatoo grass
Brachiachne convergens	Native couch
Chrysopogon elongatus	Tall Tamil grass
Imperata cylindrica	Blady grass
Indigofera linnaei	Birdsville indigo
Juncus usitatus	Tussock rush
Lomandra longifolia ssp. hystrix	Mat rush

Table 4.9 Assumed Parameters in Townsville for WAVES Modelling

Parameter	Phytocap		Conventional Cover (Topsoil as per Phytocap)	
	Sandy loam	**Loam**	**Compact Clay**	**Cracked Clay**
Saturated hydraulic conductivity (m/s)	5.8×10^{-6}	2.9×10^{-6}	1×10^{-8}	1×10^{-7}
Saturated moisture content (vol/vol)	0.42		0.4	0.56
Dry moisture content (vol/vol)	0.11		0.24	0.24
Macroscopic capillary length (m)	0.15		2	
Shape factor	1.5		10	2
Depth	1.5 m or 2 m		0.3m topsoil over 0.5 m clay	
Slope	5% or 10%			
Vegetation	Eucalypts and C4 grass		C4 grass	

The slope was changed from 5% to 10% for both the conventional cover and phytocap to assess the impact on runoff generated. The vegetation on the phytocap was modelled as a Eucalypt overstorey and a C4 grass understorey, using the standard parameters provided by Dawes *et al.* (1998). Only a C4 understorey was modelled for the conventional cap as this is standard revegetation practice at the Vantassel Street Landfill.

The modelling showed that the phytocap can perform equivalently to the conventional cap, presuming that the compacted clay desiccates and increases in permeability (Figure 4.21). The modelling results are from an uncalibrated model and hence should not be viewed as accurate but used to compare scenarios. The drainage can be expected to increase by an order of magnitude from the conventional cap if the clay cracks. For the phytocaps, the reduced permeability of a clayier soil resulted in the model predicting lower drainage; however, this change did not affect the conventional cap drainage to the same extent.

The conventional cap with compacted clay had lateral flow predicted to occur; however, the largest difference between the scenarios was for the predicted runoff. The runoff was highest from the conventional cap with the compacted clay, suggesting that an hydraulic head developed above the clay layer saturating the topsoil. This saturation would have a major impact on plant growth which is not explicitly modelled by WAVES.

The modelled performance of the covers was not sensitive to a change in slope, which is expected from a 1 dimensional model, which mainly uses slope to determine if lateral flow is generated from a perched water table.

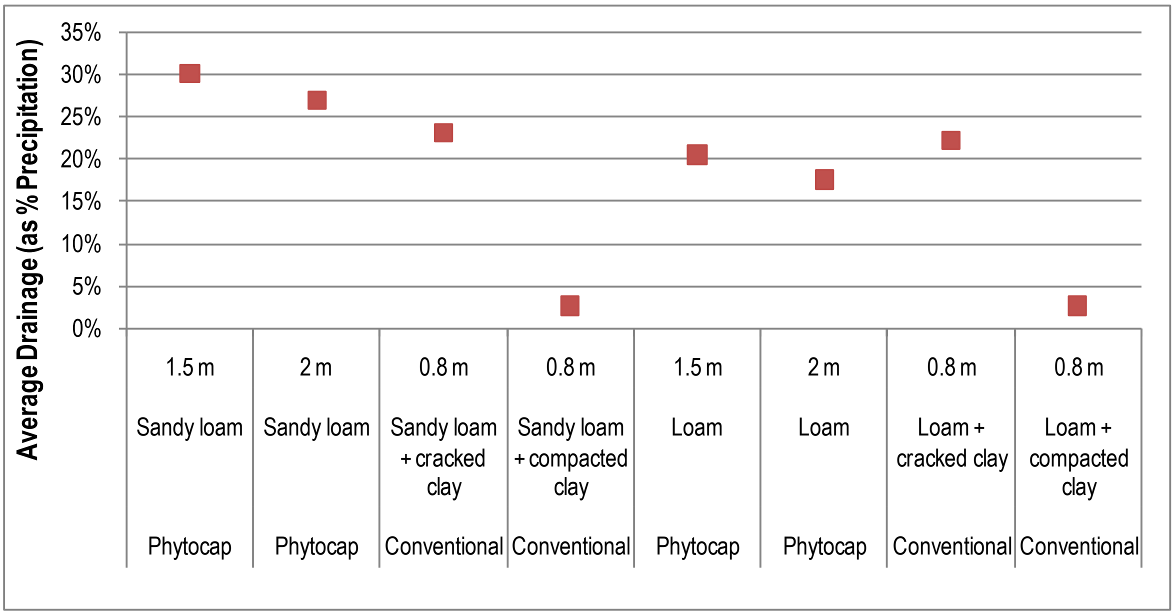

Figure 4.21 Estimated Drainage from Phytocap and Conventional Cap for Townsville

Overall, water balance modelling suggested that drainage was likely to occur from all covers, regardless of construction type or depth.

4.3.6 Construction

Construction of the phytocap and conventional cap was undertaken from June to August 2007. A Construction Report has been drafted by AECOM (2010a) and is summarised below. The lysimeter areas were constructed with a 5% slope and a 1% crossfall on existing landfill covered with an interim cover and a sand cushion layer. Plywood panelling was used to support the 2 mm HDPE used for construction of the lysimeters (Figure 4.22). Flownet™ was placed in the base of the lysimeter between A24 Bidim™ geotextile and then a layer of loam (used for the capping) was placed over the drainage layer. Trifluralin™ was sprayed as a root barrier onto the loam.

The final cover profiles were placed above the root barrier. The phytocap was placed in lifts 6 lifts of 250 – 330 mm using a D3 dozer (Figure 4.23, left) to create a 1.5 m deep profile. The compacted clay barrier of the conventional cap was placed in 2 lifts of 250 mm and compacted with a padfoot roller to achieve standard compaction of over 100% (Figure 4.23, right). A 300 mm lift of topsoil, as used for the entire phytocap, was placed over the top of the compacted clay.

Grasses were hydroseeded onto phytocap plots in November 2007 and the site fenced. Supplementary irrigation was provided to facilitate rapid germination. Trees and shrubs tubestock were planted in March 2008, with replanting in some areas undertaken in June 2008. Grasses were slashed prior to planting and jute mat placed around seedlings to improve survival. Supplementary irrigation of the phytocap was provided for 6 months while trees and shrubs established (Figure 4.24, left). Rhodes grass established quickly on the conventional cover (Figure 4.24, right).

Figure 4.22 Sand Cushion Layer and Lysimeter Wall Support at Vantassel Street Landfill (Photos courtesy of G. Zhu)

Figure 4.23 Phytocap Lysimeter (left) and Compacted Clay Barrier (right) During Construction (Photos courtesy of G. Zhu)

Figure 4.24 Phytocap (left) and Conventional Cap (right) in October 2008, Less Than 12 Months After Planting (Photos courtesy of Townsville City Council)

4.4 Lismore Site

4.4.1 Landfill Description

The Lismore Waste Facility (also known as the Wyrallah Road Waste Facility), Wyrallah Road, East Lismore, New South Wales (28.84° S;153.28° E) is owned and operated by Lismore City Council. The landfill commenced operating in 1974 and is licensed by NSW Environment Protection Authority to receive Class 1 solid waste, which includes municipal waste and construction and demolition wastes. The site received almost 23,000 tonnes of waste in 2006/07 and has a site expectancy of 15 years in its current footprint (Lismore City Council, undated). The site and the trial site location are shown in Figure 4.25.

Figure 4.25 Lismore Waste Facility and Trial Area (Source of base plan: Google, 2011)

4.4.2 Climate

Lismore experiences a subtropical climate with no dry season and a warm to hot summer (BoM, 2005). The closest BoM weather stations are located at Lismore Airport (Station No. 58214, 2 km WNW), which commenced recording in 2002, and Lismore (Station No. 58221, 8 km ENE), which opened in 2004. Lismore Airport and Lismore (Richmond Hill) are only recently opened and hence long-term climate data are not available. Prior to these stations opening, Lismore (Centre Street) (Station No. 58037) recorded weather data from 1884 to 2003 but not evaporation. Evaporation is recorded at Alstonville Tropical Research Station but is at a significantly higher elevation than Lismore. A patched point dataset was created for Lismore (Centre Street) from 1957 to 2007.

The mean annual rainfall calculated from the dataset for Lismore is 1,321 mm, with a minimum annual rainfall of 753 mm and a maximum of 2,092 mm. The mean monthly rainfall is > 100 mm/month for 6 months from December to May and is lowest in September with 40 mm (Figure 4.26). Intense rainfall events can occur with 246 mm rainfall recorded on 1 day. The annual evaporation exceeds rainfall, with an average of 1,525 mm/yr and pan evaporation exceeds rainfall from July to January.

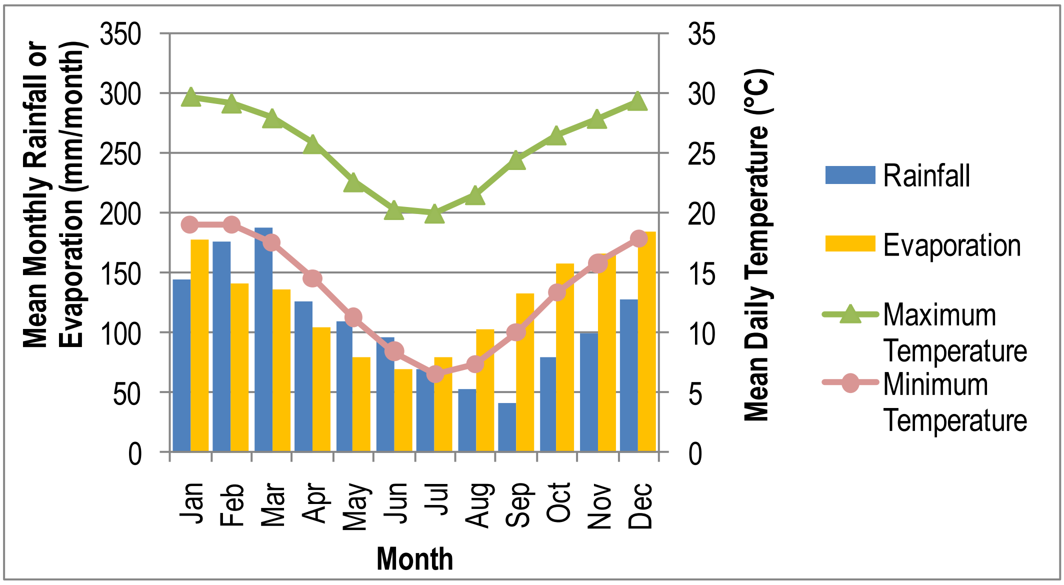

Figure 4.26 Mean Climate Data for Lismore Waste Facility

The average daily temperature varies from a maximum of 20 – 30 °C and a minimum of 6 – 19 °C (Figure 4.26). On average, approximately 8 days/year exceed 35 °C but only 1 day every 3 years would exceed 40 °C. Frost would occur on an annual basis with 7 days/yr with a minimum temperature < 2 °C and 1 day/yr < 0 °C.

During autumn (Mar – May), monthly rainfall is high and exceeds evaporation and temperatures are falling, suggesting that plant growth may be reduced during this period and infiltrating rainfall will need to be stored in the soil until evaporation and daily temperatures increases and rainfall continues to decrease through August and September.

4.4.3 Soil Characterisation

The soil available on site is a fine textured soil from a basaltic parent material. The soil was sampled and analysed for a range of physical and chemical properties, as summarised in Table 4.10. Soil saturated hydraulic conductivity and standard compaction testing were undertaken by Coffey Geotechnics and chemical analyses were undertaken by CSBP, both commercial laboratories. Moisture retention testing was undertaken in Adelaide on undisturbed samples collected during construction.

Table 4.10 Soil Physical and Chemical Properties for Lismore Final Cover

Property (units)	Average Phytocap Soil Property
Particle size distribution[a] (%)	
Gravel (>2 mm)	44
Sand (0.02 – 2 mm)	13
Silt (0.02 – 0.002 mm)	30
Clay (<0.002 mm)	13
Texture[b]	Silt loam
Soil water characteristic	
Permanent wilting point (volumetric moisture content @ 1500 kPa)	0.09
Field capacity (volumetric moisture content @ 100 kPa)	0.42 – 0.53[b]
Saturated hydraulic conductivity (m/s)	3×10^{-10}
Compaction	
Maximum dry density (t/m^3)	1.63
Optimum moisture content (g/g)	0.25
As constructed dry density (t/m^3)	1.13 – 1.32[b]
Plastic limit (gravimetric moisture content)	0.27
Linear Shrinkage (%)	17
pH ($CaCl_2$)	6.0
Electrical conductivity (dS/m)	0.110
Exchangeable cations (mEq/100 g)	
Sodium	2.26
Potassium	0.10
Calcium	13.38
Magnesium	10.39
$\sum$(exch. cats)	26.12
ESP	8.7
Ca:Mg	1.3
Total Organic Carbon (%)	0.51
Extractable Phosphorus (mg/kg)	33

[a] Particle size distribution and texture based on Australian soil textural classifications.(Marshall, 1947)

[b] the density of the first lift, lowest in the profile, was 1.32 t/m^3 while the last lift at the surface was 1.13 t/m^3, this affected the field capacity measurement which was higher at the bottom and lower at the top

The soil is a gravelly silt loam with a large moisture holding capacity. The saturated hydraulic conductivity is very low; however, the extremely low value reported by Coffey may be the result of laboratory influences or may be the result of sodicity (ESP > 6%), indicating potential dispersivity. The soil is slightly acidic and non-saline and, as expected with a basaltic soil, the soil fertility is high as indicated by the organic carbon and exchangeable phosphorus concentration.

4.4.4 Vegetation

Lismore City Council is proposing for the site to become a regional botanic garden open to the community once landfilling has ceased (Lismore City Council, undated). As a result, the vegetation for the trial was developed in consultation with Friends of Lismore Botanic Gardens and comprised a variety of grasses, herbs, shrubs and trees (Table 4.11). One of each species were planted at 1 m centres in a 5 m x 5 m square, resulting in 8 plants of each species in the lysimeter and 8 of each species in the control area.

4.4.5 Cover Design

Due to the financial constraints of constructing lysimeter and control pads for both the phytocap and conventional cap, Lismore City Council elected to only construct the phytocap to allow assessment of its hydraulic performance.

The cover was again designed using the WAVES model and 50 years of daily, patched point, climate data for Lismore. The soil depth chosen was 1 m, which was thicker than the proposed capping profile of approximately 0.7 – 0.8 m depth. Laboratory results were used for the soil hydraulic properties. The vegetation was assumed to be a Eucalypt overstorey with a C4 perennial grass understorey.

The results of the modelling showed the drainage to be highly dependent on the saturated hydraulic conductivity (Table 4.12). The laboratory value of 3×10^{-10} m/s resulted in the majority of the rainfall being lost as runoff, with poor plant growth, due to a lack of moisture and almost no drainage. The laboratory reported value is markedly lower than published values for silty loam soil. As a result, three other saturated hydraulic conductivities were investigated, being 1.16×10^{-8} m/s, 1.16×10^{-7} m/s and 1.16×10^{-6} m/s. Changing the saturated hydraulic conductivity by 3 – 4 orders of magnitude resulted in water balance outputs similar to expected based on other studies (see Chapter 2).

The highly variable drainage results for Lismore resulted in large uncertainty in the potential performance of the phytocap. Annual drainage of over 200 mm/year was considered excessive;

Table 4.11 Species Planting List for Lismore Waste Facility Phytocap

Species	Common Name
Trees	
Acacia melanoxylon	Blackwood
Callistemon salignus	Willow bottlebrush
Corymbia intermedia	Pink bloodwood
Eucalyptus tereticornis	Forest red gum
Ficus fraseri	Sandpaper fig
Guioa semiglauca	Guioa
Lophostemon suaveolens	Swamp mahogany
Rhodamnia rubescens	Scrub turpentine
Shrubs	
Callicoma serratifolia	Black wattle
Cordyline stricta	Narrow-leaved palm lily
Decaspermum humile	Silky myrtle
Desmodium acanthocladum	Thorny pea
Homalanthus populifolius	Bleeding heart
Macaranga tanarius	Nasturtium tree
Pilidiostigma glabrum	Plum myrtle
Trema tomentosa	Poison peach
Grasses/Herbs	
Capillipedium spicigerum	Scented-top grass (C4 grass)
Cymbopogon refractus	Barded wire grass (C4 grass)
Dianella caerulea	Blue flax-lily
Geranium solanderi	Native Geranium
Lomandra longifolia	Spiny-headed mat-rush
Poa sieberiana	Snowgrass (C3 grass)
Sorghum leiocladum	Wild sorghum (C4 grass)
Themeda australis	Kangaroo grass (C4 grass)
Viola banksii	Wild Violet

Table 4.12 Modelled Water Balance for Lismore with Varying Saturated Hydraulic Conductivity

Water Balance Parameter	Average Annual Water Balance (mm/yr) and As % Precipitation (in brackets) Predicted for Varying Saturated Hydraulic Conductivities (m/s)			
	$K_{sat} = 3 \times 10^{-10}$	$K_{sat} = 1.16 \times 10^{-8}$	$K_{sat} = 1.16 \times 10^{-7}$	$K_{sat} = 1.16 \times 10^{-6}$
Precipitation	1321.1	1321.1	1321.1	1321.1
Interception	33.4 (3%)	138.7 (10%	168.1 (13%)	163.3 (12%)
Evapotranspiration	157.3 (12%)	702.3 (53%)	981.3 (74%)	893.5 (68%)
Runoff	1130.9 (86%)	481.8 (36%)	135.8 (10%)	4.1 (<1%)
Drainage	0.0002 (<1%)	0.01 (<1%)	37.6 (3%)	261.9 (20%)

however, measurable drainage was considered important in the assessment of the phytocap's performance. A safety factor was added to the phytocap profile, resulting in a 1.3 m deep profile.

4.4.6 Construction

The phytocap lysimeter, control area and planting pad were constructed in November and December 2007. The As Constructed Report has been drafted by AECOM (2010b) and a summary of the construction details is presented herein.

The trial area was constructed on a previously landfilled area and graded to a 5% slope from north to south, with a 1% cross fall on the lysimeter test section. The subgrade consisted of compacted waste, with little or no interim cover in place. As with the other trial site 2 mm HDPE was used for the lysimeter boundaries with Flownet™ surrounded by geotextile (A24 Bidim™) used to facilitate drainage to the collection area. A 200 mm interim soil layer was placed over the Bidim™ and was then sprayed with Trifluralin™ to limit root growth into the interim cover. Phytocap soil material was placed in approximately three lifts with a standard compaction of approximately 85% maximum dry density.

Vegetation was planted in stages. Trees were planted initially in March 2008, followed by shrubs and grasses in April 2008 (Figure 4.27). Replanting of approximately 10% of species was undertaken in September 2008 (Figure 4.27). Further details on vegetation growth and survival are presented by Benaud (2011). A perimeter fence was established; however, neighbouring cattle breached the fence on a number of occasions and grazed and trampled vegetation within the test section.

Figure 4.27 Phytocap Lysimeter in May 2008 (left) and November 2008 (right). Photo courtesy of Grant Zhu

4.5 Perth Site

4.5.1 Landfill Description

Henderson Waste Recovery Park (Figure 4.28), Rockingham Road, Henderson (32.16° S; 115.8° E) in Western Australia is located approximately 30 km SSW of Perth. This landfill is operated by City of Cockburn and is licensed by the Department of Environmental Protection to accept Class 2 waste, which includes municipal and commercial putrescible waste and industrial waste that conforms to the minimum "TCLP" contaminant leachate levels. The waste cells are lined and gas extraction is undertaken.

Figure 4.28 Henderson Waste Recovery Park and Trial Area (Source of base plan: Google, 2011)

4.5.2 Climate

The climate of the Henderson area is temperate with distinctly dry and hot summer, often referred to as Mediterranean climate. Bureau of Meteorology climate stations are located at Medina (Station No. 9194, 6.8 km S) and Garden Island (Station No. 9256, 14 km SW). Comparison with site data suggests Garden Island experiences similar weather conditions; however, evaporation is only recorded at Medina. Long-term climate data for the site from 1957 to August 2006 was generated from SILO's data drill system using the site coordinates.

Average annual rainfall calculated from the datset for Henderson is 791 mm and varies from 598 mm in 1977 to 1,037 mm in 1963. Monthly rainfall has a distinctly winter dominant pattern (Figure 4.29). From May to August, average monthly rainfall exceeds 100 mm/month, while December to March receives an average of < 20 mm/month. Evaporation also shows a distinct pattern with average annual evaporation 1,763 mm predominantly occurring in summer, when evaporation exceeds 200 mm/month. From May to August, evaporation is less than rainfall, resulting in 280 mm surplus rainfall.

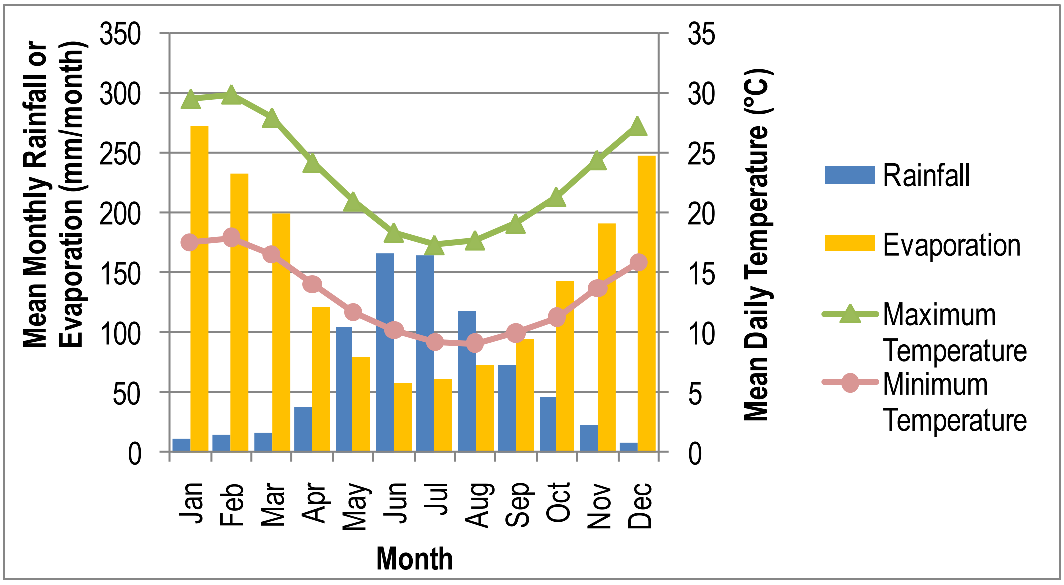

Figure 4.29 Average Climate Data for Henderson Waste Recovery Park

Temperatures range from an average daily temperature of 16 – 30 °C in summer and 9 – 18 °C in winter (Figure 4.29). Summer temperatures can exceed 35 °C for an average 13 days/year and on average exceeds 40 °C for 1 day/year. Frosts are unlikely, with minimum temperatures remaining above 0 °C and only dips to < 2 °C one day in every 5 years, on average.

Overall the climate is likely to cause plants to suffer extreme temperature and moisture stress during summer with hot days and little rainfall. The establishment of plants in this climate will also be difficult and the soil will need to be able to store winter moisture over summer to assist plant survival. Cooler temperatures and rainfall in winter will result in growth being predominantly restricted to late Autumn to mid Spring unless supplementary irrigation is applied.

4.5.3 Soil Characterisation

The soil selected for the phytocap at the Henderson Waste Recovery Park was sourced on-site and is a very sandy soil derived from limestone. Two to three soil layers were identified during material placement. The first lift (L1) at the base of the profile tended to be grey brown sand, the second and third lift (L2 and L3) was red brown to brown sand (Figure 4.30). Although colour variations were noted, there were few differences in physical properties and hence the average properties of all soil materials are shown in Table 4.13. Standard compaction testing was undertaken by Western Geotechnics, Bentley, WA. Chemical analysis, undertaken by CSBP, showed the grey brown sand had higher extractable phosphorus and potassium but the reported concentrations were still in the low range. In Table 4.13, chemical results are shown as the range of reported values.

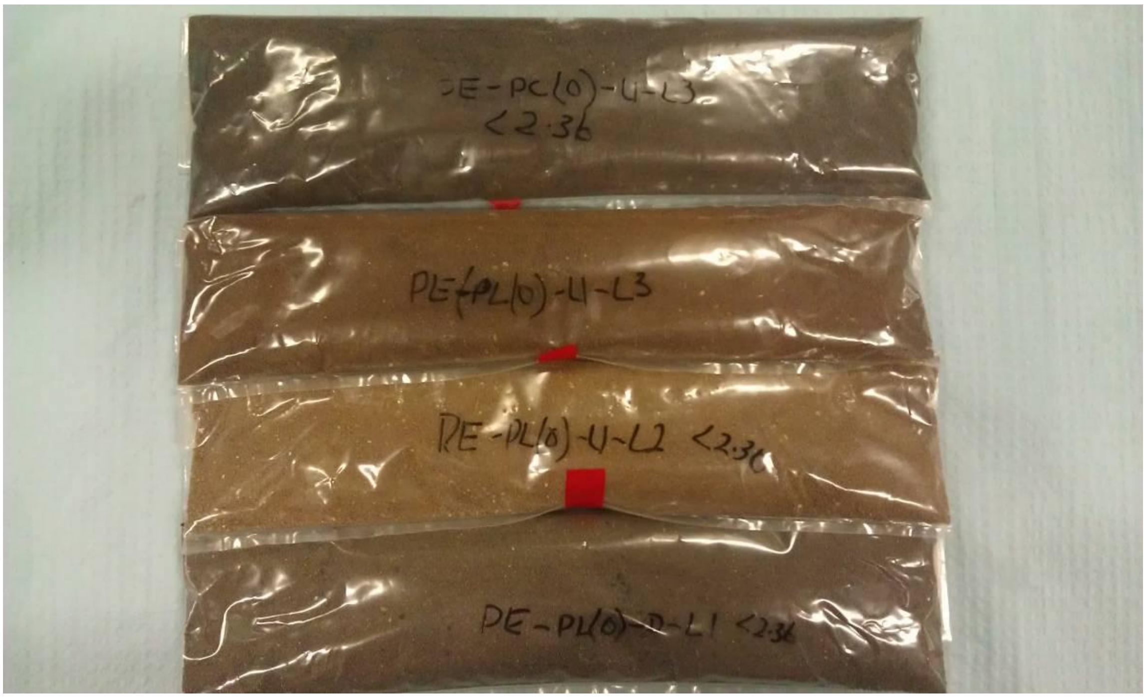

Figure 4.30 Soil Samples from Henderson Waste Recovery Park showing Colour Differences. Post Script Code Indicates Lift 1 (L1), Lift 2 (L2) and Lift 3 (L3) Sampled

The soil is sand and contains almost no silt or clay. As a result, the soil has limited soil moisture storage capacity and has a high saturated hydraulic conductivity. The as constructed bulk density was 1.51 t/m^3; however, during the moisture retention tests, which were undertaken on undisturbed samples taken during construction, the soil slumped by 4 – 8 mm over the 73 mm high core. This increased the bulk density to 1.63 – 1.78 t/m^3. The soil has a neutral pH and is non-saline. Exchangeable cations were not measured on the sample as the high sand content can make accurate determination difficult.

4.5.4 Vegetation

The vegetation planted on the site consisted of a range of trees, shrubs and grasses to maximise the potential evapotranspiration. The sandy soil has limited moisture retention and hence performance

Table 4.13 Soil Physical and Chemical Properties for Perth Final Cover Soil Material

Property (units)	Average Phytocap Soil Property
Particle size distribution[a] (%)	
Gravel (>2 mm)	7
Sand (0.02 – 2 mm)	91
Silt (0.02 – 0.002 mm)	1
Clay (<0.002 mm)	1
Texture[b]	Sand
Soil water characteristic	
Permanent wilting point (volumetric moisture content @ 1500 kPa)	0.03
Field capacity (volumetric moisture content @ 100 kPa)	0.08
Saturated hydraulic conductivity (m/s)	8×10^{-6}
Compaction	
Maximum dry density (t/m^3)	1.68
Optimum moisture content (g/g)	0.095
As constructed dry density (t/m^3)	1.51
pH ($CaCl_2$)	7.2 – 7.6
Electrical conductivity (dS/m)	0.082 – 0.09
Total Organic Carbon (%)	0.31 – 0.5
Extractable Phosphorus (mg/kg)	3 – 16

[a] Particle size distribution and texture based on Australian soil textural classifications.

of the phytocap will be highly dependent on optimum plant transpiration. Tree planting density was proposed as 1 tree/8 m^2 and 1 shrub/3 m^2. The species selected for the Henderson Waste Recovery Park are shown in Table 4.14.

4.5.5 Cover Design

Phytocap cover designs for Perth were modelled using WAVES. The cover was modelled from 1957 to September 2006 with a 2 layered soil profile, both of which were sandy and freely draining, and assuming the vegetation was comprised of C3 grasses. The subsoil proposed for construction had higher clay content than the topsoil, though was still predominantly sand; however, this material was used elsewhere and was not available during construction. The C3 grasses were allowed to grow to the full depth of the profile. Modelling scenarios considered the sensitivity of the water balance to changing soil depth and surface soil saturated hydraulic conductivity. The saturated hydraulic conductivity was varied to simulate the potential impact of dry, hydrophobic soil, known to be an issue with the on-site soil. The input parameters for modelling are shown in Table 4.15.

Table 4.14 Species Planting List for Henderson Waste Recovery Park

Species	Common Name	Notes
Tree		
Eucalyptus gomphocephala	Tuart	
Eucalyptus utilis	Coastal Moort	
Eucalyptus rudis	Flooded gum	
Eucalyptus decipiens	Redheart gum	
Shrubs		
Calothamnus sanguineus	Silky-leaved blood flower	
Calothamnus rupestris	Mouse ears	
Kunzea baxteri	Scarlet kunzea	
Grass		
Austrodanthonia caespitosa	Common or Ringed wallaby grass	C3 grass. Initial planting
Austrostipa compressa	Spear grass	C3 grass. Initial planting
Austrostipa macalpinei	Annual spear grass	C3 grass. Initial planting
Themeda australis	Kangaroo grass	C4 grass. Initial planting
Cymbopogon obtectus	Silkyheads	C4 grass. 2nd planting
Microlaena stipoides	Weeping grass	C3 grass. 2nd planting
Poa poiformis	Coast tussock grass	C3 grass. 2nd planting
Walwhalleya proluta	Rigid panic	C3 grass. 2nd planting. Formerly *Homopholis proluta*

Table 4.15 Assumed Parameters in Perth for WAVES Modelling

Parameter	Phytocap		
	Topsoil	**“Hydrophobic” Topsoil**	**Subsoil**
Saturated hydraulic conductivity (m/s)	8×10^{-6}	8×10^{-7}	4×10^{-6}
Saturated moisture content (vol/vol)	0.40		0.45
Dry moisture content (vol/vol)	0.05		0.10
Macroscopic capillary length (m)	0.05		0.1
Shape factor	1.05		1.05
Profile Depth	1 m, 1.2 m, 1.5 m, 2 m		
Slope	8.7%		
Vegetation	C3 grass		

The water balance predicted by the modelling suggested that drainage would constitute a large proportion of rainfall, with the long term annual average being 10 – 20% of rainfall received. Increasing the depth of the profile reduced the drainage resulting in proportionally decreasing drainage (Figure 4.31). If the surface soil becomes hydrophobic, drainage is reduced by increasing runoff but the trend in drainage with depth is not affected.

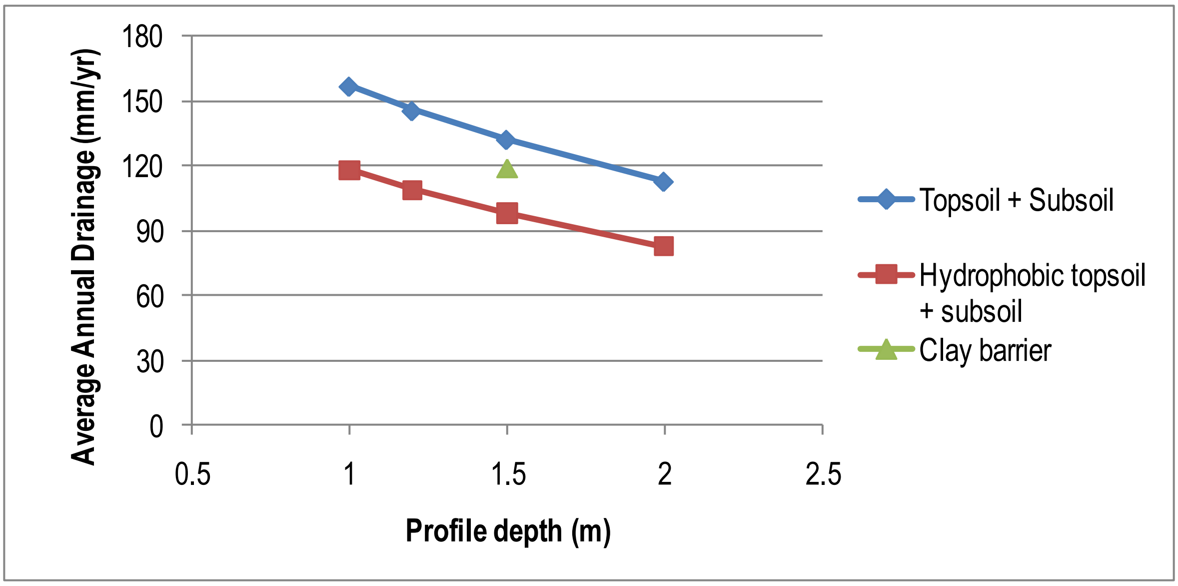

Figure 4.31 Drainage Modelled for Varying Sandy Profile Depths and Compared to 1.5 m Clay Barrier (Clay K_{sat}= 1 × 10^{-7} m/s)

As a comparison, a clay barrier profile was modelled, where the profile consisted of 0.1 m topsoil, 0.8 m subsoil and 0.6 m clay barrier with a saturated hydraulic conductivity of 1 × 10^{-7} m/s. The drainage was predicted as 119 mm/yr on average (Figure 4.31) and assuming a hydrophobic surface reduced the predicted drainage to 92 mm/yr. Drainage predictions for the clay barrier were similar to the modelled phytocaps, suggesting the high net rainfall over winter is a critical period for final cover performance, regardless of soil type.

The final cover proposed for the Henderson Waste Recovery Park was 1.6 m depth. To reduce the predicted drainage, it was proposed to include trees and shrubs in the vegetation to maximise evapotranspiration.

4.5.6 Construction

The trial site at the Henderson Waste Recovery Park was constructed in September and October 2007. A conventional cap test section was not constructed at the Perth site due to the construction costs and the availability of suitable clay at the site. Details of the phytocap construction are provided by IW Projects (2010) and a summary is provided following.

The trial site was located on previously landfilled areas and was graded to 25% slope. The subgrade was prepared by removing vegetation (predominantly weeds) and protruding waste, then spreading 100 mm finer-grained material and grading. The lysimeter was supported by plywood panels affixed to star pickets, as used in Townsville and Lismore (Figure 4.32). 2 mm HDPE was placed followed

Figure 4.32 Lysimeter Box Erected on 25% Slope at Henderson Waste Recovery Park (Photo courtesy of IW Project (2010))

Figure 4.33 Completed Test Sections with Lysimeter (right) and Control (left) Sections. (Photo courtesy of IW Projects (2010))

by cushion geotextile (A64 Bidim™), 150 mm layer 50:20 crushed concrete (for drainage), woven geotextile (Bontec SG 28/28) and 200 mm interim soil cover (as per the phytocover material). The interim soil cover was sprayed with Trifluralin™ to limit root penetration.

The phytocap soil was placed in lifts by excavator and tamped using the bucket to achieve 87% maximum dry density. Due to the steep slope and concerns with stability of the constructed profile, the phytocap material was placed in lifts of 3 m wide by 300 mm thick with placement commencing downslope and progressively moved upslope. The complete test section is shown in Figure 4.33.

The vegetation was planted in October 2007, with grass seeds broadcast by hand and trees and shrubs planted as tubestock. Protective irrigation was supplied for the summer of 2007/08; however, grasses failed to germinate and replanting of grass tubestock (6 seedlings/m^2) was undertaken in June 2008 and again in August/September 2008. The grass species planted initially and during replanting are listed in Table 4.14.

4.6 Summary and Conclusions

Five trial sites were constructed in general accordance with the proposed design and included lysimeters and control areas, with additional planting pads provided at most sites. Three sites, Adelaide, Melbourne and Townsville, comprised side-by-side comparisons between a phytocap and conventional cap, while the remaining two sites, Lismore and Perth, comprised the phytocap only.

The conditions at the trial sites varied markedly. The climate of the trial sites varied from tropical to temperate, with Adelaide close to semi-arid. Rainfall varied in volume, timing and intensity and temperatures ranged from frosty to hot.

The soil types depended on locally available soil and hence the climate, topography and geology of the area. In Townsville an alluvial loam was available on site while Lismore's volcanic geology resulted in a silt loam soil. Sedimentary geology dominated the southern sites, with sandstones around Dandenong, shales at McLaren Vale and limestone of the Swan Coastal Plain around Henderson, resulting in sandier, less fertile soil available for phytocaps.

The vegetation also varied across the sites. Grasses were planted at all sites but Townsville was predominantly C4 grasses and the southern states generally the C3 grasses established better, with the exception of Perth were grasses failed to establish, even after replanting. Trees and shrubs were planted at all sites, except Adelaide, and the species utilised at each site varied depending on those indigenous to the area and the seedlings available. Some of the same plant species were planted at Townsville and Lismore, while the Melbourne and Perth sites included different species, but the indigenous trees tended to be dominated by Eucalypts.

Predictions of the performance of the final covers varied for each site but drainage was predicted to occur from most of the phytocaps, with the drainage from the conventional covers dependent on the magnitude of hydraulic change occurring in the compacted clay barriers. Overall, the covers will provide a range of locally representative data for scientific analysis.

5. Field Water Balance

The water balance has been monitored at the five field trial sites for varying periods between 3 and 4 years. The monitoring period has included cyclones and droughts and has captured the period during plant establishment, including poor plant establishment and unexpected plant death.

This chapter presents the results of the field monitoring for each site and discusses the relationship between the water balance components and any changes over time. At Adelaide, Melbourne and Townsville, the side-by-side comparison of phytocaps with conventional caps also allows comparison of their hydraulic performance. Findings from each of the trial sites are also compared with one another to determine any consistencies between the sites' water balances. Prior to the discussion of the results from each trial site, a summary of the field data quality, with particular attention given to events with missing drainage, is provided.

Comparison between the hydraulic performance of the phytocap and conventional caps is important for understanding the potential application of the phytocap in Australia. Although minimising drainage is the performance goal of a landfill final cap, these research trials were designed to compare all water balance aspects within the constraints of the site environment, including natural as well as man-made constraints, e.g. available labour skilled in phytocap design, installation and maintenance. This approach allows for a more realistic assessment of phytocaps and allows the determination of potential improvement methods. If minimising drainage had been the only goal then loam soil with optimum hydraulic properties could have been imported to all sites, placed metres thick and mature grasses, shrubs and trees established and provided with a high level of management to optimise growth and survival.

The field water balance is presented in terms of a water or weather year (WY). The advantage of a weather year is that it encompasses drainage events and plant growth changes which do not correspond to a calendar or financial year. The weather year commences at the start of the "wet" season and finishes at the end of the "dry" season. The wet season was defined by the period of the year when rainfall was expected to exceed evapotranspiration. For sites with distinct rainfall patterns the weather year was easily defined. The most difficult site was Lismore, where rainfall and evaporation are higher in summer than winter and evaporation exceeds rainfall in winter but colder winter temperatures limit evapotranspiration.

5.1 Adelaide Site

The Southern Waste Depot (SWD) trial site has been monitored from 2 July 2007. Some data were collected prior to this date; however, the weather station and soil moisture content sensors were installed and operational by 2 July 2007. The trial site is still maintained and data are analysed herein until 31 March 2011, i.e. the end of weather year 4 (WY4). Rainfall, soil moisture, lateral flow and drainage data were collected on 98 – 99% of days, with consecutive days of missing data limited to < 4 days. The weather years for this site are WY1 from July 2007 to Mar 2008; WY2 from April 2008 to March 2009; WY3 from April 2009 to March 2010; WY4 from April 2010 to March 2011.

5.1.1 Trial Weather

Annual rainfall measured at SWD during the trial ranged from 361 mm in WY2 (April 2008 to March 2009) to 708 mm in WY4 (April 2010 to 2011) compared to the average annual rainfall of 518 mm. The monthly rainfall ranged from some of the driest months on record, with < 1 mm/month received in January and February 2009, to the wettest (Figure 5.1). The winter periods in 2007 and 2008 were below the long-term average with the summers of 2007/2008 and 2008/2009 continuing the extended dry period. From March to September 2009, near or above average rainfall was received. With the exceptions of October 2009 and May 2010, this trend of near or above average rainfall continued into 2011, with rainfall near or above the monthly 90th percentile occurring in 8 months.

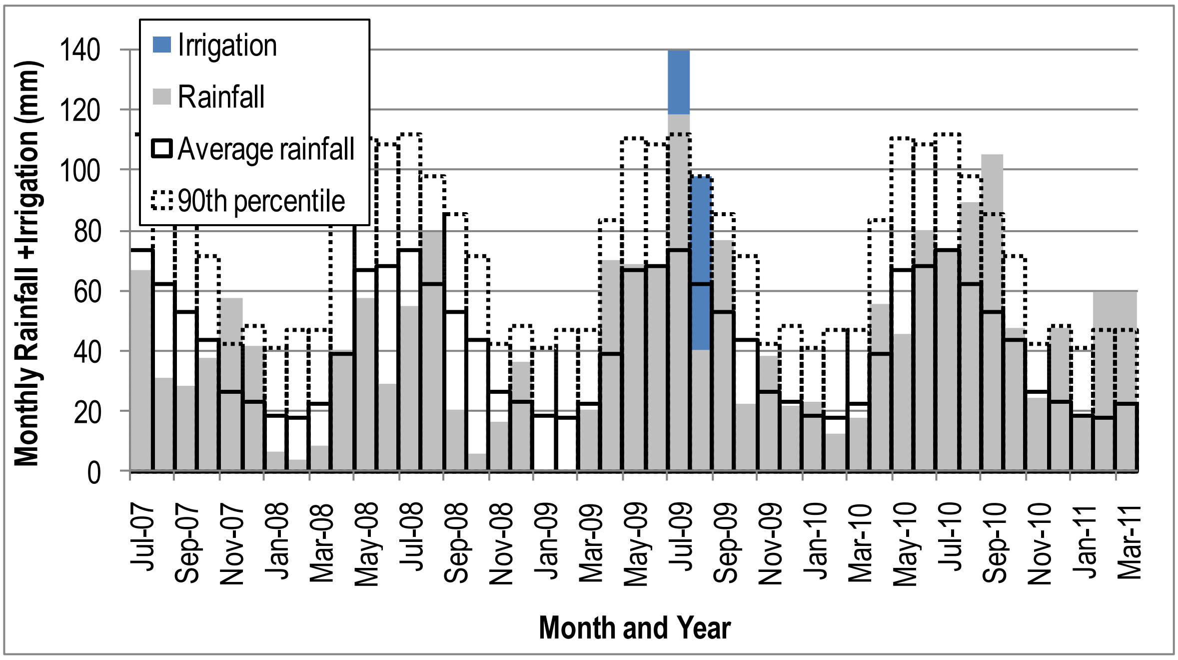

Figure 5.1 Measured Monthly Rainfall + Applied Irrigation at Southern Waste Depot Compared with Long-term Average and 90th Percentile Rainfall

Irrigation was applied to the phytocap and conventional lysimeter in July and August 2009 to force drainage to occur and has been included as precipitation in the water balance. As drainage had not been recorded in 2007 or 2008 and the long-term forecast for 2009 suggested rainfall would be near or below average, 83 mm was irrigated to simulate more extreme winter rainfall. To reduce the artificial effects associated with irrigation, the irrigation was applied by surface drippers on days when rainfall was occurring or likely to occur. The use of surface drippers removed the loss due to plant interception and allowed more accurate measurement of additional moisture applied. Irrigation on inclement days ensured that evapotranspiration rates were not artificially increased by increased potential. The scheduling and volumes of irrigation applied are shown in Table 5.1. The irrigation application rate was equivalent to 8.8 mm/hr rainfall event with irrigation applied in 1 – 4 shifts/irrigation day over runtimes of 30 minutes to 1 hour and 23 minutes, averaging 59 minutes.

Table 5.1 Irrigation Volumes Applied in 2009 to Force Drainage at Southern Waste Depot

Date	Irrigation Volume Applied (mm)		
	Conventional Lysimeter	Phytocap Lysimeter	Average
28/07/2009	10.42	10.72	10.57
31/07/2009	14.82	16.21	15.52
10/08/2009	12.42	12.25	12.34
11/08/2009	36.96	36.92	36.94
19/08/2009	8.33	8.22	8.27
TOTAL	**82.96**	**84.32**	**83.64**

Temperatures received over the trial period were similar to the long-term average daily minimum and maximum temperatures (Figure 5.2). Over the trial period, 8 days were above 40 °C and 57 days were above 35 °C, which is above the expected long term average for this time period of 3 days and 34 days, respectively. Low temperatures were within the expected long term average with 2 days < 2 °C and 0 days < 0 °C.

5.1.2 Phytocap Water Balance

As shown in Table 5.2, the water balance measured in the phytocap showed that little drainage occurred during the first few years of plant establishment but that in WY3, after irrigation was applied, and WY4, when consecutive months of high rainfall were received, drainage was recorded. During the first 2 years of monitoring, evapotranspiration exceeded rainfall as moisture was removed from the initially moist soil. In WY3, precipitation (including 83 mm irrigation) increased by 300 mm. Soil moisture storage accounted for 53 mm and 20 mm drained from the profile resulting in an ET of 590 mm, even though the ET could have potentially been higher, as was calculated in WY4. This

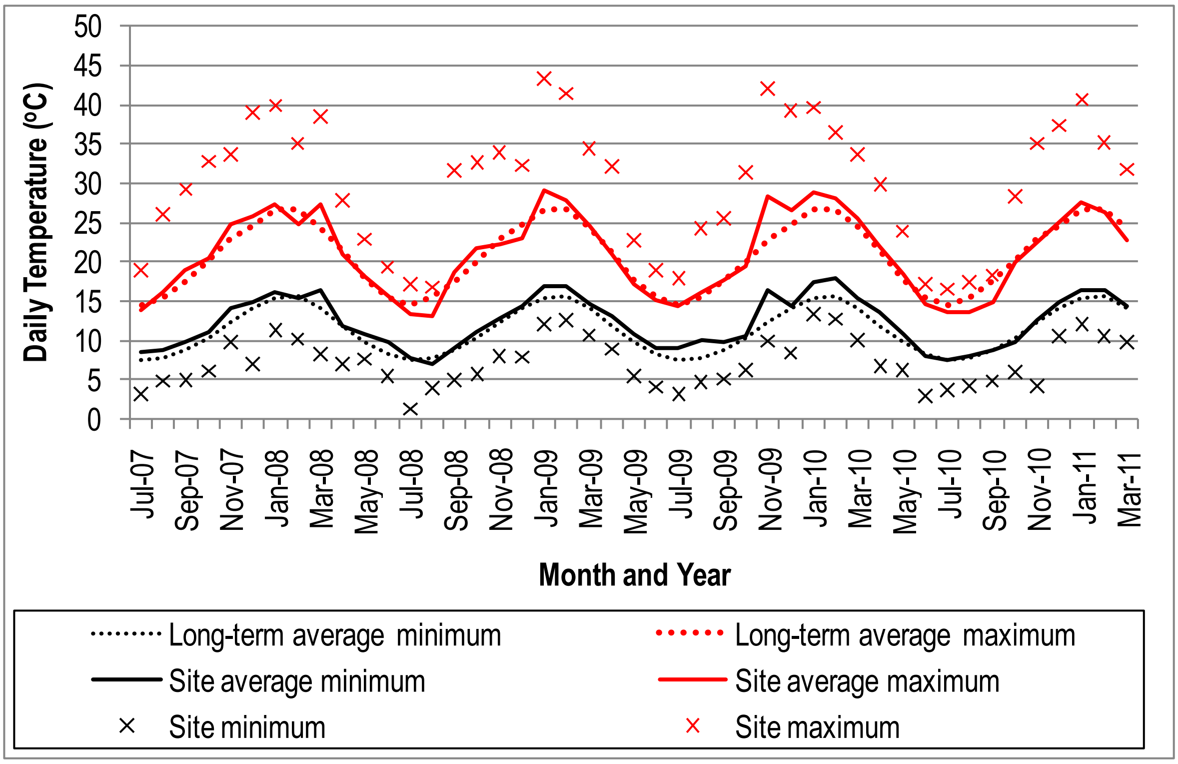

Figure 5.2 Long-term and Site-Measured Average and Extreme Minimum and Maximum Daily Temperatures at Southern Waste Depot

suggests that plant growth was affected in WY3 or that rainfall occurrence did not coincide with plant growth periods as well as in WY4.

The runoff measured was very low (Table 5.2). The rainfall intensity at the site averaged 1 mm/hr with 90% of rainfall events < 3 mm/hr, suggesting runoff events may have been below the resolution of the flow meters. Observations made of the site during rainfall events once the vegetation had established suggested that little or no runoff occurred from the trial plots which was consistent with the measurements.

Table 5.2 Measured Phytocap Water Balance for Southern Waste Depot

	Measured Water Balance (mm) for Weather Year			
	WY1 (July 2007 – March 2008)	**WY2 (April 2008 – March 2009)**	**WY3 (April 2009 – March 2010)**	**WY4 (April 2010 – March 2011)**
Precipitation	281.6	360.8	662.7*	708.2
Evapotranspiration (calc)	335.9 (119%)	372.1 (103%)	589.5 (89%)	690.8 (98%)
Phytocap runoff	0.8 (0.2%)	1.4 (0.4%)	0.03 (0%)	0 (0%)
Phytocap change in storage	-55.1 (-20%)	-12.7 (-4%)	53.2 (8%)	6.7 (1%)
Phytocap drainage	0 (0%)	0.0 (0%)	19.9 (3%)	10.7 (2%)

* includes irrigation applied until drainage was measured

The cumulative water balance over the monitoring period showed that the rainfall had a distinct stepped pattern, with the drier summer of WY1 (2007/2008) and WY2 (2008/2009) evident by the nearly zero accumulation of rainfall (Figure 5.3). In WY3, a more consistent rainfall pattern is evident with no extended dry periods. Drainage occurred twice over the monitoring period, commencing in August or September and ceasing in mid-November. Drainage occurred after the soil profile moisture content remained high for an extended period of time and not solely when a specific moisture content was exceeded. The soil profile moisture storage generally increased in winter and decreased in summer, as expected.

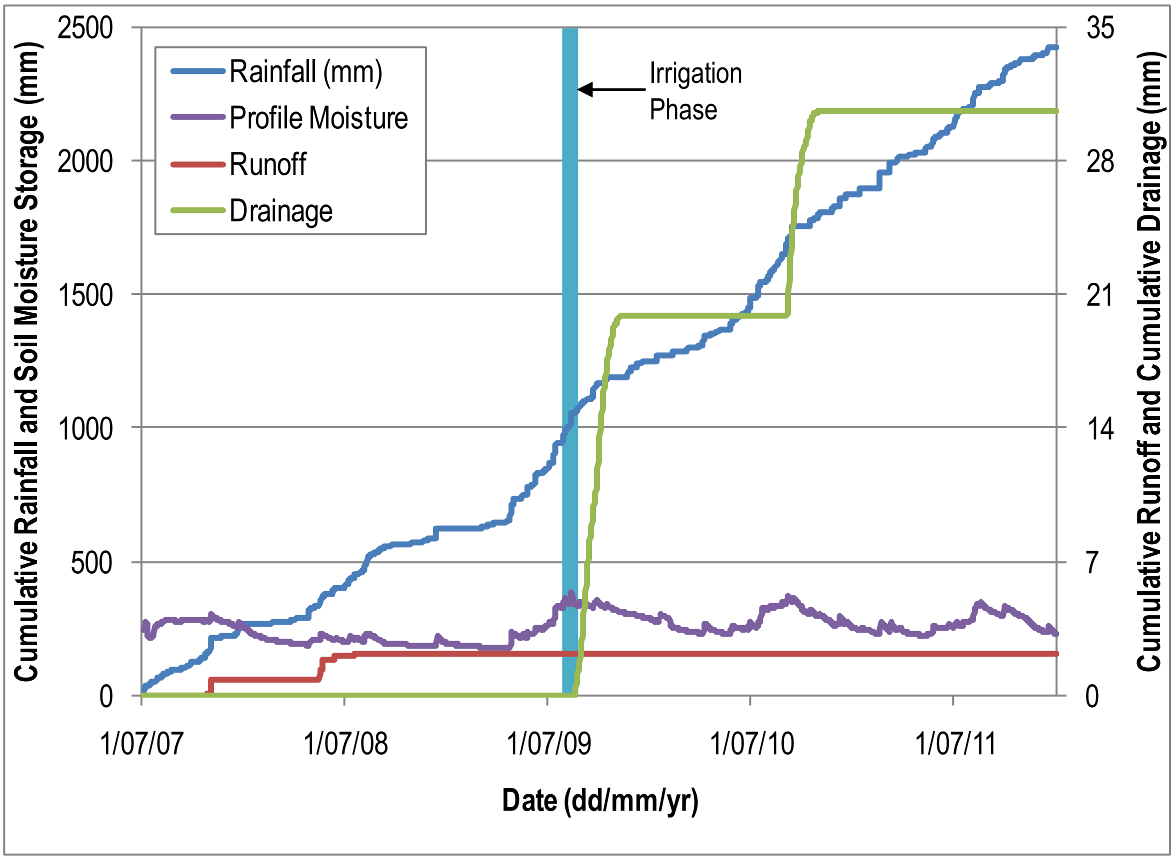

Figure 5.3 Cumulative Rainfall, Runoff and Drainage and Soil Moisture Storage of Phytocap at Southern Waste Depot

The soil profile moisture content steadily declined from WY1 through to the beginning of WY3 and then showed a pattern of increase during winter and decrease during summer (Figure 5.3). The maximum profile moisture storage was 350 – 380 mm while the minimum profile storage was 175 mm. The pattern of profile moisture storage changed from WY3 when an increased moisture volume was stored in the profile (Figure 5.3).

The topsoil moisture content increased rapidly in response to rain but also decreased rapidly from July 2007 to May 2009 (Figure 5.4). After May 2009, the topsoil moisture content increased rapidly in response to rain but decreased slowly, with the profile remaining moist, particularly at depth, through the summer of WY3 (2009/2010). On 13/12/08, the topsoil moisture content rose to 21.4% after a 33 mm storm event. After 15 days and no further rainfall, the soil moisture content decreased to 11.9%, a reduction of 9.5% moisture. In the following year over a 15-day dry period commencing on 17/12/09, the moisture content reduced from 17.8% to 14.9%, i.e. a reduction of only 3%. Though these measurements were taken at similar times of the year with similar temperature, humidity and plant water use, a major difference was evident in moisture lost from the topsoil.

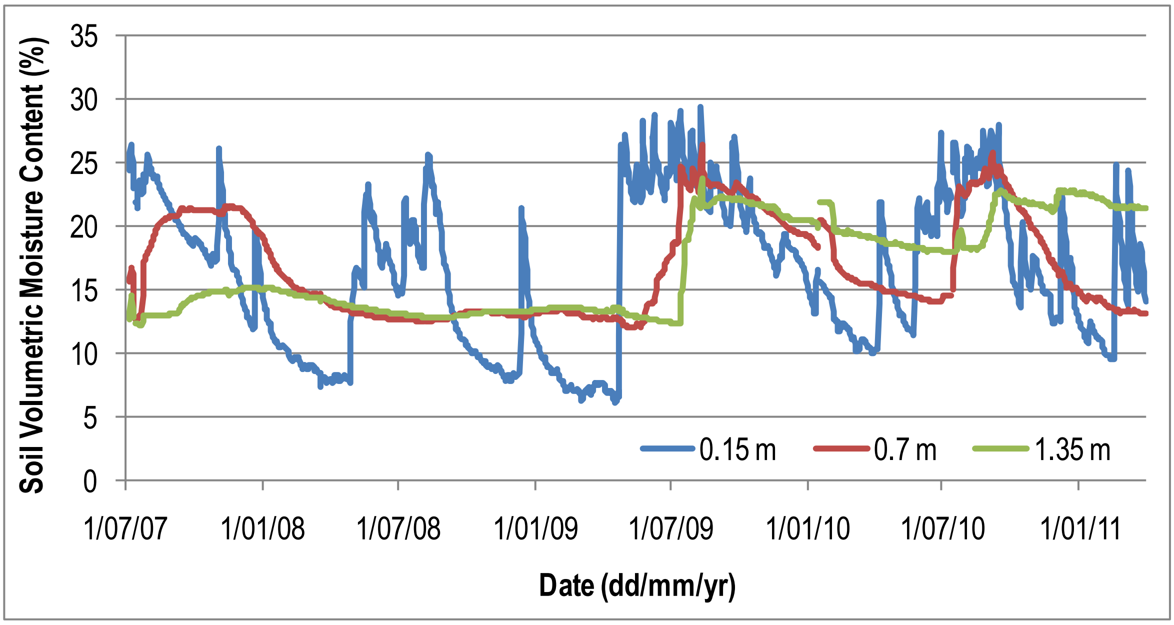

Figure 5.4 Average Volumetric Moisture Content in Phytocap at Southern Waste Depot

The moisture content in the deeper soil layers (0.7 m and 1.35 m depth) did not change until WY3, with the exception of increased moisture at 0.7 m depth during WY1. After the WY2 summer, the moisture content at 0.7 m and 1.35 m decreased to a minimum volumetric moisture content of 12%. By the end of the following year (WY3), the minimum moisture content recorded was higher at 14.1% and 17.9% for the 0.7 m and 1.35 m depths, respectively. In WY4, the minimum moisture content of the 0.7 m depth interval after summer decreased from WY3 to 13% even though more rain fell in WY4 than in WY3. The moisture content deeper in the profile remained higher than the previous year's minimum at over 20% moisture by the end of WY4. These changes in moisture pattern at the end of the weather year suggest that detrimental changes occurred at the end of WY2 or beginning of WY3 and that over WY4 the change began to lessen, reverse or change again.

The reason for the change in moisture content trend was the death of the vegetation in the lysimeter. In early 2009, the vegetation on the phytocap, mainly on the lysimeter but also along the edge of the control area where the monitoring equipment was placed, was observed to be grey in colour, rather than the usually yellow-brown of the grass in summer (Figure 5.5).

Figure 5.5 Time Series Site Photos of Phytocap with Good Grass Establishment in October 2008 (top left), with Dead Grass in May 2009 (top right), with Vegetation Recovering and Weeds Establishing in September 2009 (bottom left) and with Recovered Vegetation but Different Species Mix, including Volunteers in October 2010 (bottom right).

Rapid weed colonisation occurred in Autumn 2009 and a broad-leafed selective herbicide suitable for use on established native grasses was sprayed to reduce competition for the native grasses. However, the grasses died leaving the lysimeter plot and surrounds sparsely vegetated, predominantly with weeds, for most of WY3 (Figure 5.5, top right). In WY4, native grasses have re-established on the phytocap along with a number of introduced grasses, such as couch and kikuyu, and weeds (Figure 5.5, bottom right). The decrease in minimum moisture content at the end of WY4, after a wetter winter than WY3, suggests that the plant roots have started to remove moisture from 0.7 m depth.

Native grass roots have been shown by others to reach over 1 m depth (Mitchell, 2001; Rab *et* al., 2002; Saint Pierre *et al.*, 2002) and can take between 3 months for species like *Bothriochloa macra* to 24 months to grow to 1 m depth (Mitchell, 2001). On 31 May 2010, a single auger hole was drilled into the lysimeter to investigate potential causes of the grass die-back. During these investigations, roots were observed to over 1 m depth, suggesting that the native grasses in the lysimeter should utilise the moisture currently stored deeper in the profile.

During WY1 and WY2 no drainage was measured from the phytocap. The profile moisture storage increased to approximately 300 mm during WY1 but was less than the profile moisture content at field capacity (Figure 5.6). As the profile dried over the drier years of WY1 and WY2 it can be seen that the profile remained above the profile moisture content estimated for permanent wilting point but over time was tending toward this very dry state.

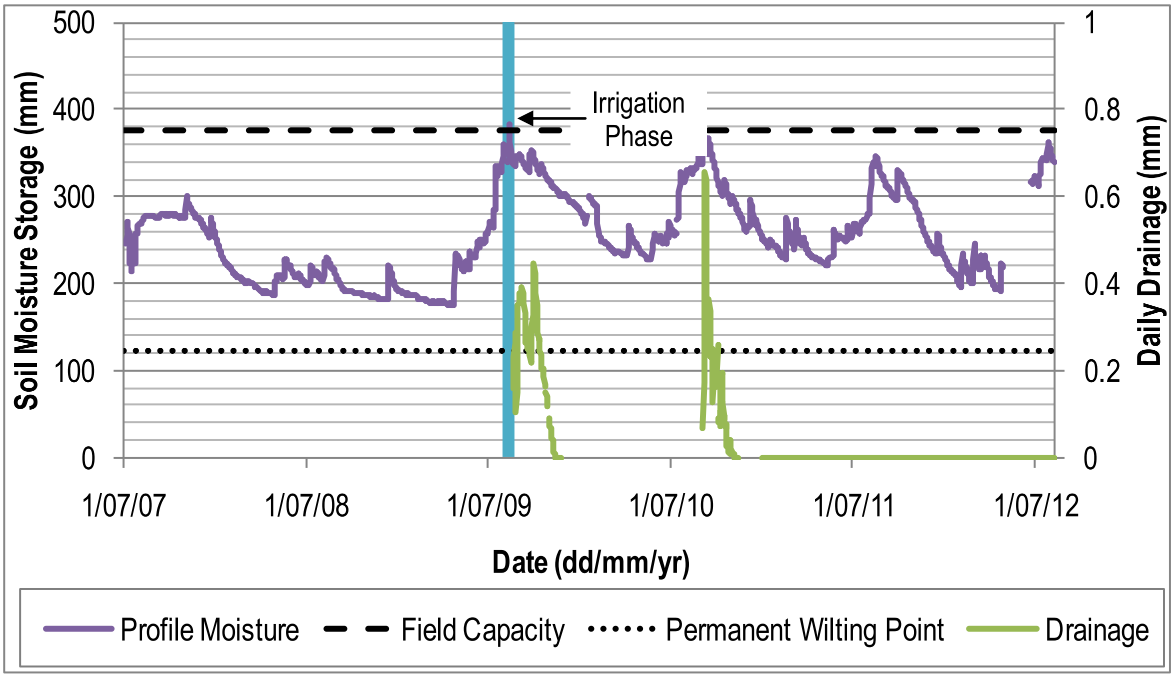

Figure 5.6 Average Daily Soil Profile Moisture and Daily Drainage Measured from Lysimeter at Southern Waste Depot. Irrigation Period and Profile Moisture Content at Field Capacity and Permanent Wilting Point are Also Shown

In WY3 (2009), drainage was recorded from the phytocap lysimeter in response to the addition of irrigation. Irrigation of 83 mm increased the soil moisture profile to over 340 mm and 20 mm of drainage was recorded (Figure 5.6). The drainage (20 mm) was less than the irrigation volume applied; however, the moisture content increased at the 1.35 m depth in the control area (where irrigation was not applied) as well as the lysimeter (Figure 5.7). This suggests that drainage may have occurred without irrigation, though the volume may have been less, and that the lack of vegetation was a greater influence on drainage occurring than irrigation. At the end of WY3, the profile moisture content remained high and held approximately 40 mm more moisture than at the end of WY2 (Figure 5.6).

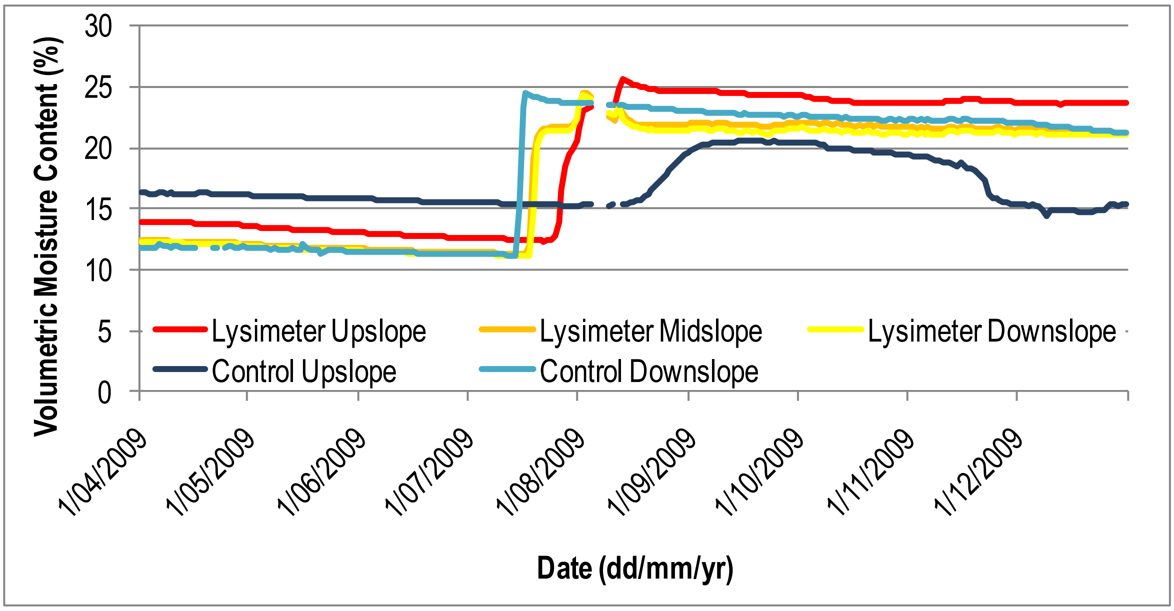

Figure 5.7 WY3 Soil Moisture Content at 1.35 m Depth in Southern Waste Depot Phytocap

In WY4, the above average rainfall combined with the events of WY3, resulted in further drainage (11 mm) being recorded after the profile moisture content exceeded approximately 340 mm. It is evident that if the profile had dried the additional 40 mm to the WY2 minimum, then it is unlikely that drainage would have been recorded. Although the profile dried more rapidly at the end of winter in WY4 compared with WY3, the profile moisture content has remained relatively high to the end of WY4, suggesting drainage is again likely in the following year, depending on weather. This continued higher moisture content may be caused by the plant roots not yet having regrown substantially into deeper layers or that the changed vegetation includes a higher proportion of shallow rooted species.

5.1.3 Conventional Cap Water Balance

The water balance measured from the conventional cap from July 2007 to March 2011 showed that evapotranspiration was the major loss of precipitation in the water balance (Table 5.3). Evapotranspiration was calculated to account for 97% or more of precipitation for all years. The higher calculated evapotranspiration in the first year, caused by decreasing soil moisture content, would be predominantly evaporation as the plants were observed to establish more slowly on the conventional cap than the phytocap. Runoff accounted for < 1% of the precipitation received in all

Table 5.3 Measured Conventional Cap Water Balance for Southern Waste Depot

	Measured Water Balance (mm) for Weather Year			
	WY1 (July 2007 – March 2008)	**WY2 (April 2008 – March 2009)**	**WY3 (April 2009 – March 2010)**	**WY4 (April 2010 – March 2011)**
Precipitation	281.6	360.8	662.7*	708.2
Evapotranspiration (calc)	366.3 (114%)	361.3 (100%)	642.5 (97%)	710.7 (100%)
Runoff	0.3 (0.1%)	1.5 (0.4%)	4.9 (0.7%)	0.4 (0.1%)
Change in storage	-85.0 (-30%)	-2.0 (0.6%)	7.1 (1%)	-4.1 (-0.6%)
Lateral flow	0 (0%)	0 (0%)	6.7 (1%)	1.0 (0.1%)
Phytocap drainage	0 (0%)	0 (0%)	1.5 (0.2%)	0 (0%)

* includes irrigation applied until drainage was measured

years. As discussed for the phytocaps, there are a number of reasons for this, but observations suggest that runoff was relatively small once vegetation established.

The profile moisture content decreased over the first two years, though the decrease in the first year is partly an artefact of the incomplete year of data. The soil moisture storage increased in WY3 as a result of the higher rainfall combined with irrigation but in WY4 the plants utilised some of this stored moisture. The pattern of profile moisture content over the monitoring period (Figure 5.8) shows that the profile moisture increased over winter to reach a maximum moisture storage of 380 – 390 mm in September and decreased after summer of minimum around 270 – 280 mm by late March/early April. The maximum and minimum are different from the calculated profile moisture content at field capacity and permanent wilting point, which are 521 mm and 217 mm respectively.

The moisture content at three depths in the profile (Figure 5.9) showed that the topsoil responded to rainfall. At 0.9 m depth, i.e. above the compacted clay barrier, two peaks in moisture content were evident in the winter of WY3 and again in WY4. The compacted clay barrier was placed at around 30% volumetric moisture content, i.e. near optimum moisture content, but then steadily dried to around 25% moisture. After irrigation was applied in WY3, the clay moisture content gradually increased to nearly 30% moisture and then decreased to the end of WY3. Following winter in WY4, the moisture content of the clay increased again and peaked slightly higher at 31% and then dried to 24% by the end of WY4. This changing moisture content of the clay suggests that desiccation cracking would have occurred after the first summer after placement. The increasing range of moisture content further suggests changes in soil structure allowing higher field capacity and more significant drying over summer.

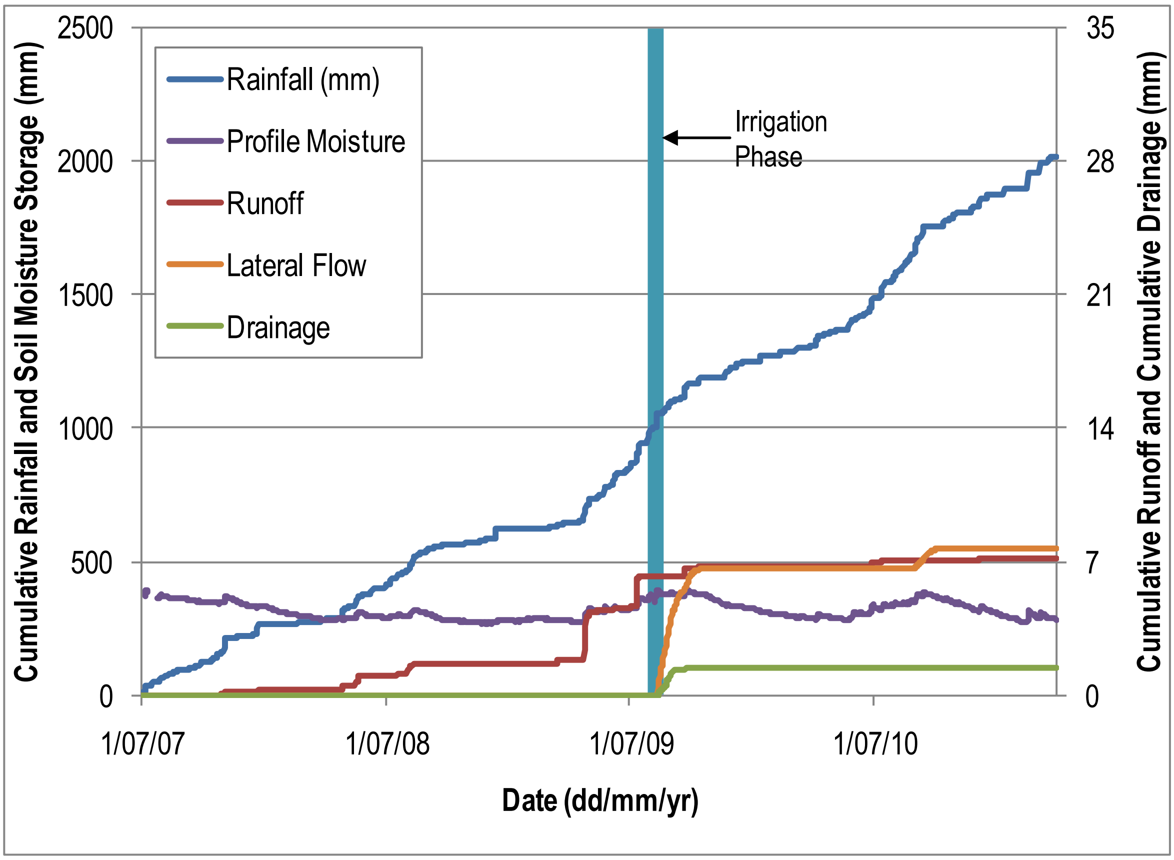

Figure 5.8 Cumulative Rainfall, Runoff and Drainage and Soil Moisture Storage of Conventional Cap at Southern Waste Depot

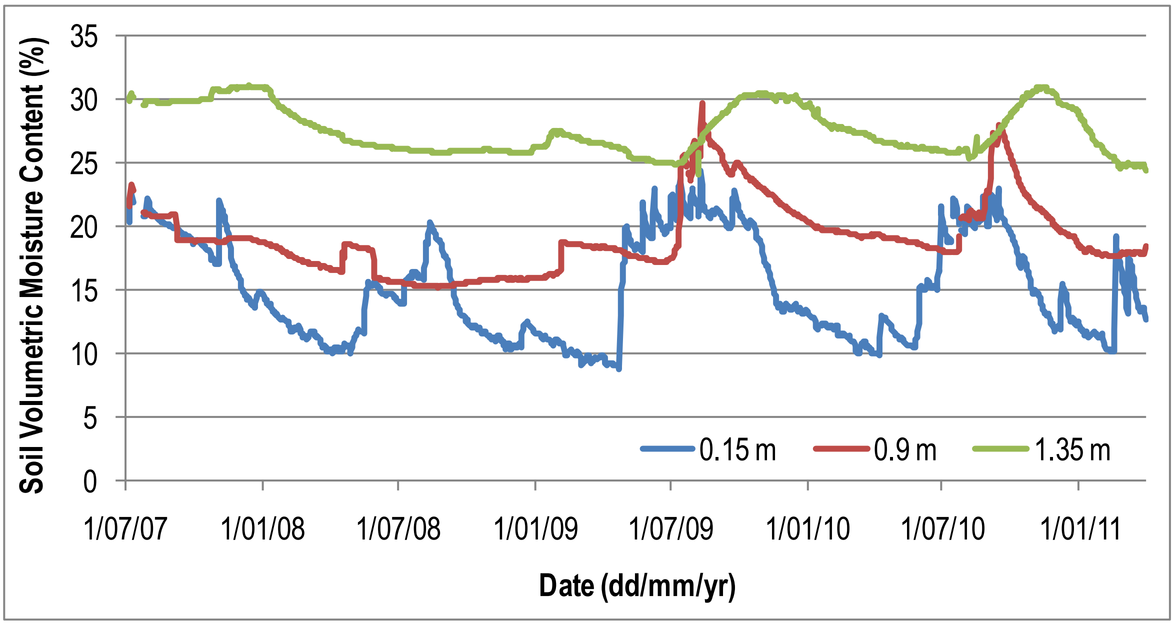

Figure 5.9 Average Volumetric Moisture Content in Conventional Cap at Southern Waste Depot

Lateral flow and drainage were not recorded during the first 2 weather years. After irrigation was applied in WY3 (see Section 5.1.1), both lateral flow and drainage were measured (Figure 5.8). In the final weather year (WY4), lateral flow occurred again but no drainage. Lateral flow occurred as two discrete events, the first from 2 August to 21 October 2009 and in the following year from 27 August to 4 October 2010 (Figure 5.8). The single drainage event occurred from 12 August to 4 October 2009.

Lateral flow commenced when the moisture content at the interface (0.9 m depth) was above approximately 25% (Figure 5.10). In WY3, the moisture content at 0.9 m depth increased rapidly in response to irrigation, while in WY4 the moisture content increased more slowly and in stages. Drainage commenced in WY3 when the clay barrier was relatively dry, at approximately 27%, and was still increasing in moisture, while drainage did not occur in WY4 though similar moisture contents were measured. This pattern suggests that the clay had cracked and preferential pathways had formed, resulting in the "short-circuiting" of the soil mass and drainage occurring before saturation. In WY4, the slower wetting of the soil may have allowed the clay to swell slowly and the cracks to shrink, thus drainage did not occur.

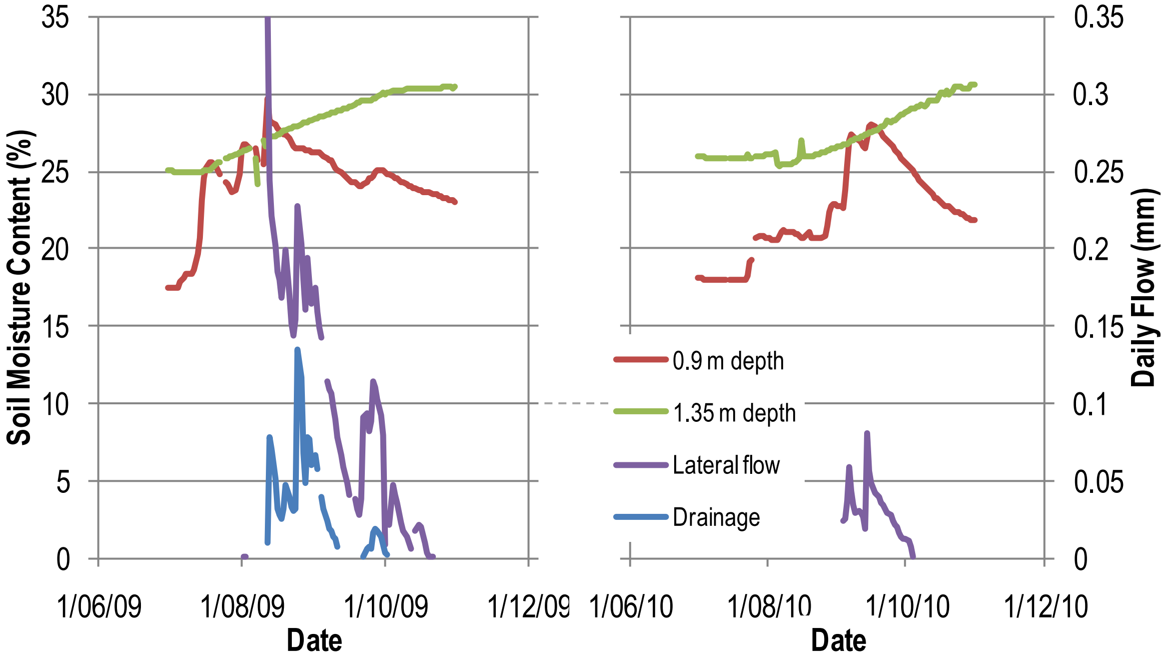

Figure 5.10 Southern Waste Depot Conventional Cap Soil Moisture Content at 0.9 m and 1.35 m depth, Daily Lateral Flow and Drainage for June to November in WY3 and WY4

5.1.4 Phytocap vs Conventional Cap

The water balance of the phytocap and conventional cap show a number of importance differences. The runoff from the conventional cap was greater than the phytocap which may lead to greater erosion of the surface. The irrigation of the phytocap and conventional cap resulted in an increase in moisture content over WY3 for both profiles but the net effect was an increase of 53 mm in the phytocap compared with the conventional cap which was 7 mm. In WY4, the conventional cap utilised some of this moisture while the phytocap stored moisture. The vegetation was the same on both caps, being native grasses, but the die back of vegetation, which affected mainly the phytocap lysimeter, had a major effect on the moisture lost as ET for WY3 and to a lesser extent in WY4.

The profile moisture content of the covers also varied. Also, although the conventional cover theoretically could store 521 mm of moisture at field capacity, the maximum storage calculated was 394 mm. In contrast, the phytocap could theoretically store 375 mm and the maximum storage calculated was 410 mm. It should be noted that the theoretical storage is based upon the entire profile achieving field capacity at the same time and that the storage calculated from field measurements is based on assumptions of the moisture content recorded at the sensor depth being representative of average moisture content for a nominated thickness of soil. Although these two situations are unlikely to be found in the field, they provide estimates for comparison and in the case of the phytocap indicate that the profile was near its storage capacity during the trial, while that the conventional cap did not reach its storage capacity and yet drainage was still recorded from this profile.

The minimum storage estimated from the field moisture content also varies for the profiles. The profile storage at permanent wilting point was theoretically 217 mm for the conventional cap but the minimum profile storage measured in the field was 267 mm. The phytocap dried to 128 mm, as calculated from field measurements, which was near its theoretical minimum of 123 mm. This shows that the phytocap dried throughout the profile while the conventional cap retained some moisture, indicating that the native grasses grew better (and thus transpired more) and had roots to deeper depths in the phytocap than the conventional cap. Comparison of the moisture content near the surface shows that the rate of moisture changes and the minimum moisture recorded was faster and greater for the phytocap than the conventional cap, though this is not as evident during WY3 when the vegetation died on the phytocap (Figure 5.11).

The phytocap at Southern Waste Depot allowed more drainage through the cover over the four years than the conventional cover, though it should be noted that the volume of drainage from both caps was small and comprised < 3% of the rainfall received. However, the performance of the conventional cap was not predictable as the compacted clay barrier dried and allowed drainage to occur. Over time, further intrusion by plant roots would be likely to increase this occurrence and may result in more drainage over time. In addition, the lateral flow from the conventional cap could

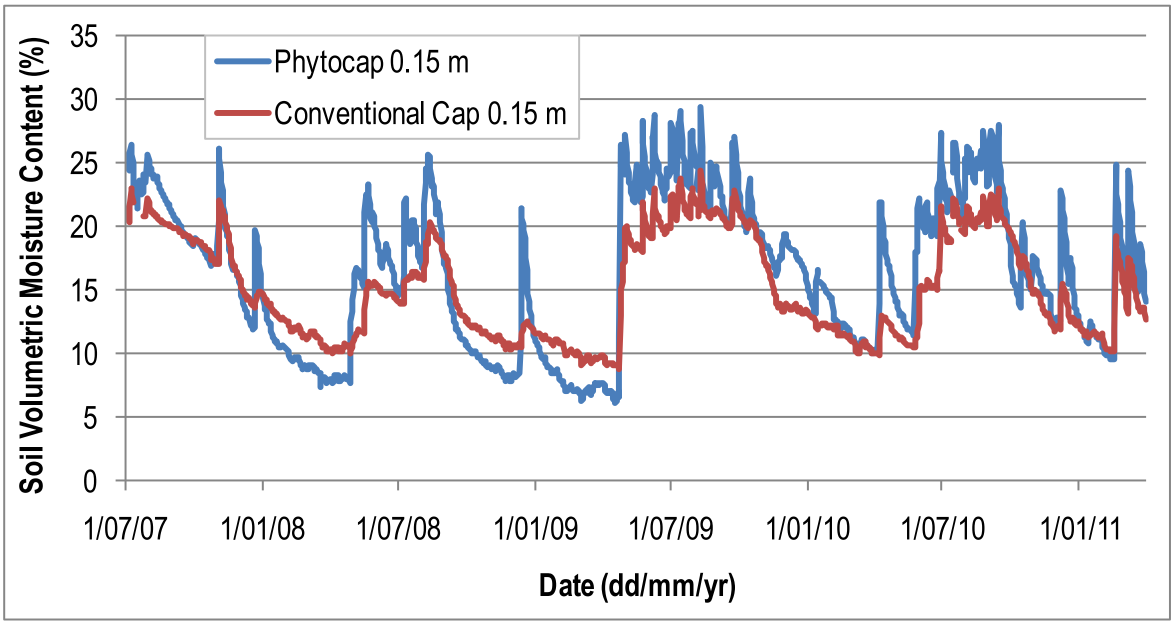

Figure 5.11 Average Daily Soil Moisture Content at 0.15 m Depth in the Phytocap and Conventional Cap at Southern Waste Depot

potentially become drainage by "short circuiting" the compacted clay through preferential cracks and also where differential subsidence of the waste mass results in a discontinuous clay barrier.

The drainage from the phytocap was greater than the conventional cap but there are more mechanisms available to improve the performance of the phytocap design for this site. The trialled design only included native grasses and adding trees and shrubs to the vegetation would increase transpiration and thus reduce the potential for drainage to occur. In addition, clay could be placed at the base of the profile, as is the natural soil profile in this area, thus increasing moisture holding capacity and reducing drainage. Unlike a compacted clay barrier, this material would not need to be a barrier layer placed near maximum dry density. Although the phytocap water balance was affected by the vegetation die-back, vegetation has re-established on the site without further planting being undertaken. This suggests that although the phytocap relies on the vegetation as part of its function, the design is robust as the vegetation regenerated quickly. As most native vegetation has fire tolerance mechanisms, it could be expected that a similar rapid regrowth response would occur.

5.1.5 Lysimeter vs Control Plot

The lysimeter incorporates a plastic liner which could prevent the transference of moisture and temperature from the decomposing waste mass underlying the trial plots. The liner also prevents landfill gas, particularly methane, from entering the soil within the lysimeter. As the oxidation of methane results in the generation of moisture, the lysimeter may affect the "real" water balance of the cap. In addition, deformations in the lysimeter pan may hold moisture and the drainage net may form a capillary break which may change the soil moisture content in the lysimeter compared to control area. Comparison of the moisture and temperature data recorded from the lysimeter and the control can be used to assess the affect of the underlying waste mass on the cap water balance and whether the lysimeter pan has affected the water balance.

At Southern Waste Depot, there were no apparent differences between the monitoring data collected from the lysimeter and control plots. The main difference would be expected to be observed at the deepest monitoring location were the potential impact of the HDPE lysimeter pan on preventing interaction with the underlying waste should be greatest. Comparison of the soil volumetric moisture content and the soil temperature showed no differences were evident. For example, the soil temperature for WY1 as measured at 1.35 m depth in the phytocap and the conventional cover (Figure 5.12) showed no trend between sensors located in the lysimeter and the control. Moisture sensors also did not show any marked differences (as shown in Figure 5.7).

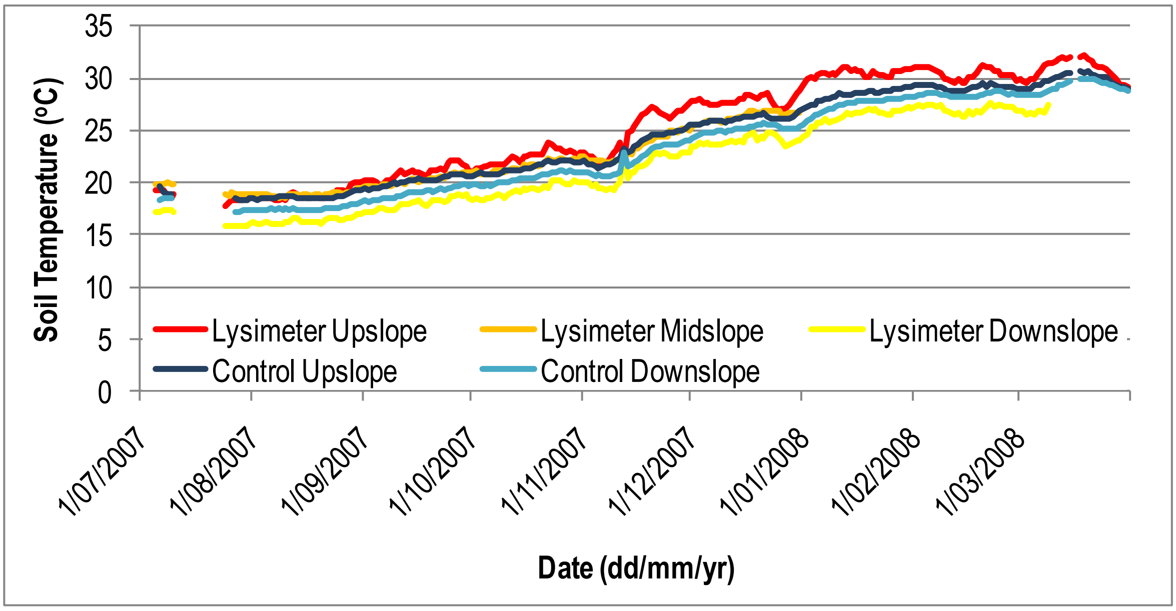

Figure 5.12 Soil Temperature at 1.35 m Depth During WY1 in the Conventional Cap at Southern Waste Depot

5.1.6 Summary

The Adelaide phytocap was affected by vegetation die back, which reduced ET and resulted in drainage. Revegetation occurred and plants appear to be accessing moisture to 0.7 m depth within 18 months. Native grass roots can grow to > 1 m and hence as the vegetation regrows, the moisture content of the deeper soil should reduce and drainage should cease. Even with vegetation die back, the drainage was < 20 mm/yr in an above average rainfall year, equivalent to < 3% of precipitation.

The Adelaide conventional cap dried throughout the compacted clay layer and drainage was measured in 2009, after irrigation. Drainage was not measured in 2010 when the moisture increase through winter was gradual, suggesting that the cracks which allowed preferential flow in 2009 had shrunk or in-filled.

The conventional cap resulted in less drainage than the phytocap but more runoff. The phytocap performance was more predictable and can be improved by the addition of trees and shrubs or clayier soil material. Overall, the phytocap appeared to be a more sustainable design with the cap able to repair itself in the event of impacts on its integrity, i.e. the vegetation died but regenerated. The same ability is not present in compacted clay barriers, where repair requires excavation and recompaction to maintain its integrity.

5.2 Melbourne Site

Monitoring at Taylors Road Landfill (TRL) commenced on 16 February 2007 with the weather station and soil moisture sensors. Runoff and drainage measurement commenced on 27 March 2007 with the lateral flow tipping bucket installed in May 2008 and backup dosing siphons for drainage installed in May 2009. The soil temperature sensors were installed during October – November 2007. After substitution (as described in Section 3.6), over 97% of rainfall, drainage and soil moisture content data were available for interpretation. The lateral flow tipping bucket functioned near perfectly (> 99% of data captured) in WY3 and WY4; however, in WY2 the tipping bucket functioned for approximately 50% of the period. Overall, data gaps were generally intermittent, i.e. usually < 1 – 2 hours, and do not exceed 4 days (excluding the lateral flow tipping bucket). Four weather years of data, WY1 from April 2007 to March 2008; WY2 from April 2008 to March 2009; WY3 from April 2009 to March 2010; WY4 April 2010 to March 2011 have been analysed.

5.2.1 Trial Weather

The weather at Taylors Road Landfill varied from below average for the first 2 years and then above average for the last 2 years. Annual rainfall ranged from 630 mm in WY2 to 1451 mm in WY4. WY4 is almost double the long-term average rainfall for Dandenong of 761 mm. The monthly rainfall pattern shows that the majority of months from April 2007 to February 2009 were below the long-term average (Figure 5.13). The exceptions were November and December 2007 and December 2008, where the monthly rainfall was above average and December 2007 was also above the 90 percentile rainfall. From March 2009, this trend was reversed with all months receiving average or higher rainfall with the exception of May and June 2009 and July 2010. The rainfall in February 2011 was 272 mm which is the highest monthly rainfall on record for any month of the year; the next highest was 199 mm in 1973, also in February.

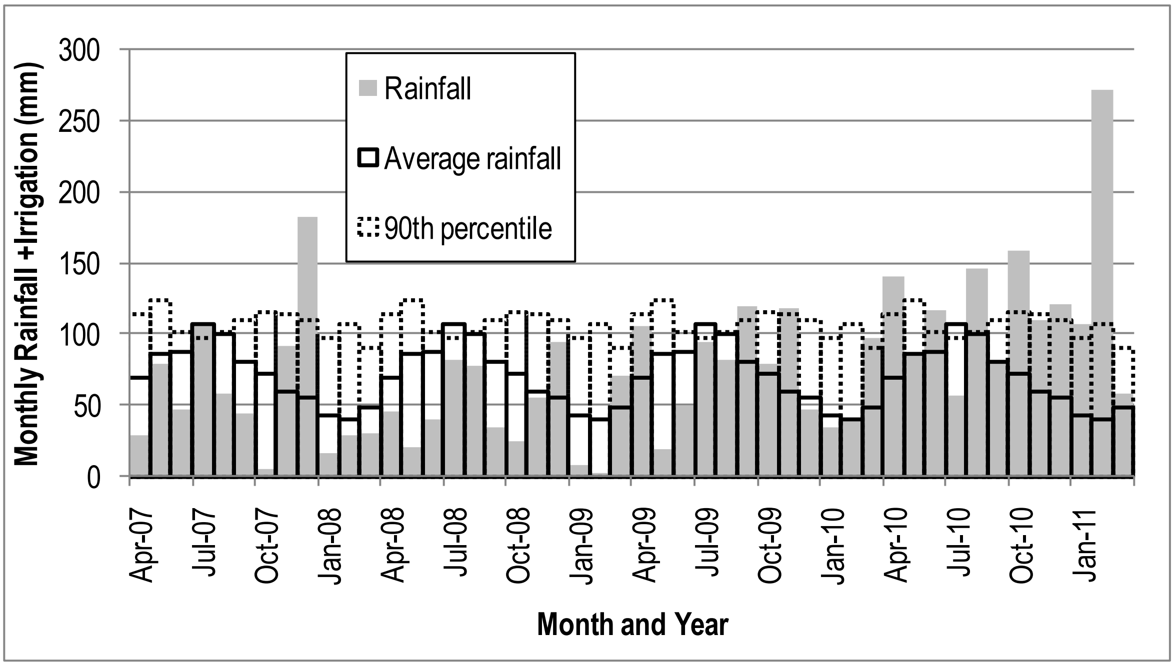

Figure 5.13 Measured Monthly Rainfall at Taylors Road Landfill Compared with Long-term Average and 90th Percentile Rainfall

Irrigation was applied to the phytocap plots to aid plant establishment. After planting in April 2007, irrigation was applied during 2007/2008 with further irrigation applied in 2009 to aid the establishment of seedlings planted in September 2009. The irrigation (Table 5.4) was unlikely to have affected the water balance due to the small volume and to application during peak evaporation and transpiration. As the irrigation was only applied to the phytocap lysimeter, these volumes are only included in the precipitation for the phytocap (discussed in Section 5.2.2) and not in the conventional cap.

Table 5.4 Irrigation Applied to Phytocap at Taylors Road Landfill

Period irrigation applied	Irrigation Applied to Phytocap (mm)
1 – 24/12/2007	10.5
1 – 31/01/2008	7.0
1 – 28/02/2008	2.0
13 – 18/03/2008	4.0
16 – 24/04/2008	6.25
16 – 24/05/2008	2.75
Late 09/09 to mid 11/09	14.5

The temperatures recorded at the site show average daily minimum and maximum temperatures for each month were similar to long-term average temperatures (Figure 5.14). The extremes of temperature were generally hotter than long-term averages would suggest. From April 2007 to March 2011, 41 days were > 35 °C with 9 days > 40 °C compared to expected long-term averages of 24 days/4 years and 2 days/4 years, respectively. The hotter temperatures occurred in every year, though fewer hotter days occurred in WY4 compared to the previous 3 years.

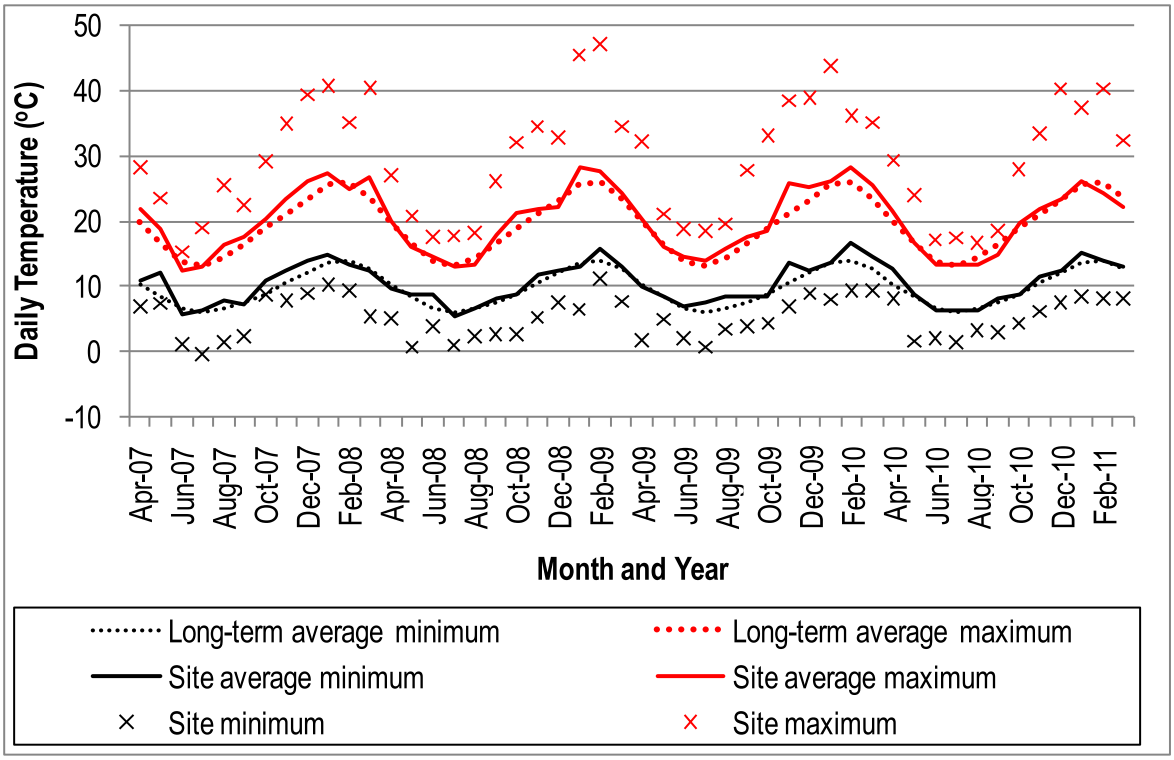

Figure 5.14 Long-term and Site-Measured Average and Extreme Minimum and Maximum Daily Temperatures for Taylors Road Landfill

The site did not experience as cooler conditions as expected based on the long-term average. Over the 4 years of monitoring, 20 days recorded temperatures < 2 °C and while only 1 day was < 0 °C. The long-term average suggests that 28 days < 2 °C and 2 days < 0 °C were expected over the monitoring period. Temperatures < 2 °C were experienced in each year of monitoring suggesting that winter frost would have occurred.

5.2.2 Phytocap Water Balance

The phytocap water balance showed highly variable precipitation (rainfall + irrigation) for the four years, with rainfall in WY4 (April 2010 – March 2011) almost double the rainfall received in the first year (Table 5.5). The rainfall, i.e. not including irrigation, shows no distinct seasonal pattern with the cumulative precipitation increasing at a relatively constant rate (Figure 5.15).

Table 5.5 Measured Phytocap Water Balance for Taylors Road Landfill

	Measured Water Balance (mm) for Weather Year			
	WY1 (April 2007 – March 2008)	WY2 (April 2008 – March 2009)	WY3 (April 2009 – March 2010)	WY4 (April 2010 – March 2011)
Precipitation	774.7	639.0	896.7	1451.0
Evapotranspiration (calc)	712.1 (92%)	689.6 (108%)	908.3 (101%)	1401 (97%)
Runoff	40.1 (5%)	4.1 (0.6%)	1.7 (0.2%)	1.0 (<0.2%)
Change in storage	-23.6 (-3%)	-59.0 (-9%)	-13.6 (-2%)	21.0 (1%)
Drainage	46.1 (6%)	4.3 (0.7%)	0.3 (<0.1%)	28.0 (2%)

* includes irrigation applied until drainage was measured

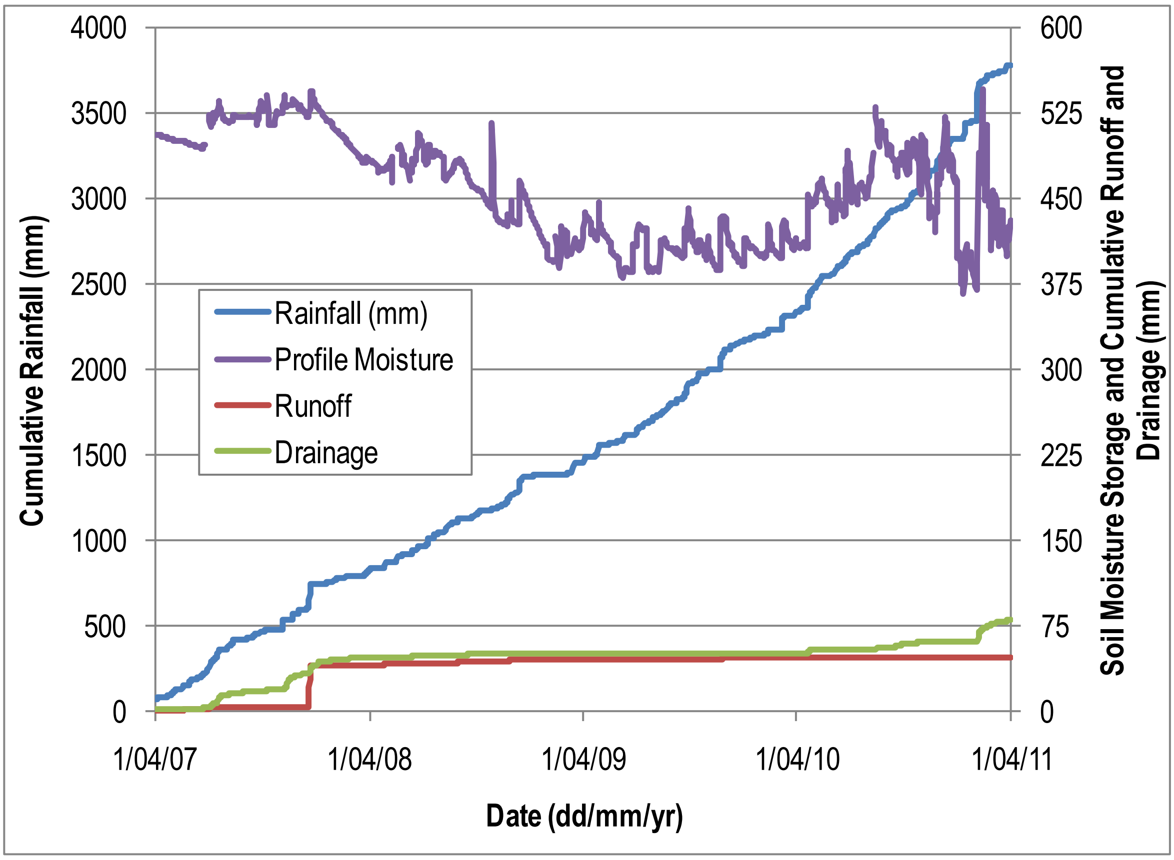

Figure 5.15 Cumulative Rainfall, Runoff and Drainage and Profile Moisture Storage of Phytocap at Taylors Road Landfill

Evapotranspiration is the major loss of precipitation from the soil accounting for over 90% of the rainfall received. The volume of moisture evapotranspired from the soil has increased most years and has removed moisture from the soil. The exception is in WY4 when the evapotranspiration was highest but the moisture storage increased. Plant transpiration potential would have increased as the vegetation established. Although moisture storage increased in WY4 due to the above average rainfall, the calculated evapotranspiration exceeded the average annual pan evaporation of 1,247 mm/yr which suggests the vegetation is almost mature.

The runoff measured from the phytocap has decreased over time both in terms of volume and as a percentage of precipitation (Table 5.5). This decrease would be related to increased plant biomass as the lowest runoff was recorded in the year with the highest rainfall and includes the intense storm event of February 2011, when high runoff was expected.

The soil moisture storage decreased over the first three years of the trial as the plants established. In WY4 the profile moisture generally increased but though the precipitation was over 500 mm higher in WY4 than previous years, < 5% of the additional precipitation was stored in the soil by the end of the year. The soil moisture pattern changed toward the end of WY2, with the more gradual increases in profile moisture reported in WY1 and WY2 becoming more reactive and generally maintaining a drier profile (Figure 5.15). This may be related to soil structure changes and/or increased plant growth and root proliferation.

The soil moisture content was recorded at 3 depths in the profile, 0.15 m, 0.8 m and 1.55 m depth. As with the profile moisture content, the surface moisture content increased and decreased gradually in WY1 and WY2 and the minimum moisture content decreased each year (Figure 5.16). After WY2, the topsoil moisture content more rapidly increased and decreased and also exhibited a greater range of moisture content. The soil moisture content near the middle of the phytocap (0.8 m) exhibited little change in moisture content, with occasional small peaks, until WY4 (Figure 5.16) when greater changes occurred. The moisture content near the base of the phytocap appears to be more variable than the middle depth (Figure 5.16). The construction of the phytocap over aggregate would create a capillary break which would result in the moisture content increasing in the soil above the capillary break until sufficient head forces the moisture into the underlying layer and hence this may be reflected in the more variable moisture content of the bottom layer.

The drainage measured from the phytocap was greatest in WY1 and was less in WY3 and WY4 though precipitation increased (Table 5.5). Drainage commenced in WY1 and continued into WY2 (Figure 5.15). In WY3, little drainage occurred though the precipitation continued at similar rates to previous years. In WY4, drainage commenced again after sustained higher profile moisture content. However, unlike the drainage event in 2007/2008 and although precipitation occurred at a higher rate, drainage ceased in a shorter time period and did not continue to seep from the base of the

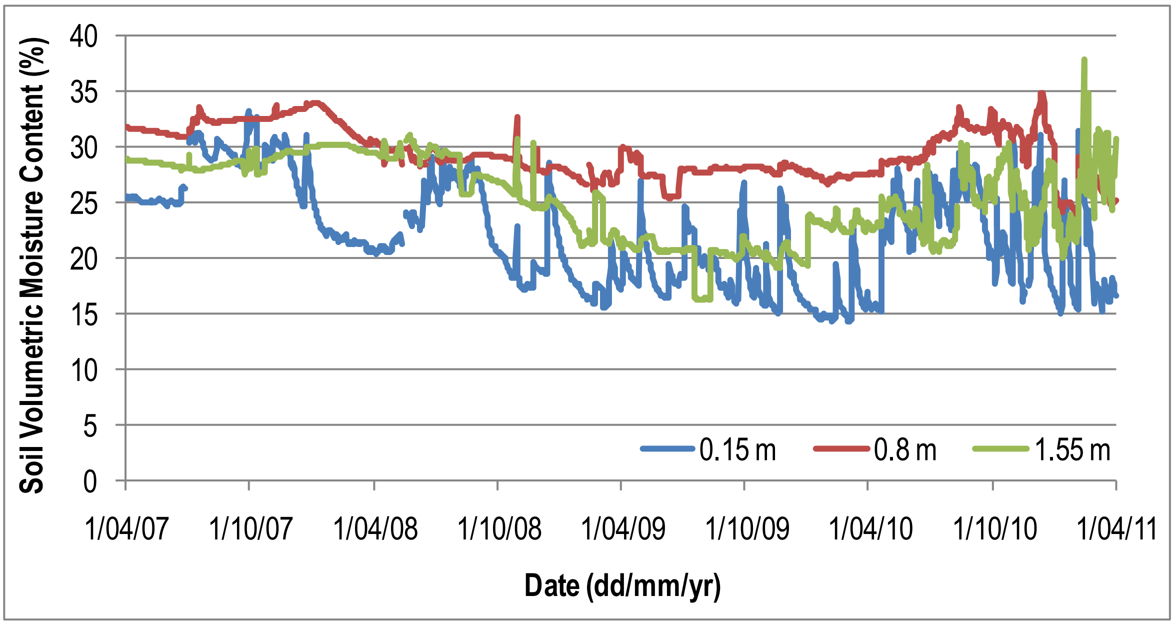

Figure 5.16 Average Volumetric Moisture Content in Phytocap at Taylors Road Landfill

profile. This change in drainage pattern is likely to be related to increased plant water use, particularly at depth.

5.2.3 Conventional Cap Water Balance

The conventional cap water balance includes the soil moisture measured from the lysimeter, which was constructed at the same time as the phytocap, but not the control area, where the sensors were installed in the existing cap which had been constructed 3 years earlier. Differences were observed between the moisture content in the lysimeter and the control area (which are discussed further in Section 5.5.3) and hence discussion of the water balance is limited to the relevant moisture content data from the lysimeter.

The water balance in the conventional cap was measured from 2007 resulting in 4 weather years, with the exception of lateral flow, where measurement commenced in May 2008. The precipitation for the conventional cap is only rainfall as irrigation was not applied to the conventional cover, as is standard practice. This is has result in a lower precipitation for WY1 and WY2 but both the phytocap and the conventional cap received the same rainfall in WY3 and WY4.

Evapotranspiration is the major loss of precipitation in the water balance ranging from < 93 – 100% of precipitation received (Table 5.6). The evapotranspiration was calculated as equal to or less than the precipitation in all years, even when stored moisture was used over the year, (indicated by a negative change in storage).

Table 5.6 Measured Conventional Cap Water Balance for Taylors Road Landfill

	Measured Water Balance (mm) for Weather Year			
	WY1 (April 2007 – March 2008)	WY2 (April 2008 – March 2009)	WY3 (April 2009 – March 2010)	WY4 (April 2010 – March 2011)
Precipitation	751.2	630.0	896.7	1451.0
Evapotranspiration (calc)	698.5 (< 93%)	623.9 (99%)	893.2 (100%)	1326.6 (91%)
Runoff	79.3 (11%)	0.8 (0.1%)	0.2 (<0.1%)	20.3 (1%)
Change in storage	-32.0 (-4%)	-10.7 (-2%)	-11.2 (-1%)	58.1 (4%)
Lateral flow	Not measured	1.3 (0.2%)	0.0 (0%)	44.7 (3%)
Drainage	5.4 (0.7%)	14.6 (2%)	0.0 (0%)	1.4 (0.1%)

Runoff measured from the conventional cover was initially high, representing approximately 11% of rainfall received (Table 5.6). Runoff generally decreased over time with the exception of WY4. The higher rainfall in WY4 resulted in an increase in runoff compared to the previous 2 years but the runoff was still less than in WY1. Runoff in WY1 occurred more frequently initially, reflecting the bare then establishing plant conditions. As plants continued to establish and cover the soil surface, runoff occurred mainly in response to intense rainfall events, shown as nearly vertical increases in the cumulative rainfall (Figure 5.17).

The conventional cap soil profile dried over WY1, WY2 and WY3 and then increased in moisture over WY4. The soil moisture content reached a minimum of 186 mm at the end of WY1, 163 mm at the end of WY2 and 151 mm at the end of WY3 (Figure 5.17) with each layer showing a progressively drying trend each year (Figure 5.18). In contrast, the profile moisture content at the end of WY4 remained relatively high with the soil moisture content at each depth showing elevated moisture relative to previous years.

Over time the pattern of moisture content has changed, as shown in Figure 5.18. The wetting and drying cycles in the topsoil occur with greater magnitude in later years, which would be related to the grass establishing on the site and using the stored moisture. In addition, during WY1, the moisture content at the clay interface increased in response to rain; however, it is apparent during WY2 and WY3 that less moisture is infiltrating to the clay interface, which is a function of lower rainfall and also higher plant use.

The moisture content in the compacted clay was placed at an average volumetric moisture content of 26.5% which increased to 31% during the first summer and then decreased to 24% moisture by April

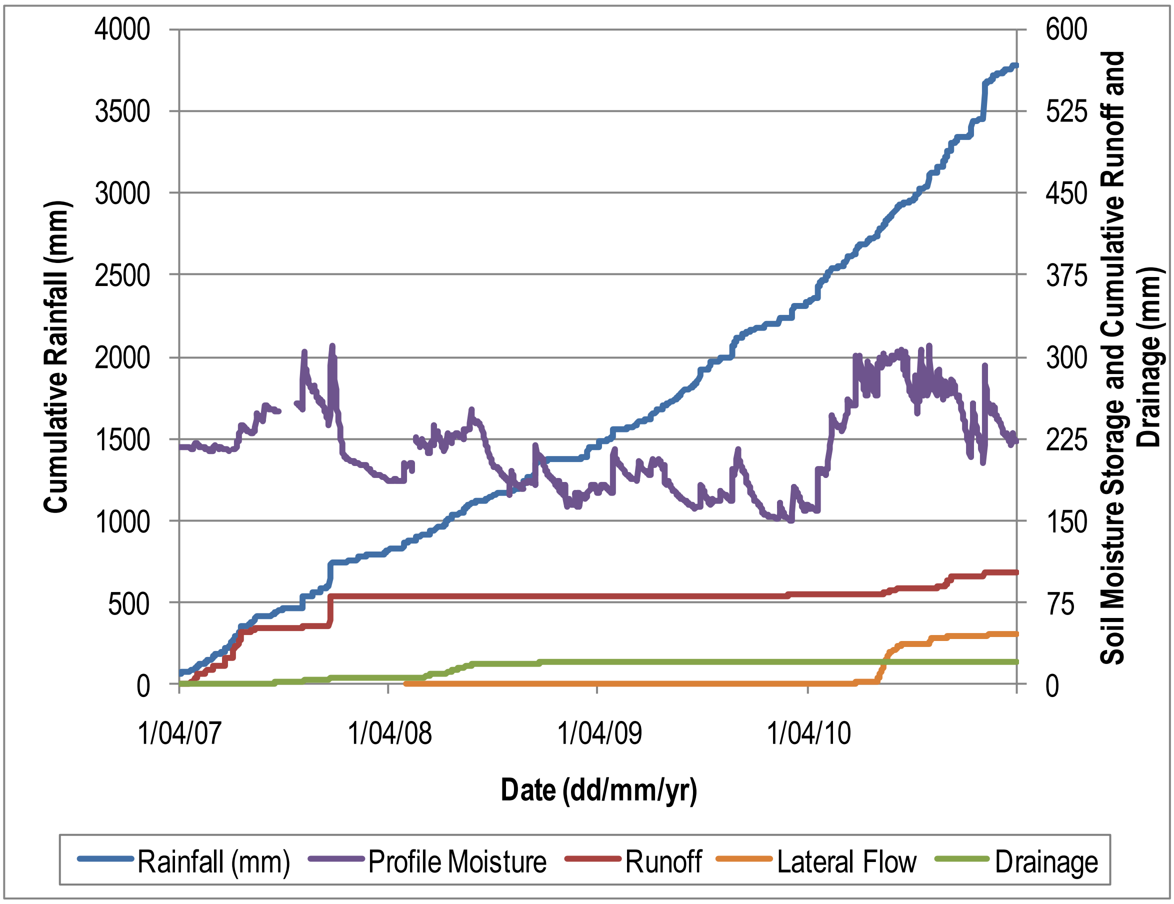

Figure 5.17 Cumulative Rainfall, Runoff and Drainage and Profile Moisture Content of Conventional Cap at Taylors Road Landfill

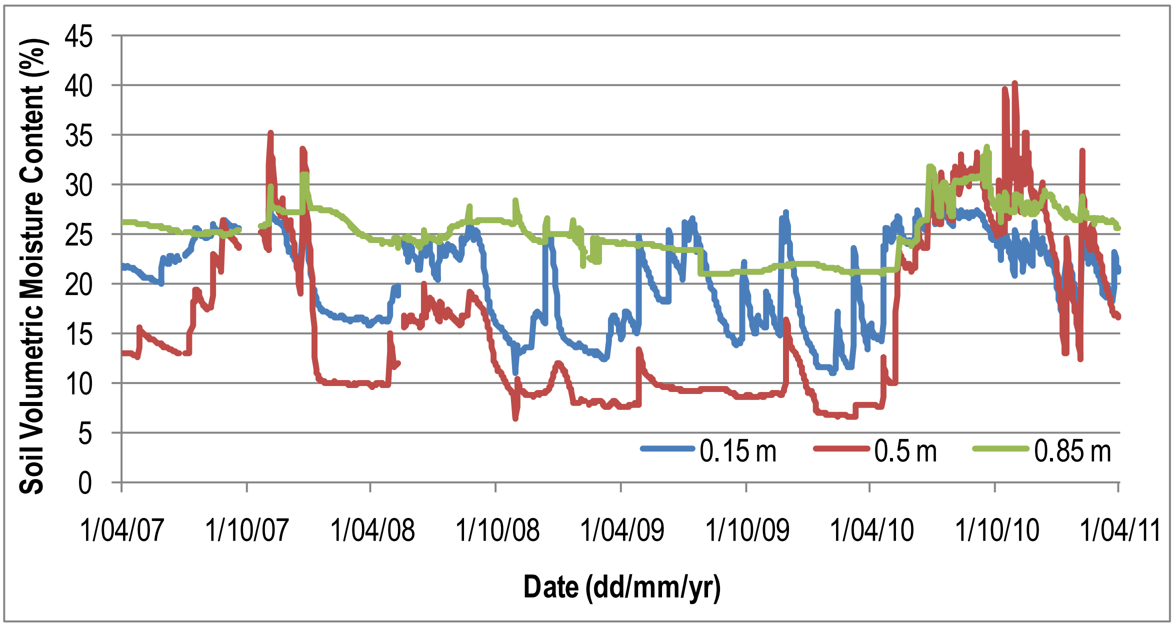

Figure 5.18 Average Volumetric Moisture Content in Conventional Cap at Taylors Road Landfill

2008 (Figure 5.17). The moisture content gain increased to 27% over winter of WY2, then decreased to 21% by July 2009 where it remained until April 2010. In May 2010, the moisture content rose to 24.5% and then in June rose further to 32% and remained above 25% through WY4. The rapid changes in moisture content at the clay interface indicated that the plant roots are actively extracting moisture in this area. The clay layer moisture content was less variable than at the interface which indicated that the roots were extracting moisture from this layer but to a lesser extent than at the interface.

Over the four years of monitoring, the lateral flow and drainage were generally low, accounting for ≤ 3% of precipitation. The lateral flow was recorded from May 2008, near the start of WY2, while drainage was recorded from the start of WY1. In WY1, 5 mm drainage was recorded (Table 5.6), which, combined with the increased moisture content at the clay interface (Figure 5.18), suggests lateral flow would also have occurred in this year. The largest drainage was recorded in WY2 and occurred at the same time as the clay layer was relatively dry at < 25% volumetric moisture content (Figure 5.19, left). The moisture content at the clay interface had increased in early May but was still < 20% moisture and only 1.2 mm of lateral flow was measured during this time. This high drainage while the soil remained relatively dry can only be attributed to the development of preferential flow paths though the clay barrier allowing the infiltrating moisture to "short circuit" the soil mass.

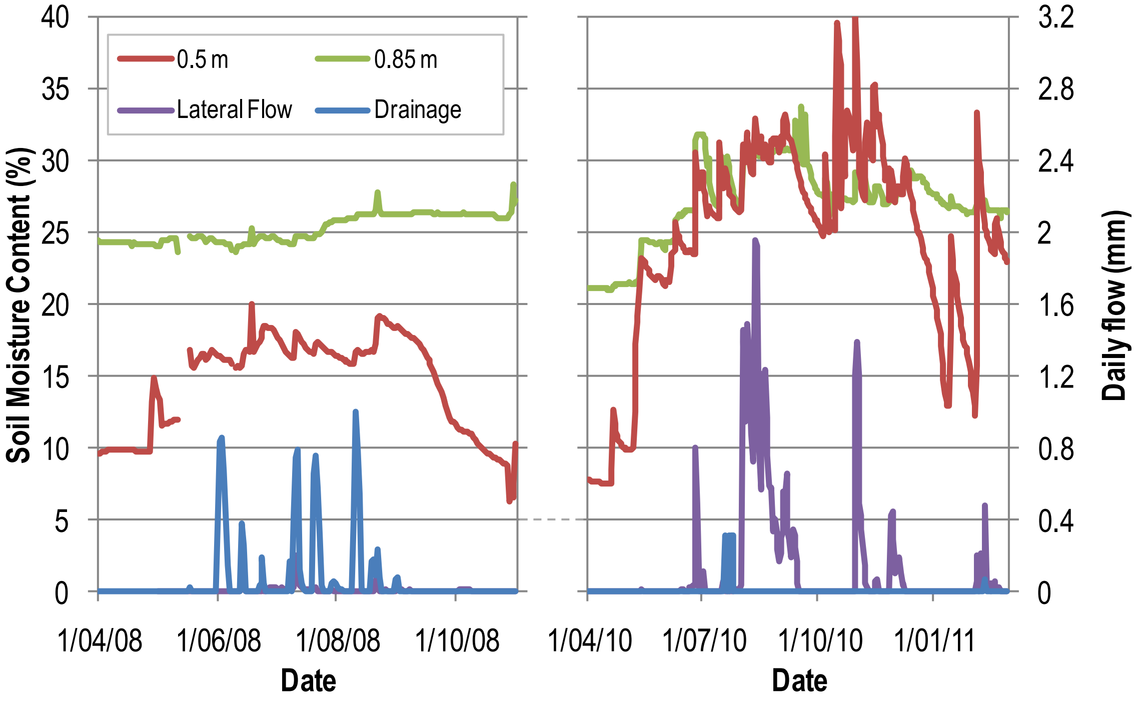

Figure 5.19 Taylors Road Landfill Conventional Cap Soil Moisture Content at 0.5 m and 0.85 m depth, Daily Lateral Flow and Drainage for April to October 2008 (left) and April 2010 to February 2011 (right)

In contrast to the high drainage with little lateral flow which occurred in WY2, in WY4 the greatest volume of lateral flow was measured but with relatively little drainage. In WY4, the soil moisture content was lower at the clay interface and in the clay than in WY2 but the moisture content increased at the interface and continued to increase until lateral flow occurred. The clay also increased in moisture with some drainage occurring but then ceasing as the moisture content continued to increase. One theory for this change is that the infiltrating water was slower in WY4 than WY2 and thus allowed the clay to swell and cracks to shrink prior to drainage occurring. However, it is also possible that rather than larger infrequent cracks, continued wetting and drying cycles may have resulted in a finer network of cracks which restricts the rate of moisture infiltration.

5.2.4 Phytocap vs Conventional Cap

The phytocap received more precipitation, through the application of irrigation, than the conventional cap; however, as the irrigation was applied when the soil was dry it is likely that it would have evaporated and transpired quickly and made little difference to the overall water balance.

Evapotranspiration was higher in the phytocap in all years, including as the vegetation established in WY1. This higher evapotranspiration of the phytocap is from the inclusion of shrubs and trees. Maximising evapotranspiration to remove precipitation has the advantage of reduced runoff, which decreases the potential for surface erosion, reduced (or no) lateral flow, which then needs to be collected and treated as stormwater or can become drainage, and reduced drainage, which can potentially generate leachate. This higher evapotranspiration potential of the phytocap suggests it is a more sustainable design in the longer term.

The drainage from the phytocap decreased over time, with the exception of the high rainfall in WY4, and was phytocap drainage was less than the conventional cap in WY2 and WY3. The soil moisture content and measured drainage from the conventional cap suggests the compacted clay barrier cracked which potentially allows lateral flow to become drainage. If preferential flow does result in lateral flow becoming drainage, then the drainage from the conventional cap in WY4 could potentially be up to 46 mm (i.e. the sum of lateral flow and drainage), which is higher than the 28 mm of drainage measured in the phytocap. The cracking of clay barrier has also resulted in difficulty in predicting the drainage which would occur from the conventional cap and also suggests the conventional cap is acting as a phytocap as it relies on evapotranspiration and soil moisture storage rather than a hydraulic barrier to reduce drainage.

5.2.5 Lysimeter vs Control Plot

As mentioned previously, comparison of the data collected near the base of the lysimeter with the control area can allow assessment of the impact of the decomposing waste mass on the temperature and moisture content of the final cap. A qualitative assessment of the potential impact of methane oxidation, and the resultant release of moisture, on the water balance can also be made. The base of the lysimeter prevents this interaction from occurring. For the Melbourne site, the control plot conventional cap was constructed 3 years prior to the lysimeter plot and hence comparison of these data can identify longer term changes that may occur.

In the phytocap, comparison of the lysimeter and control data showed no trend in the volumetric soil moisture content at 1.55 m depth, as represented by the data collected in WY2 and shown in Figure 5.20 for the upslope and downslope sensors.

Comparison of the soil temperature near the base of the phytocap suggested there is a difference between the lysimeter and control and that it is more marked in summer than winter (Figure 5.21). Soil temperature can affect the water balance, predominantly through affecting plant root growth; however, differences in root growth would also affect soil moisture content and, as discussed above, there is no evidence to support this.

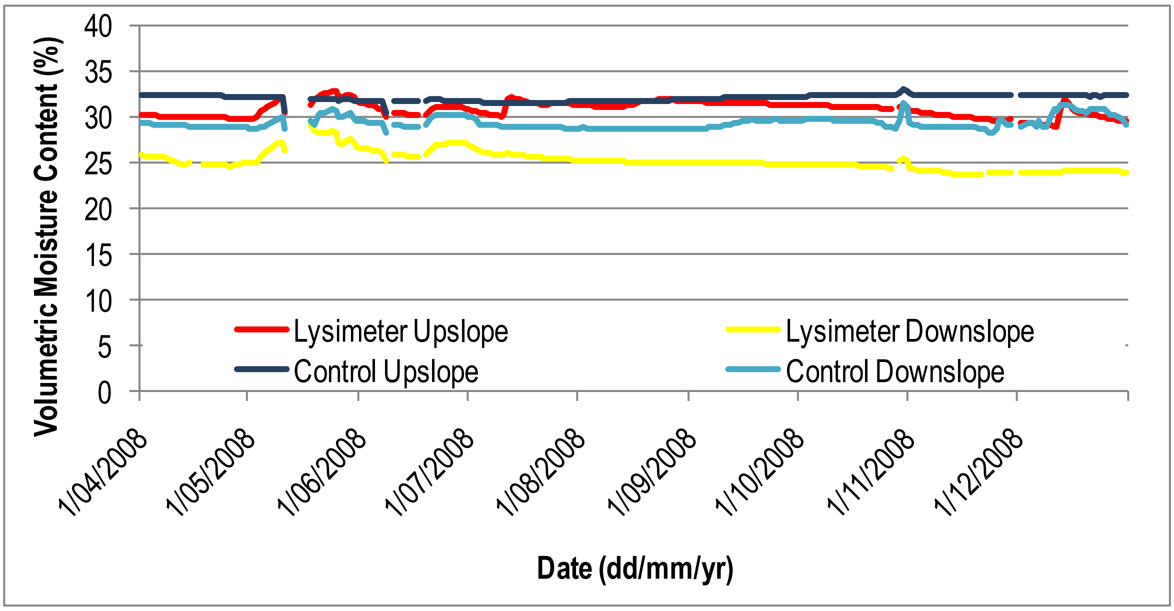

Figure 5.20 Average Daily Soil Moisture Content at 1.55 m Depth in Phytocap at Taylors Road Landfill in WY2

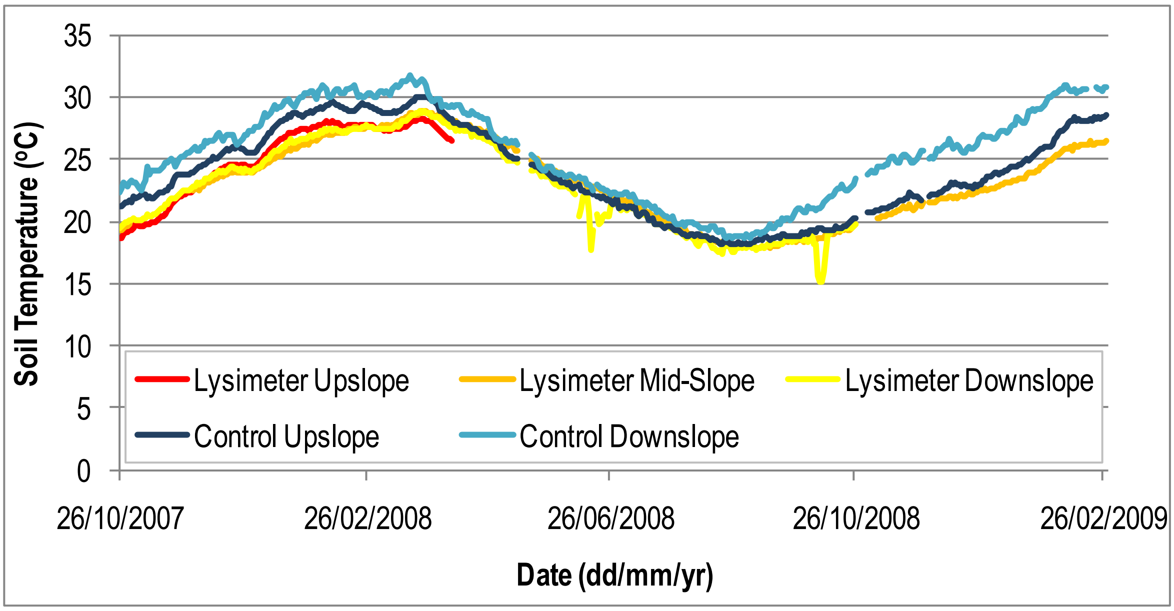

Figure 5.21 Average Daily Soil Temperature at 1.55 m Depth in Phytocap at Taylors Road Landfill

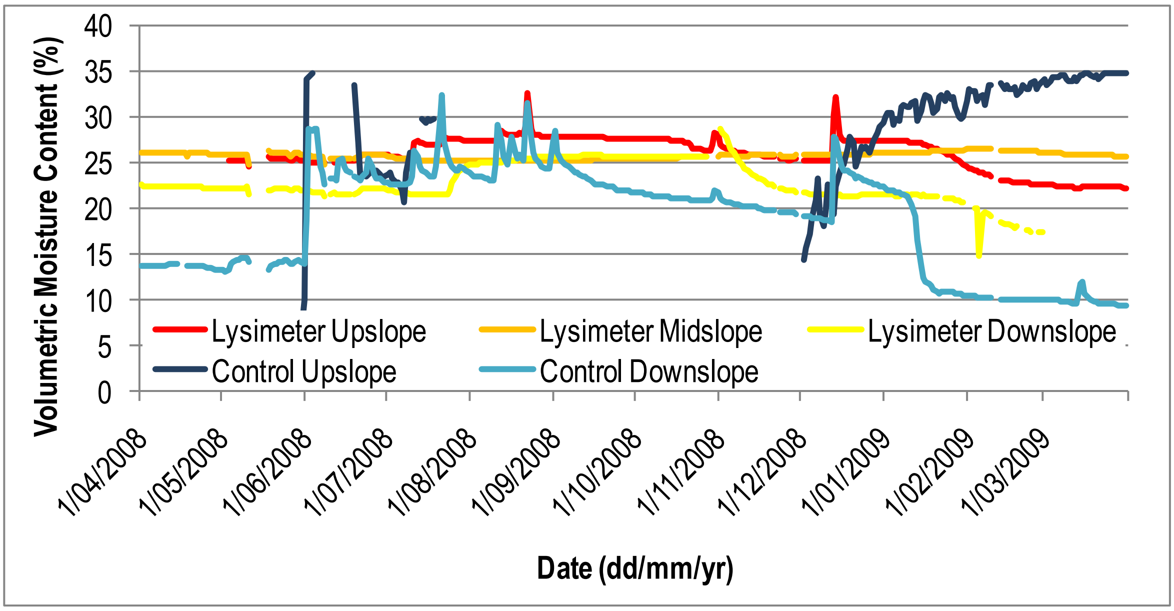

Figure 5.22 Average Daily Soil Moisture Content during WY2 at 0.85 m Depth in Conventional Cap at Taylors Road Landfill

In the conventional cap, large differences in the soil moisture content at depth were evident between the lysimeter and control plots. In WY2, the soil moisture content in the lysimeter increased slightly in winter and then decreased over summer (Figure 5.22). In contrast, the moisture content in the control was highly variable in response to rainfall over winter and summer storms. This trend continued in WY3 but by WY4 (Figure 5.23) the soil moisture content in the lysimeter was also showing increased responsiveness to rainfall.

In WY4, the upslope sensor locations tended to be less variable than mid slope and downslope positions (Figure 5.23). The clay barrier generates lateral flow which flows downslope. The more variable moisture content in lower slope positions suggest the lateral flow is infiltrating into the clay layer. This may indicate that where the conventional cap is constructed on longer slope lengths, this lateral flow may lead to increased drainage.

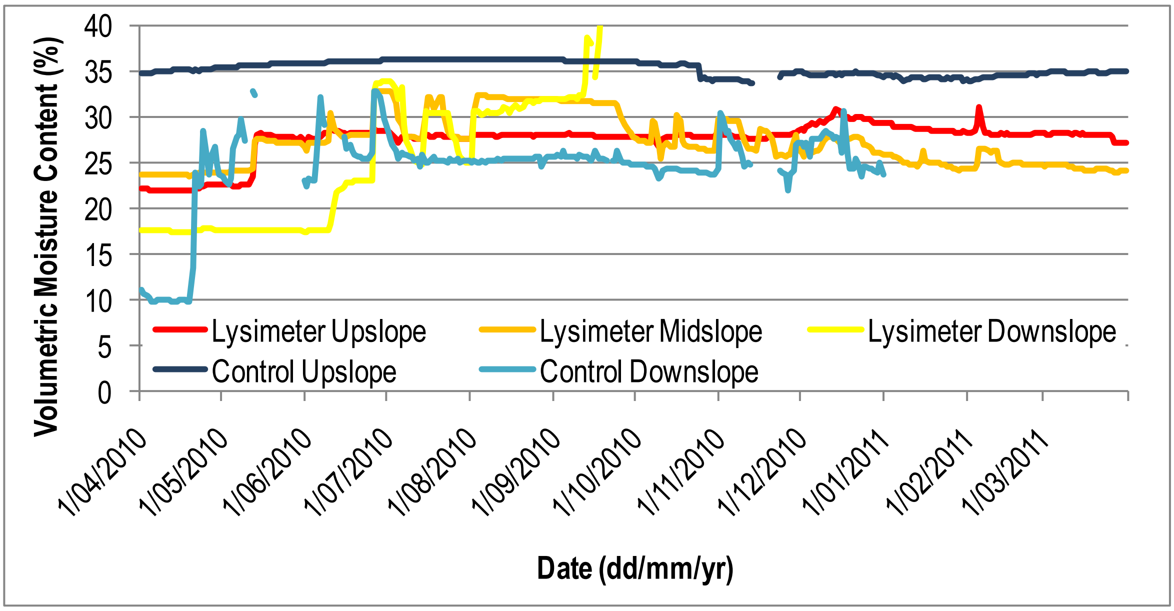

Figure 5.23 Average Daily Soil Moisture Content during WY4 at 0.85 m Depth in Conventional Cap at Taylors Road Landfill

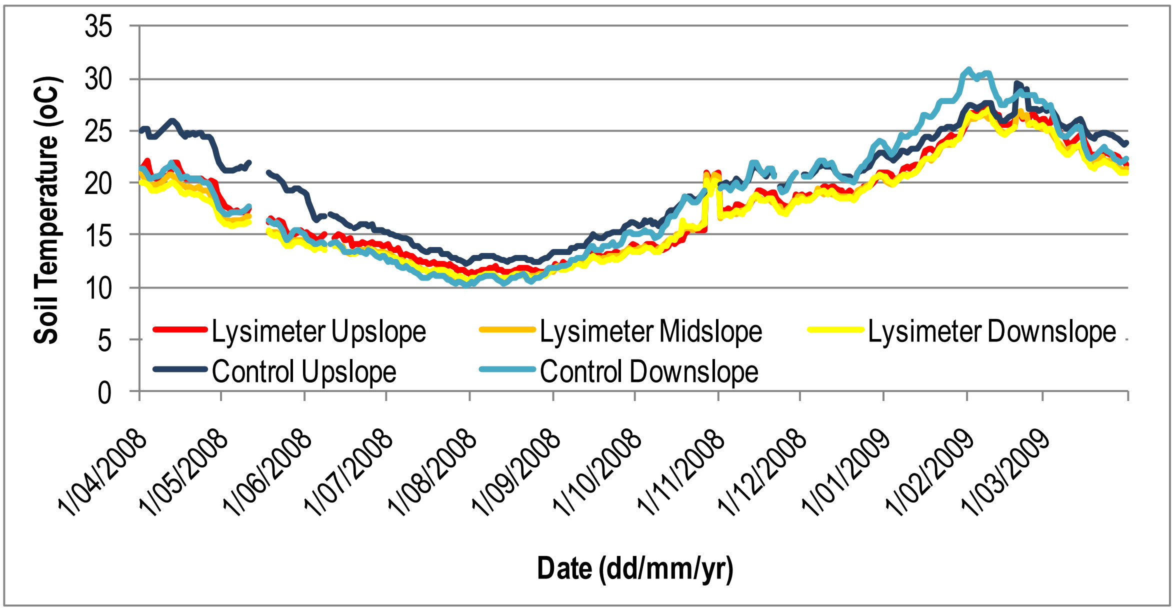

Figure 5.24 Average Daily Temperature at 0.85 m Depth during WY2 in the Conventional Cap at Taylors Road Landfill

Differences between the lysimeter and control plot in the conventional cap were evident in the temperature measured near the base of the profile. Similar to the phytocap, the control area appeared to be warmer than the lysimeter with a greater difference in summer than winter (Figure 5.24). There also appeared to be a correlation between temperature and slope position, with warmer temperatures generally recorded upslope and cooler downslope.

5.2.6 Summary

The Melbourne phytocap showed temporal changes in the profile moisture content and the drainage. The profile moisture content became more reactive with faster decreases in moisture and the drainage decreased in volume and occurred as discrete events rather than seeping from the base of the profile over longer time periods. These changes were most likely due to the establishing plants increasing rooting depth and transpiration. However, confounding effects may occur from the consolidation of the phytocap and the capillary break which was evident from the moisture content variability measured at the base of the phytocap.

The conventional cap dried and cracked which allowed drainage to occur. The evapotranspiration from the grass vegetation was less than the phytocap and hence runoff and lateral flow were greater on the conventional cap than the phytocap. Cracking of the compacted clay barrier and the development of preferential flow paths and higher hydraulic conductivity may result in lateral flow becoming drainage. If this occurs on a larger scale, the potential for the conventional cap to generate drainage was greater than the phytocap. The higher runoff and lateral flow would also result in increased maintenance requirements.

Overall, the phytocap performed equivalently or better than the conventional cap with higher evapotranspiration, lower runoff and similar (or possibly lower) drainage after vegetation established. The longer term performance of the conventional cap, as shown by the control plot, is likely to show greater change in the compacted clay layer and possibly an increase in drainage as a result.

5.3 Townsville Site

The trial site at the Vantassel Street Landfill (VSL) was monitored from late 2007, with results from 1 January 2008 until 7 August 2011 analysed herein. In October 2008, improvements were made to attempt to prevent frogs living in the pipes and maintenance of the trial site also improved. On 28 March 2009, two dosing siphons were installed to replace flow meters recording runoff and two siphons were installed as a back up to the tipping buckets measuring drainage.

The wetter, more humid conditions and more abundant wildlife in Townsville caused condensation and rust in electronic equipment and blockages in pipes and moving parts. However, after data validation and replacement, > 80% of days had reliable rainfall, drainage and soil moisture data, which is an achievement for this site. The addition of the dosing siphons in 2009 maintained data integrity and allowed for a near complete data record. Data gaps in the record are generally less than 1 week with the largest data gaps being 16 days in February 2008, 14 days in July 2009 and 48 days from 25 May to 12 July 2011.

Townsville experiences summer dominant rainfall and hence the weather year for northern Australia commences in October, which is the start of the wet season, and ceases in September, which is the end of the dry season. Four weather years of data have been compiled being WY1 from January 2008 to September 2008; WY2 from October 2008 to September 2009; WY3 from October 2009 to September 2010; WY4 from October 2010 to July 2011. It should be noted that WY1 and WY4 are incomplete years, resulting in the wetter months of November and December not included in WY1 and no confirmation that the soil moisture is removed over the dry season of WY4.

5.3.1 Trial Weather

The annual rainfall at the trial site from January 2008 until August 2011 was greater than the long-term average of 991 mm, even in the part years of WY1 and WY4. The annual rainfall in WY2, WY3 and WY4 also exceeded the 90th percentile of 1,490 mm/yr. The pattern of rainfall was characterised by wetter summer wet season, which is from November to February. January and February in 2008, 2009 and 2010 were greater than the 90th percentile rainfall from the long-term dataset (Figure 5.25). The winter of 2009 was one of the driest on record with only 2 mm rain recorded from June to October.

The rainfall in Townsville is influenced by tropical cyclones and tropical lows. During the trial 3 cyclones of varying strengths were reported around Townsville. In February 2009, Tropical Cyclone Ellie (Category 1) crossed the Australian coast 120 km north of Townsville, and 436 mm of rain fell from 1 – 4 February. In March 2010, Tropical Cyclone Ului (Category 5) crossed the coast approximately 200 km south-east of Townsville, and 152 mm rain fell on 22/23 March. In February 2011, Tropical Cyclone Yasi (Category 5) crossed the Australian coast near Mission Beach (approximately 150 km north of Townsville) and the trial site received 194 mm rain in 21 hours.

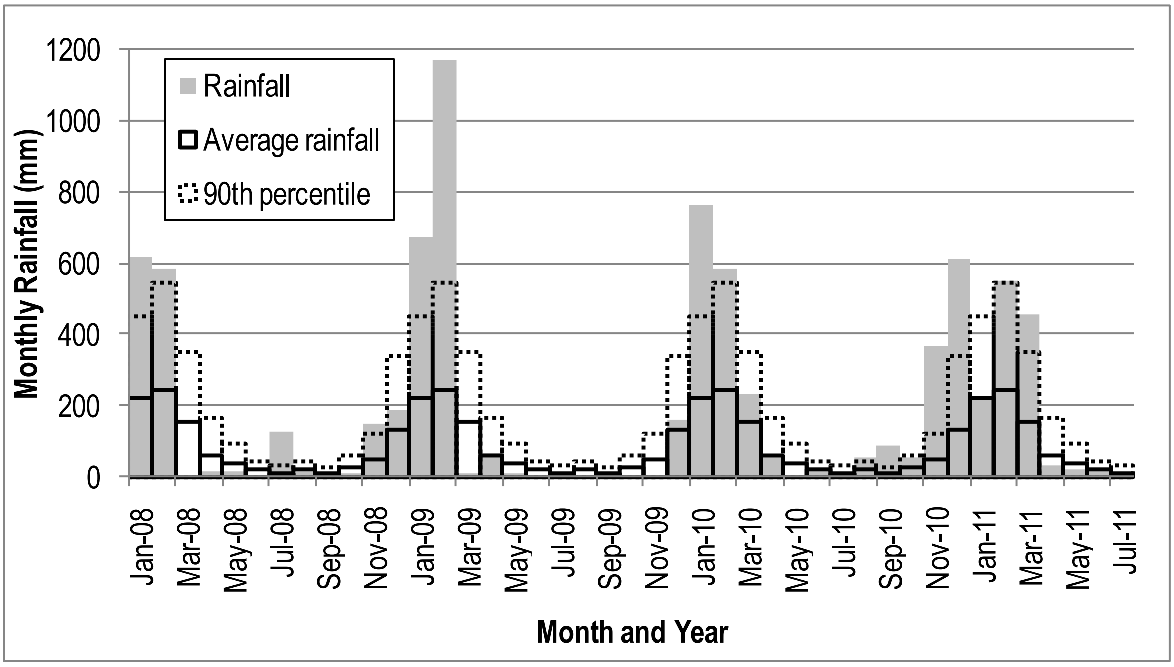

Figure 5.25 Measured Monthly Rainfall at Vantassel Street Landfill Compared with Long-term Average and 90th Percentile Rainfall

Table 5.7 Irrigation Applied to Phytocap at Vantassel Street Landfill

Period irrigation applied	Volume Irrigation to Phytocap (mm)
1 – 25 May 2008 1 – 25 June 2008 1 – 25 July 2008 1 – 25 August 2008 1 – 25 September 2008 1 – 25 October 2008 1 – 11 November 2008	1 mm/day = 161 mm
10 August 2009	8.67
16 August 2009	8.83
16, 24, 30 November 2009	0.78 mm/day = 2.34 mm
14, 21 December 2009	0.78 mm/day = 1.56 mm

Irrigation was applied to the phytocap lysimeter and control plots to ensure vegetation established. The irrigation was not applied to the conventional cap as this is not standard practice. Trees and shrubs were planted in March 2008 and supplementary irrigation was provided from May to November 2008 and again in August 2009 due to the dry winter, with follow up irrigation applied in November and December 2009. The volumes and timing of irrigation are shown in Table 5.7. These volumes have been included in the water balance for the phytocap discussed in Section 5.3.2.

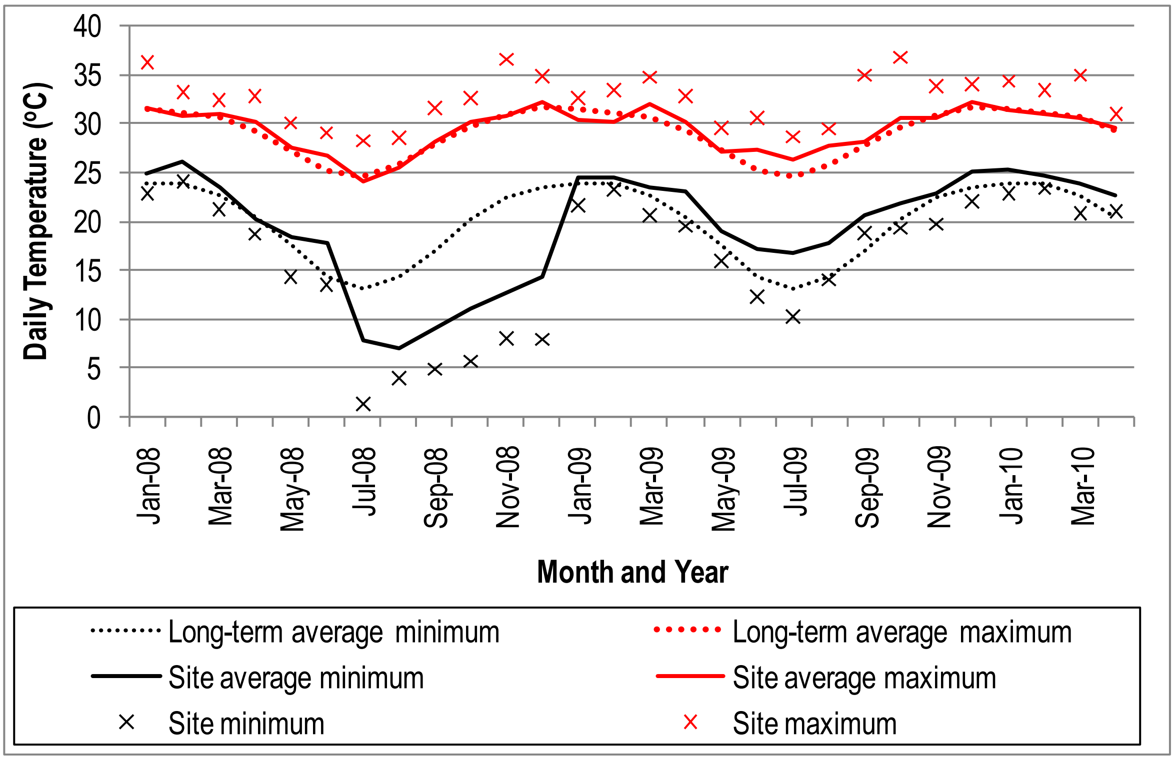

Figure 5.26 Long-term and Site-Measured Average and Extreme Minimum and Maximum Daily Temperatures for Vantassel Street Landfill

The temperatures recorded at the site have been near or below average with extreme temperatures not recorded for the trial period (Figure 5.26). July to December 2008 average minimum daily temperature was 5 – 10 °C below the long-term average. On one day in July 2008, the temperature was recorded as 1.3 °C, which is the minimum recorded for this area since 1957. On average the site is expected to experience 2.5 days/year with the maximum daily temperature above 35 °C. From January 2008 to April 2010, 4 days at the trial site were recorded with temperatures above 35 °C, which is below the average.

5.3.2 Phytocap Water Balance

The annual water balance measured from the phytocap at the Vantassel Street Landfill shows that above average precipitation was received with almost 2 m rainfall in most years (Table 5.8). The rainfall is highly seasonal with extended months of little or no rain followed by relatively short intense rainfall events (Figure 5.27). In WY4, the precipitation started earlier in the season and fell steadily compared with previous years, particularly compared with WY2 which had a similar total precipitation.

The majority of the precipitation, which includes irrigation applied to the phytocap test sections, was returned to the atmosphere via evapotranspiration (Table 5.8). The highest evapotranspiration was measured in WY2 and equates to an average ET of 5.7 mm/day over the year. Considering the seasonality of the precipitation, this shows that the vegetation has a large capacity to remove water from the soil.

The runoff from the phytocap was highest in WY2. Runoff during February 2009 was 350 mm, which was caused by the intense rainfall associated with Tropical Cyclone Ellie and seasonal tropical lows,

Table 5.8 Measured Phytocap Water Balance for Vantassel Street Landfill

	Measured Water Balance (mm) for Weather Year			
	WY1 (January – Sept 2008)	**WY2 (Oct 2008 – Sept 2009)**	**WY3 (Oct 2009 – Sept 2010)**	**WY4 (Oct 2010 – July 2011)**
Precipitation	1505.0	2322.8	1963.5	2333.2
Evapotranspiration (calc)	1496.4 (99%)	2072.7 (89%)	1878.2 (96%)	2044.3 (88%)
Runoff	21.2 (1%)	390.4 (17%)	56.8 (3%)	36.5 (2%)
Change in storage	-37.4 (-2%)	-186.9 (-8%)	22.7 (1%)	-2.8 (-0.1%)
Drainage	24.8 (2%)	46.6 (2%)	5.8 (0.3%)	255.2 (11%)

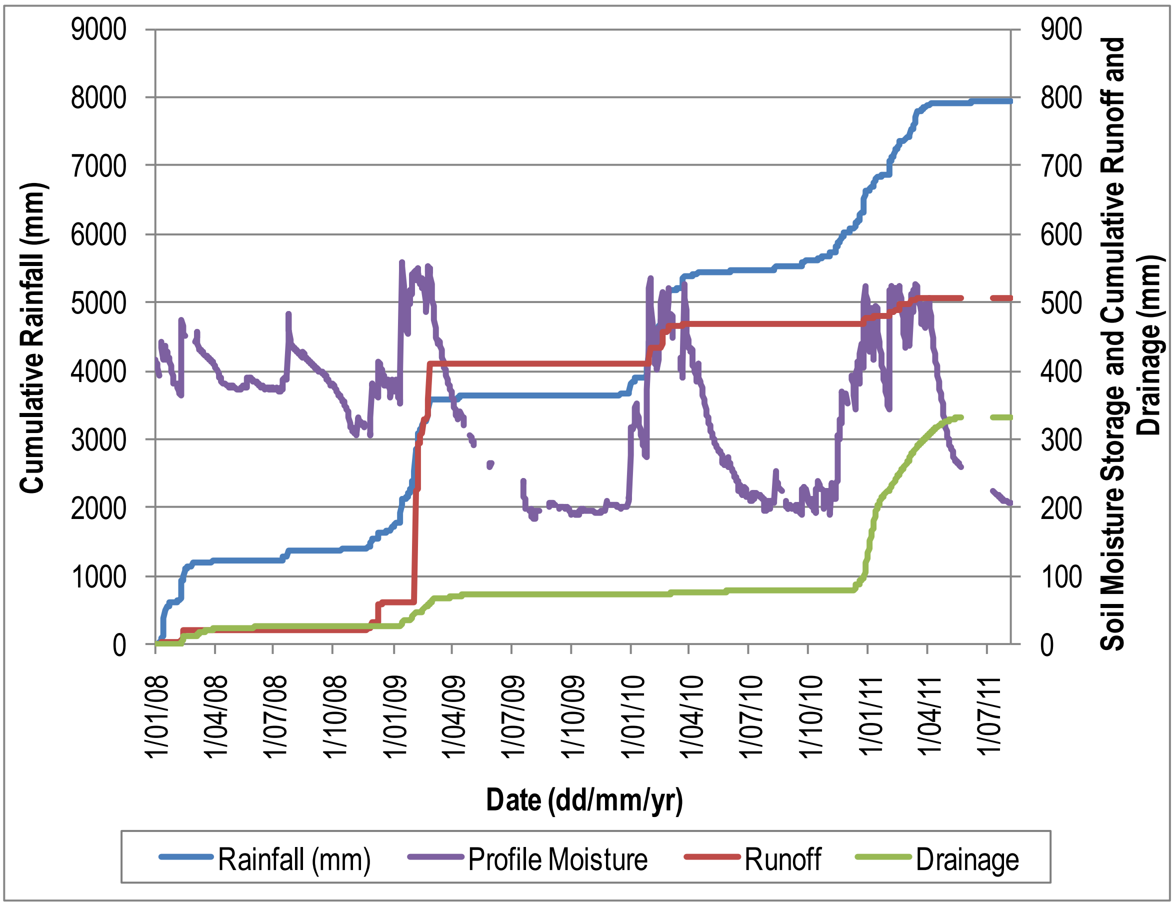

Figure 5.27 Cumulative Rainfall, Runoff and Drainage and Average Daily Profile Moisture Storage of Phytocap at Vantassel Street Landfill

which deposited 1,170 mm in one month, including storms of over 60 mm/yr, and resulted in the highest monthly rainfall since 1957. Runoff during the other years was more typical, accounting for < 5% precipitation received. In 2011, although Tropical Cyclone Yasi was a more intense cyclone than Tropical Cyclone Ellie (Category 5 vs Category 1), the rainfall intensity recorded at the site was lower with peak rainfall rates of < 20 mm/hr and hence the runoff was less at 16 mm for the month of February. The decreased runoff in WY3 and WY4 is likely to be related to the decreased intensity of rainfall events (Figure 5.27). However, the impact of the establishing vegetation can also reduce runoff, the extent of which is not known for this trial.

The profile moisture storage decreased in all years, except WY3, indicating a generally drying profile (Table 5.8). The increase in storage from WY2 to WY3 was caused by different rainfall patterns during the dry season. In WY2, almost no rainfall was measured during the dry season resulting in a very dry profile at the end of WY2. In contrast, in WY3 rainfall during August and September was above average and hence the minimum moisture content was higher.

The soil moisture storage pattern has changed over time. In WY1, the soil moisture storage decreased to 370 mm and then to 311 mm by the beginning of WY2 (Figure 5.27). During WY2, the soil moisture storage peaked at 550 mm and then decreased to 184 mm by August 2009. WY3 and WY4 showed a similar pattern to WY2 but soil moisture storage peaked at 534 mm and 526 mm respectively before drying to 188 mm and 206 mm by August in 2010 and 2011, respectively. At the "wet end", soil with strong structure is able to hold more moisture than soil with weak or no structural development; however, the phytocap did not show increasing upper moisture storage, beyond the change from WY1 to WY2, and hence there is no evidence of longer term improvement in soil structure. The minimum moisture content achieved is influenced by the depth from which the plant roots are extracting water. From WY2, the plants appear to be extracting moisture from most of the phytocap depth.

The soil moisture storage has also changed with an apparent increase in the rate of moisture loss from the soil over the monitoring period (Figure 5.27). On 13 March 2009 the soil moisture storage was initially 440 mm and after 16 days with no rain and 0.9 mm recorded as drainage, the moisture storage decreased to 373 mm, an average of 4.2 mm/day moisture lost as evapotranspiration. On 9 April 2011, the soil moisture storage was 449 mm and after 16 days with no rain and drainage of 10.9 mm, the soil moisture storage had decreased to 347 mm, an average of 5.7 mm/day lost as evapotranspiration. The measurements were from similar time periods likely to have similar prevailing conditions and hence this increased rate of moisture lost from storage is most likely related to increased plant growth and hence transpiration.

The drainage measured from the phytocap was lowest in WY3 (6 mm) and highest in WY4 (255 mm) (Table 5.8). The rainfall in WY4 was similar to WY2, with over 2200 mm rainfall, but the drainage recorded in WY4 is fives times greater. Comparison of the cumulative precipitation, runoff and the soil moisture storage for these years (Figure 5.27) shows that the precipitation in WY2 was over a shorter period (2 – 3 months) and 17% of rainfall was lost as runoff (390 mm) while in WY4 the rainfall was spread over 5 – 6 months and little runoff (37 mm) was recorded.

Comparison of the soil moisture content near the base of the profile (1.35 m) revealed the trends between the two years were different. In WY2, the soil near the base of the profile was wetter at the beginning of the wet season than in WY4 (Figure 5.28). The wetting of the profile also shows a stepped approach in WY2 with the soil drying before rewetting and reaching a peak in mid-January and then drying from early March. In WY4 the soil moisture content increased rapidly to peak in mid December and then started to dry in April. Also evident was that the peak moisture content in WY4 was not as high as in WY2. The combination of a longer wet season and the drier profile at the commencement of the wet season appears to have resulted in the higher peak daily drainage and more cumulative drainage. It should be noted that the irregular pattern shown in drainage during WY4 is an artefact of the dosing siphon resolution.

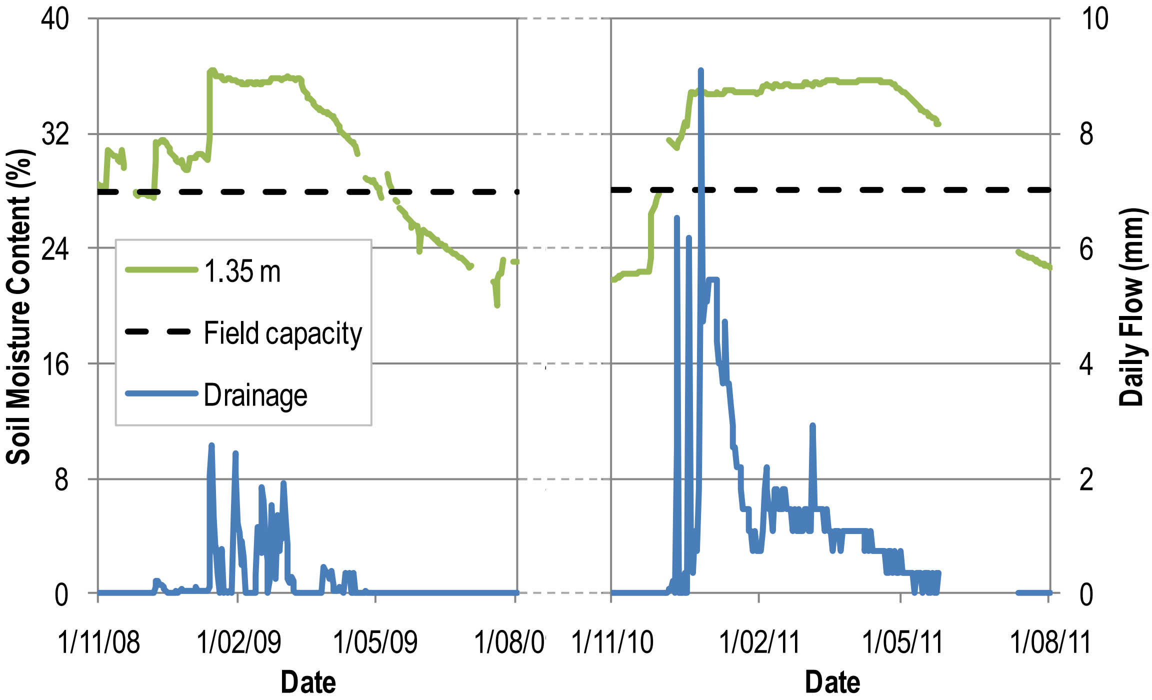

Figure 5.28 Average Daily Volumetric Soil Moisture at 1.35 m Depth and Daily Drainage in Phytocap at Vantassel Street Landfill

The drainage commenced before the soil moisture peaked in both WY2 and WY4 (Figure 5.28). This is usually an indicator that preferential flow through the profile has occurred, as was noted in the compacted clay barriers. However, the moisture content was above the field capacity and hence it is unlikely that desiccation cracks would have remained in the profile and it is more likely that this is flow through the matrix. Also of note is that the soil did not reach saturation (> 40% volumetric moisture) in either year. It is not known if this is because the bulk density has increased at this depth due to the weight of the overlying soil or if the supply of moisture was insufficient to achieve this moisture content.

5.3.3 Conventional Cap Water Balance

The precipitation measured as part of the annual water balance (Table 5.9) of the conventional cap is comprised solely of rainfall as irrigation was not applied to this trial area. Evapotranspiration accounts for the majority of the precipitation received on the site with the amount of moisture evapotranspired annually increasing through the monitoring period.

Table 5.9 Measured Conventional Cap Water Balance for Vantassel Street Landfill

	Measured Water Balance (mm) for Weather Year			
	WY1 (January – Sept 2008)	WY2 (Oct 2008 – Sept 2009)	WY3 (Oct 2009 – Sept 2010)	WY4 (Oct 2010 – July 2011)
Precipitation	1380	2269.3	1959.6	2333.2
Evapotranspiration (calc)	1329.4 (96%)	1789.2 (79%)	1853.0 (95%)	1936.5 (83%)
Runoff	147.2 (11%)	391.1 (17%)	69.1 (4%)	167.2 (7%)
Change in storage	-98.3 (-7%)	-2.0 (-0.1%)	12.6 (0.6%)	-7.9 (-0.3%)
Lateral Flow	0.0 (0%)	47.4 (2%)	11.6 (0.6%)	14.2 (0.6%)
Drainage	1.7 (0.1%)	43.7 (2%)	13.3 (0.7%)	223.2 (10%)

The runoff accounted for 4 – 17% of rainfall received. During the tropical cyclone of February 2009, the runoff flow meter was not working and hence the phytocap runoff data have been substituted as a best estimate. Runoff showed a strong relationship with rainfall which has continued regardless of the established grass vegetation (Figure 5.29).

The soil profile moisture storage dried over the part year of WY1 and then has shown a consistent variation between the wet season maximum approaching 300 mm and dry season minimum around 140 mm (Figure 5.29). During the high rainfall received in WY2, the soil moisture storage did not increase as much as other years. This was caused by the high intensity rainfall events resulting in high runoff and hence less moisture infiltrated into the soil profile. In contrast, the more consistent,

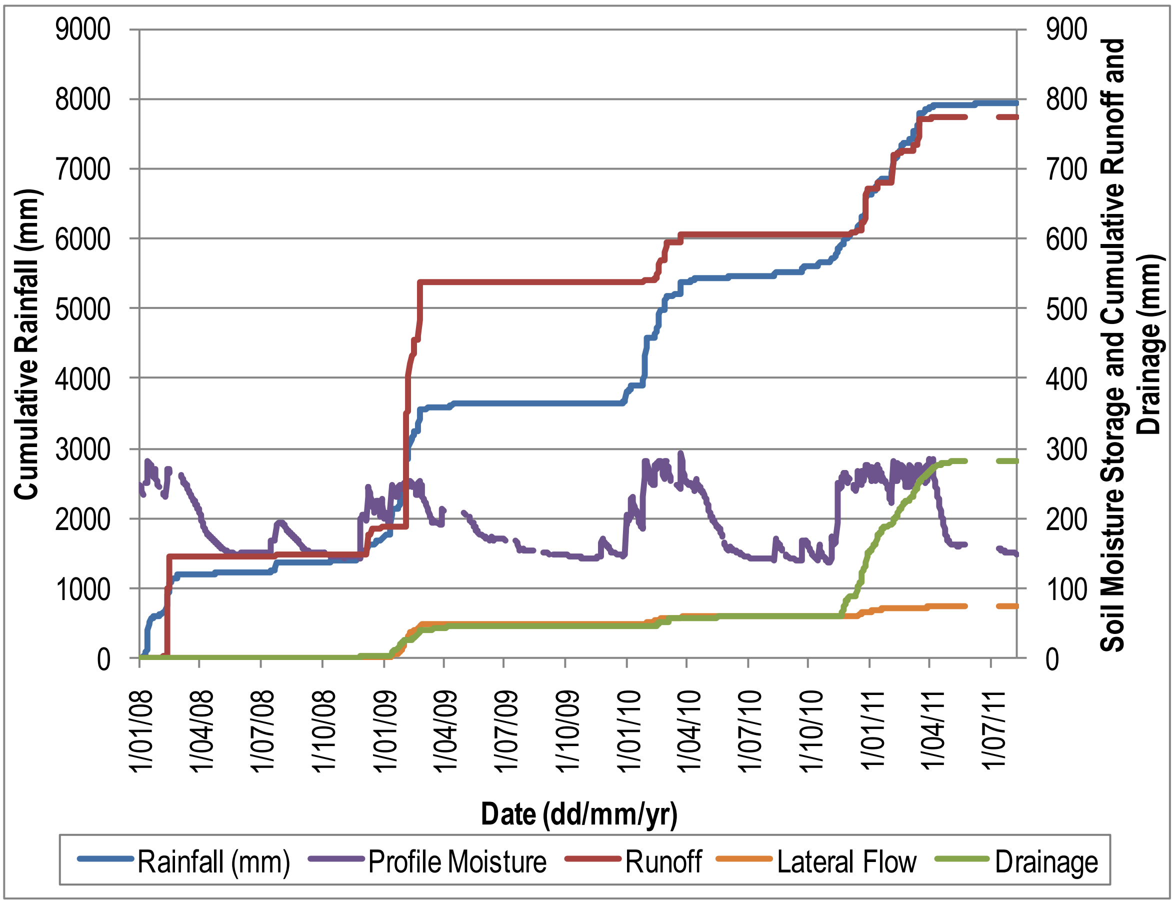

Figure 5.29 Cumulative Rainfall, Runoff and Drainage and Average Daily Profile Moisture Storage of Conventional Cap at Vantassel Street Landfill

less intense rainfall received in WY4 has resulted in the profile moisture content remaining high from mid November to the end of March.

The topsoil (0.15 m) moisture content varied from a minimum of 11 – 13% to a maximum of 35 – 40% moisture (Figure 5.30). The main change was the increase in moisture content after rainfall and the rate of moisture decrease. In WY1, after 11 mm of rainfall on 5 August 2008, the soil moisture peaked at 27% and then decreased to 23% moisture after 30 days of no further rain. This rainfall event also resulted in an increase in the moisture content at the clay interface (0.3 m). In WY3, after 48 mm of rainfall on 11 August 2010, four times more than in August 2008, the soil moisture peaked at a similar moisture content of 26% and decreased to 18% after only 9 days, i.e. more rapidly than in 2008. Little of this rainfall in 2010 infiltrated to the clay interface. This difference shows that the plants were better established and more actively growing and extracting moisture in 2010 than in 2008.

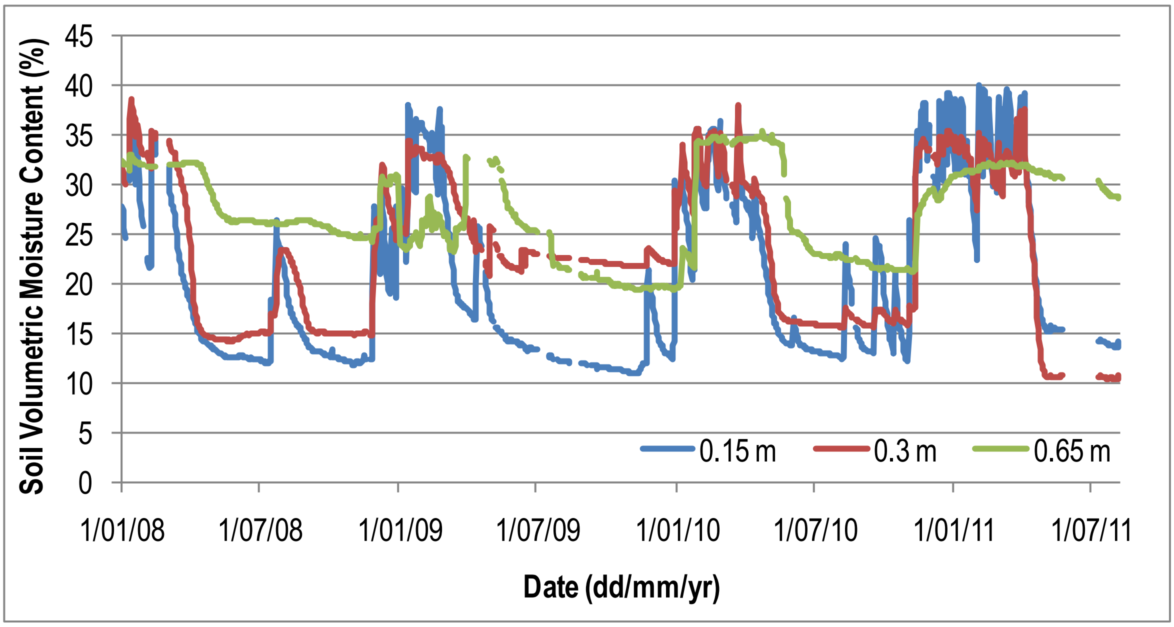

Figure 5.30 Average Daily Volumetric Moisture Content in Conventional Cap at Vantassel Street Landfill

The moisture content range at the clay interface (0.3 m depth) was more variable between weather years than the topsoil. In WY1 the volumetric moisture content at the clay interface decreased to 15% moisture then in WY2 did not dry as effectively, reaching a minimum of 22% moisture (Figure 5.30). The reason for this is unclear but could be caused by reduced plant growth after a short, intense wet season and a very dry, dry season. At the end of WY3 the moisture content again reduced to around 15% and then in WY4 decreased to 10%. In contrast to WY2, the prolonged wet season in WY4 was likely to have resulted in good plant growth and hence higher water use.

The variation in volumetric moisture content of the compacted clay barrier (0.65 m) increased from WY1, where it ranged from 24 – 33% to WY2 and WY3 where it ranged from 20 – 35% moisture (Figure 5.30). This increased moisture range could have been caused by plant roots growing into the barrier layer and/or changes in soil structure, given the medium potential for the clay to change volume.

Lateral flow, though not recorded, is likely to have occurred in WY1 as the moisture content at the clay interface was high and drainage was recorded. In October 2008, a frog was found living in the lateral flow pipe and substantial pressure was required to push the frog out of the pipe. In addition, frogs living in the pipes and in the tipping bucket funnel diverted water away from and out of the device. "Frog proofing" and improved maintenance during 2009 and 2010 should have limited this impact in subsequent years.

The drainage and lateral flow events showed similar patterns and were of similar magnitude until WY4 when drainage exceeded lateral flow (Figure 5.29). In WY4, the drainage pattern was different from previous years and more closely followed rainfall events. The reasons for the difference may be explained by comparing the monitoring from WY2 with WY4 when total rainfall was similar but very different intensity.

In WY2 the lateral flow and drainage were approximately equivalent, 47 mm and 44 mm, respectively (Table 5.9). In WY4, the drainage (223 mm) was an order of magnitude larger than lateral flow (14 mm). The soil moisture content at the clay interface (0.3 m) and within the clay (0.65 m) were different for each event and showed that greater drainage occurs when the clay remained wetter (but below field capacity at approximately 42%) than when drying occurs (Figure 5.31). The moisture content at the clay interface also remained wetter in WY4 than WY2. Under these conditions it would have been expected that greater lateral flow would have occurred and hence the pipe may have been blocked. Alternatively or in addition, the relatively gentle slope on this site may have resulted in a perched water table on the clay layer which facilitated the greater flow through the clay layer.

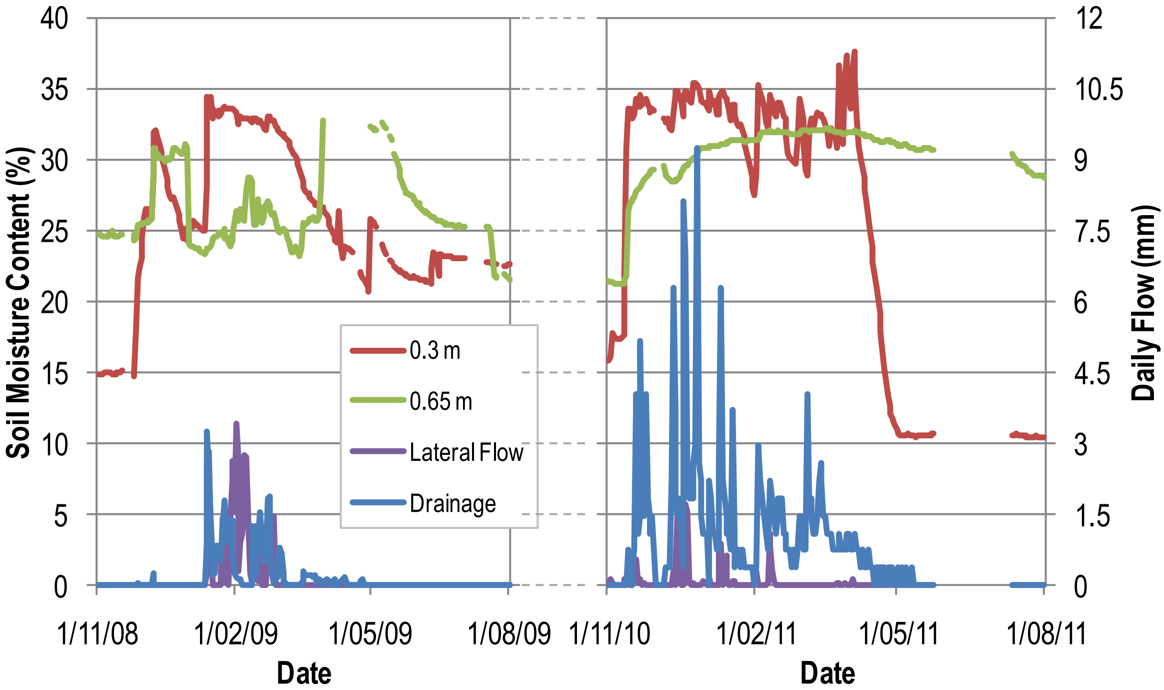

Figure 5.31 Average Daily Volumetric Soil Moisture Content at Clay Interface (0.3 m) and within Compacted Clay (0.65 m) and Daily Lateral Flow and Drainage from Conventional Cap at Vantassel Street Landfill

The rate of drainage recorded can be used to estimate the large-scale hydraulic conductivity (i.e. including any cracks) of the least permeable layer, which in this case can be assumed to be the clay barrier. The maximum drainage rate recorded in 2008/9 was approximately 3 mm/day, which is equivalent to 3×10^{-8} m/s (Figure 5.31). However, as the moisture content of the clay increased the drainage rate decreased, suggesting the saturated hydraulic conductivity of the clay barrier is likely to be $< 3 \times 10^{-8}$ m/s. After 2 drying cycles in winter 2009 and winter 2010, the maximum drainage rate in 2010/2011 had increased to 9 mm/day, which is equivalent to 1×10^{-7} m/s. This trend would indicate that the saturated hydraulic conductivity increased by at least an order of magnitude over three years of the monitoring period.

5.3.4 Phytocap vs Conventional Cap

More precipitation was applied to the phytocap than the conventional cap in 2008 and 2009 as 182 mm of supplementary water was irrigated to establish vegetation. The irrigation combined with the slower establishment of the native vegetation compared with Rhodes grass grown on the conventional cap resulted in topsoil of the phytocap maintaining a higher moisture content than the conventional cap through to early 2009 (Figure 5.32). Irrigation applied from August to December 2009 (approximately 21 mm) had little impact on the soil moisture content as the establishment of plants resulted in a drier topsoil. Since mid-2009, the phytocap topsoil has remained drier than the conventional cap even though more runoff (and hence less infiltration) occurred on the conventional cap.

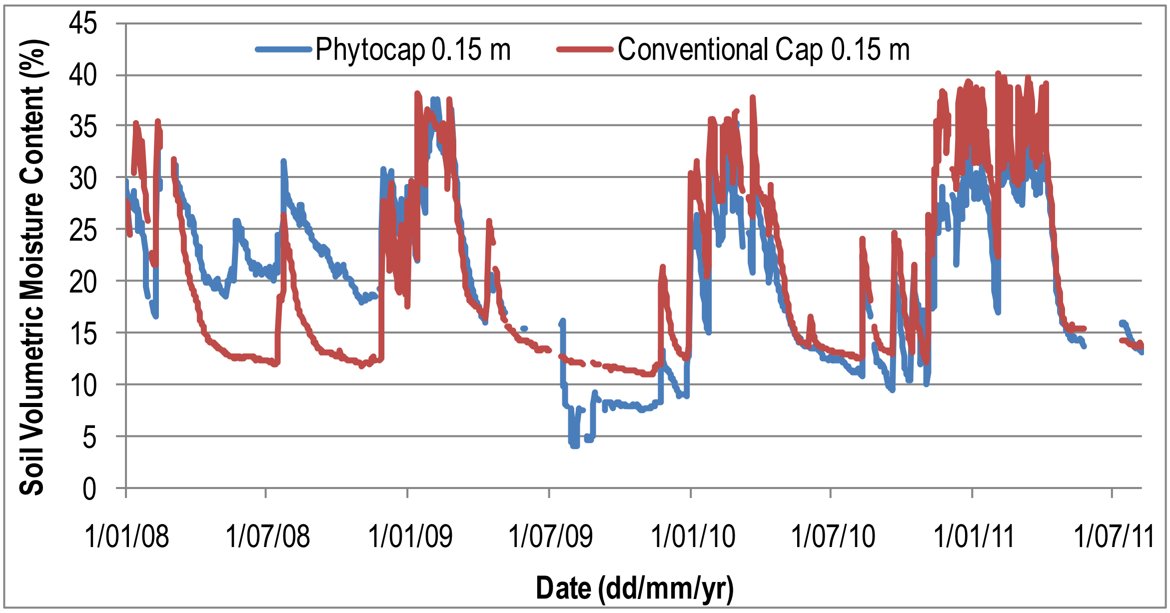

Figure 5.32 Average Daily Volumetric Soil Moisture Content at 0.15 m Depth in Phytocap and Conventional Cap at Vantassel Street Landfill

Drainage through the phytocap was measured in WY1 but no drainage was measured in the conventional cap (Figure 5.33). Since WY1, similar drainage volumes have been measured in both covers; however, the pattern of drainage varied. The conventional cap commenced draining before the phytocap in WY3 and WY4. The cracking of the clay allowed moisture to drain via preferential pathways before the clay was saturated suggesting that in lower rainfall years, the conventional cap is more likely to drain than the phytocap, as occurred in WY3. The drainage from the phytocap tended to continue for longer than the conventional cap. The proliferation of roots deeper in the profile as the trees and shrubs continue to grow may change this in the future.

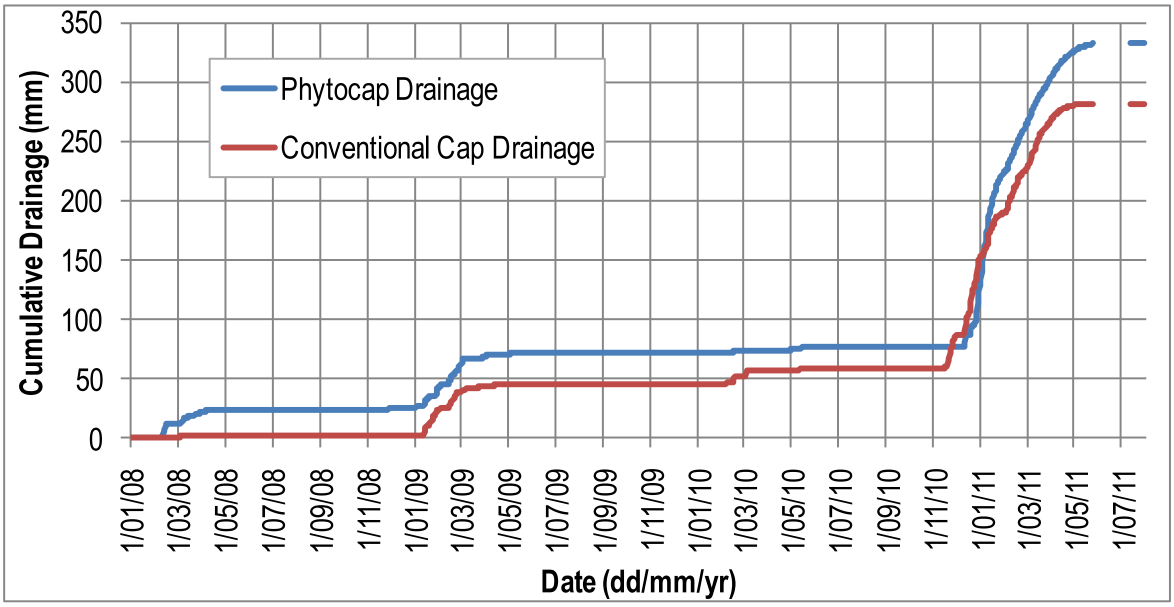

Figure 5.33 Cumulative Drainage from Phytocap and Conventional Cap at Vantassel Street Landfill

Overall, the annual water balance measured in the covers is similar in each year. The advantage of the conventional cap is that it is thinner, allowing more air space for waste disposal. However, this thin cap has limited rooting depth and moisture storage and is only able to support grass vegetation and not trees and shrubs. The trees and shrubs in the phytocap provide a more diverse vegetation community that is likely to be more robust in the event of extreme events, including pests and fire. As the conventional cap is functioning as a phytocap, with the compacted clay barrier not remaining impermeable and allowing drainage through, the lack of a diverse vegetation community will make this cap more sensitive to changes which impact on the grass and also limit the potential evapotranspiration.

5.3.5 Lysimeter vs Control Plot

The soil moisture data for the lysimeter and control plot in the phytocap in 2008 showed minimal difference between the moisture content at depth in the lysimeter and control plots and varied by 5 – 10% over the period shown (Figure 5.34). Temperature data are not available for the phytocap at the Townsville site.

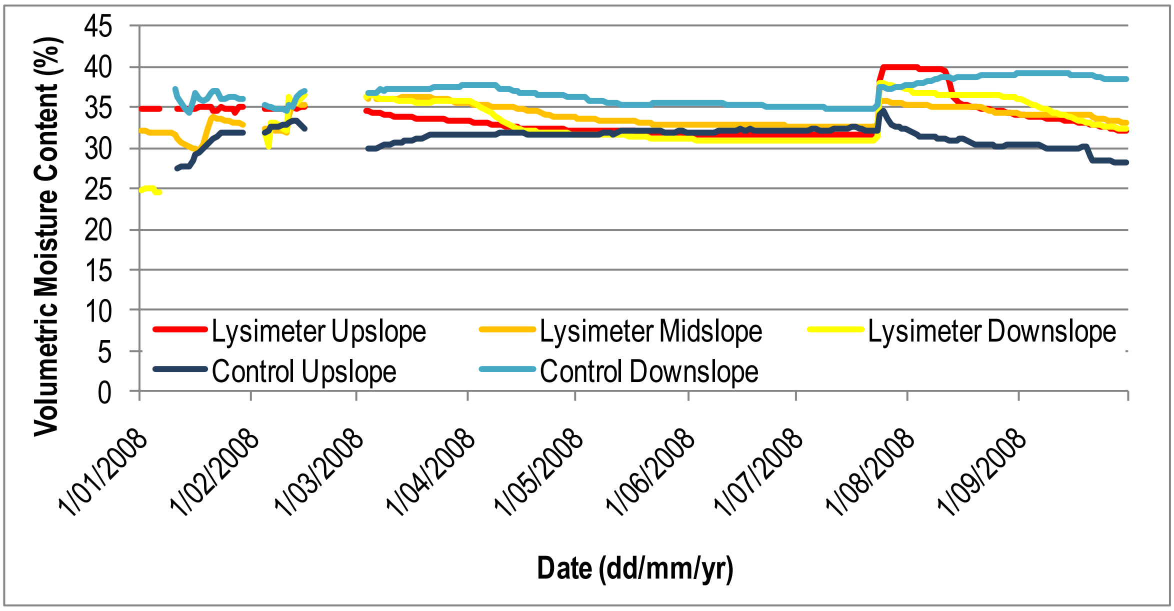

Figure 5.34 Soil Volumetric Moisture Content near Profile Base (1.35 m depth) in Phytocap at Vantassel Street Landfill

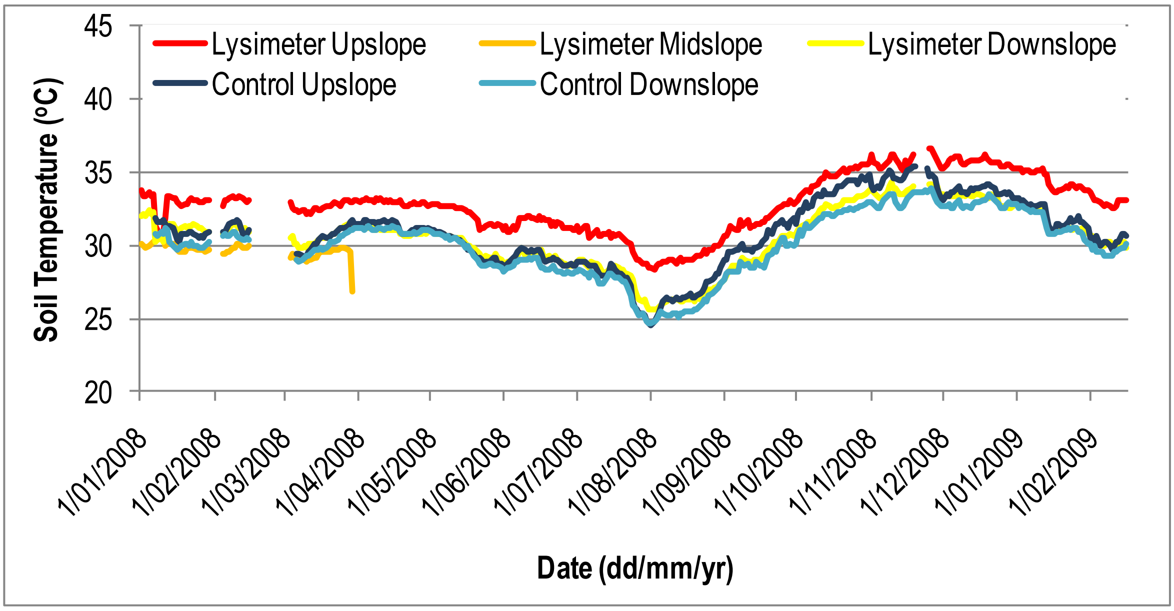

Figure 5.35 Soil Temperature at 0.65 m in Conventional Cap Lysimeter and Control Areas at Vantassel Street Landfill

The soil temperature at the base of the conventional cap can be compared to assess any potential differences caused by interaction with the decomposing landfill mass. Comparison of data from January 2008 to early February 2009 showed no difference between the temperatures within the lysimeter and the control areas (Figure 5.35).

Overall, minimal difference in the temperature or moisture content near the base of the soil profile in the lysimeter and control plots was evident, suggesting that the contribution of moisture and temperature from the decomposing waste mass did not significantly affect the overall water balance, i.e. the lysimeter data are likely to be an accurate representation of the water balance for a full-scale cap over the landfill.

5.3.6 Summary

The weather at the Vantassel Street Landfill over the monitoring period included above average rainfall and cooler minimum temperatures than the long-term average. The monitoring period included a Category 1 tropical cyclone (TC Ellie) and a Category 5 tropical cyclone (TC Yasi). Though a Category 1 cyclone is the lowest intensity cyclone, this system was closer to Townsville and rainfall at the landfill site was heavier and greater than the rainfall from the Category 5 system.

The phytocap at the Vantassel Street landfill showed that it can reduce drainage to < 3% of rainfall during most years. WY4 was an extremely wet year with the wet season starting earlier and most months reporting above average rainfall. The vegetation at the site was not mature and hence it could be expected that drainage would be further reduced in the future. In WY4, the evapotranspiration rate averaged 5.6 mm/day, which is much greater than the peak ET rates reported for eucalypt forests in southern Australia (Dunin *et al.*, 2001).

The conventional cap had lower evapotranspiration and higher runoff than the phytocap and similar drainage. The grass cover on this test section had a lower evapotranspiration rate than the trees and shrubs on the phytocap, which is in part related to the higher runoff resulting in less moisture available for plant growth and also to the greater leaf area index of trees and shrubs, which allows them to transpire more water when moisture is not limited. The shallow compacted clay barrier dried and the permeability increased which allowed drainage to occur.

The phytocap and conventional cap performed similarly over the trial period. However, the conventional cap is performing as a phytocap as the compacted clay has dried and cracked allowing drainage and can no longer be regarded as a barrier. The conventional cap has the advantage of a thinner cap profile; however, this limits the vegetation able to be grown and hence increases the risk of failure. Also, the thinner cap tends to drain more in drier years as the preferential pathways allow “short circuiting” of the soil mass.

5.4 Lismore

The Lismore trial site, which consists of a phytocap lysimeter and control area, was constructed in late 2007. The datalogger commenced recording on 10 December 2007 with runoff and drainage measurement devices installed in May 2008 and the dosing siphon as a backup drainage measurement device was installed in November 2008.

Similar to Townsville, the humid and warm conditions in Lismore reduced the data quality. After data validation and substitution, rainfall and drainage data were recorded for > 94% of events over the period they were installed. The soil moisture sensors recorded data on 91% of days; however from 17 January 2011, the moisture sensors near the bottom of the profile in the lysimeter and control plot had ceased to record, reducing the data record to 71% of days for this depth. Periods of missing data were generally less than 3 days with the exception of the following periods: 6 days from 6 – 12 February 2009; 9 days from 16 – 25 February 2009; 13 days from 29 April – 12 May 2009; 17 days from 26 June – 13 July 2009; 4 days from 18 – 21 March 2011.

The climate at Lismore is sub-tropical and rainfall may occur throughout the year and hence defining a “weather year” was more difficult for this site. Higher summer temperatures and increased PET should result in the driest soil profile occurring in summer or early Autumn, similar to the southern sites and hence the weather year for water balance purposes was commenced in April, which for Lismore resulted in three weather years: WY1 from April 2008 to March 2009; WY2 from April 2009 to March 2010; WY3 from April 2010 to March 2011.

5.4.1 Trial Weather

The annual rainfall during the trial was higher than the average annual rainfall of 1,313 mm in WY1 and WY2 with 1,868 mm and 1,841 mm received respectively. The annual rainfall for WY3 was less than average with 846 mm received. Monthly rainfall varied markedly in each year with 14 of the 18 months prior to July 2009 recording average or above rainfall and 15 of the 21 months from this month on recording below average to average rainfall (Figure 5.36). Six months during the trial period received rainfall higher than the 90% long-term monthly rainfall. The lowest rainfall for any month was recorded in July and August 2010 with 19.4 mm and 19.6 mm recorded respectively.

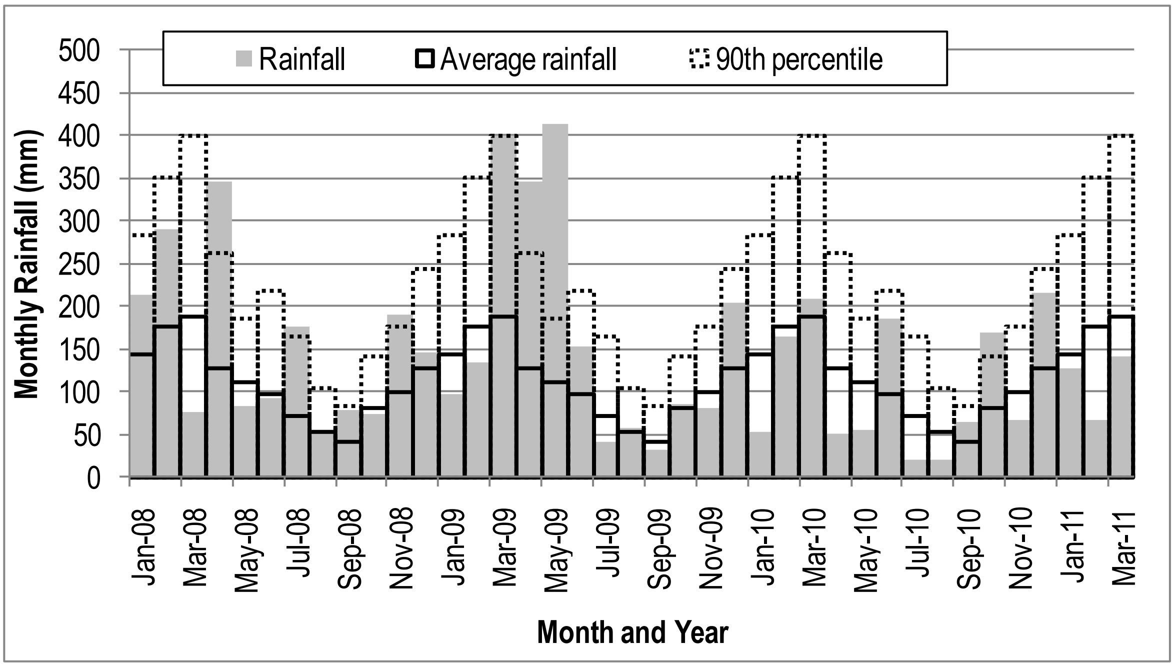

Figure 5.36 Measured Monthly Rainfall at Lismore Waste Facility Compared with Long-term Average and 90th Percentile Rainfall

The Wilson River flows through Lismore and is formed from the convergence of a number of smaller rivers flowing from the steep valleys surrounding Lismore. Floods are common in this area and the Wilson River flooded a number of times over the trial period and may be used to indicate the intensity of rainfall received over the monitoring period. A summary of the flood peak dates and height along with the associated rainfall event details is shown in Table 5.10. Floods have shown no seasonal pattern. Moderate and major floods are associated with high rainfall over a shorter time period (< 1 day) while minor flooding has been the result of rainfall over a number of days.

Table 5.10 Flood Data for Wilson River at Lismore and Associated Site Rainfall Record

Lismore Flood Data		Preceding Site Rainfall Information
Peak Date	Peak Height (m)	
5 January 2008	9.4 (moderate)	91 mm on 3/1
22 May 2009	10.4 (major)	250 mm on 21/5
12 October 2010	4.6 (minor)	57 mm on 9 – 11/10
28 December 2010	6.9 (minor)	128 mm on 24 – 28/12
11 January 2011	5.1 (minor)	30 mm on 6/1 and 29 mm on 10/1

The average daily temperatures at the trial site were similar to the long-term averages (Figure 5.37). Over the trial period, the extremes of temperature tended to be warmer than the long-term average. Thirty-six days were recorded above 35 °C which is greater than the 23 days expected from the long-term average. Only 1 day was recorded with a maximum temperature > 40 °C which is as

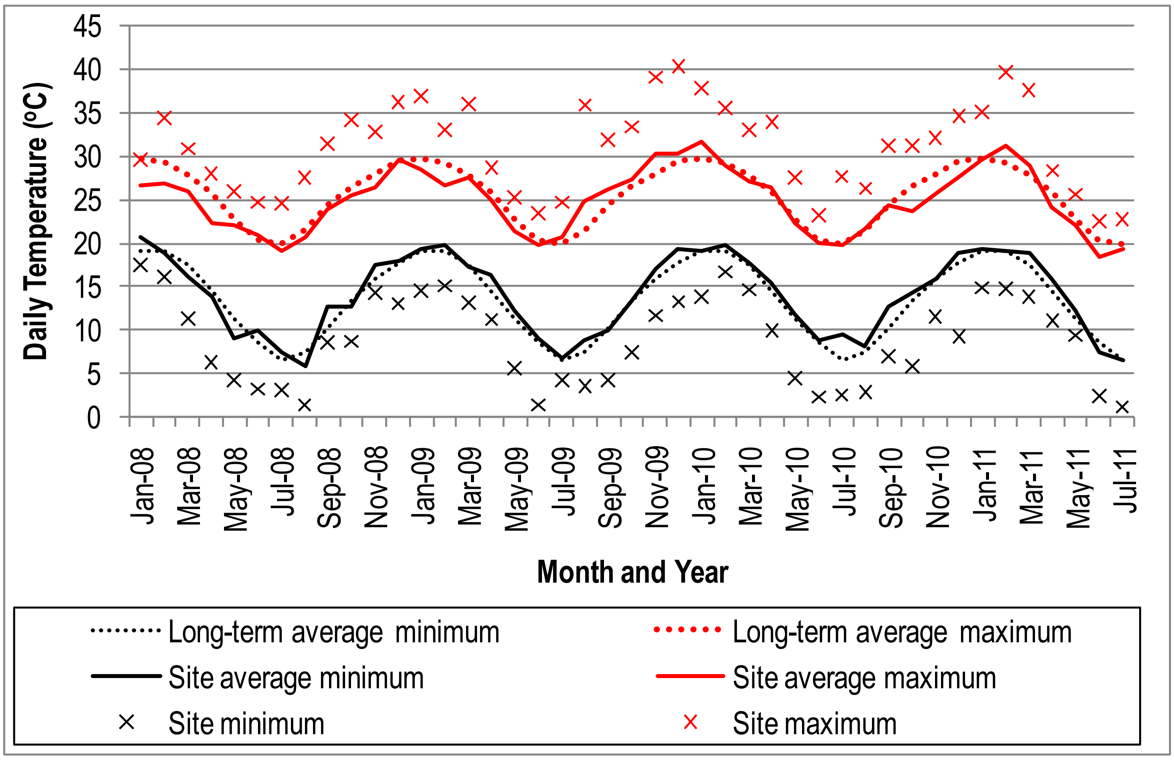

Figure 5.37 Long-term and Site-Measured Average and Extreme Minimum and Maximum Daily Temperatures for Lismore Waste Facility

expected from the long-term averages. The minimum temperatures were higher than expected with 4 days recorded with a temperature < 2 °C but none < 0 °C. Based on the long-term averages, 22 days were expected to be < 2 °C with 3 – 4 days also < 0 °C over the 3 years of monitoring. The reduced number of frosts would be likely to favour improved plant growth over the trial period.

5.4.2 Phytocap Water Balance

The annual water balance measured in the phytocap showed that evapotranspiration was the major loss of precipitation, removing over 79% of rainfall received (Table 5.11). The average daily evapotranspiration was approximately 4 mm/day but as less rainfall was received the ET decreased to approximately 2 mm/day in WY3. During August of each year, 7 – 15 days occur with no rain and little or no drainage. In 2008, the average moisture removed from the profile over this dry period was 1.4 mm/day, which increased to 2.5 mm/day in 2009 and to 3.6 mm/day in 2010. The starting profile moisture in each successive year was less, suggesting that the evapotranspiration potential of the vegetation increased each year which would also reflect increasing rooting depth over this period.

Annual runoff at the site accounted for up to 14% of precipitation on an annual basis. The two largest runoff events (Figure 5.38) accounted for two-thirds of the total runoff over the 3 weather years. During the first event from late March to mid April 2009, 580 mm of rainfall and 264 mm of

Table 5.11 Measured Phytocap Water Balance for Lismore Waste Facility

	Measured Water Balance (mm) for Weather Year		
	WY1 (April 2008 – March 2009)	WY2 (April 2009 – Mar 2010)	WY3 (April 2010 – March 2011)
Precipitation	1868	1840.6	845.7
Evapotranspiration (calc)	1479.4 (79%)	1485.7 – 1550.8 (81 – 84%)	854.4 (101%)
Runoff	256.4 (14%)	317.7 (17%)	76.3 (9%)
Change in storage	27.2 (1%)	-34.2 (-2%)	-91.2 (-11%)
Drainage	15.2 (1%)	6.3 – 71.4 (0.3 – 4%)	6.2 (0.7%)

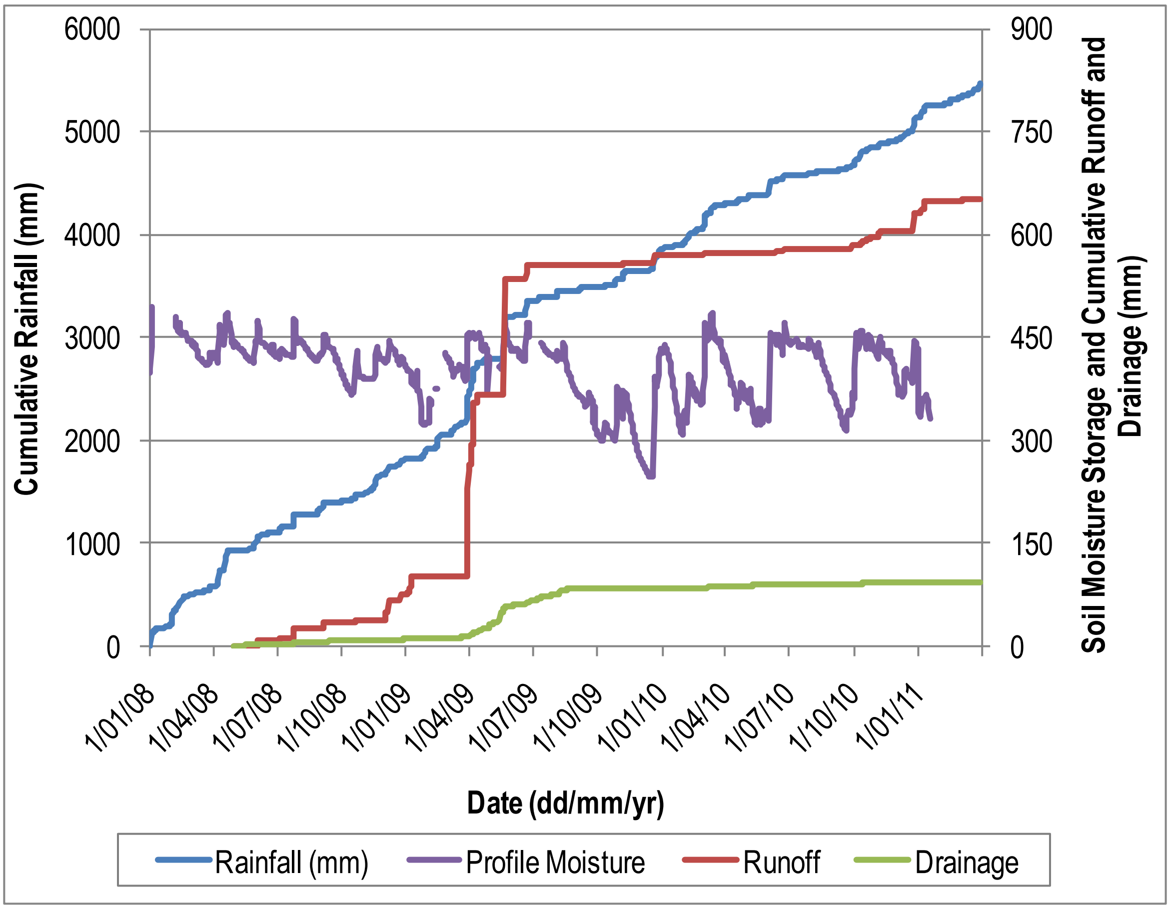

Figure 5.38 Cumulative Rainfall, Runoff and Drainage and Average Daily Profile Moisture Storage of Phytocap at Lismore Waste Facility

runoff were recorded. Approximately 6 weeks later, 391 mm of rainfall from 18 – 23 May 2009 resulted in second runoff event of a further 168 mm. This latter event coincides with major flooding of the Wilson River.

The soil moisture storage in the profile increased during WY1 but then decreased in WY2 and WY3 (Table 5.11). The soil moisture storage ranged from 325 mm to 480 mm in WY1 and increased in range from 246 mm to 486 in WY2 and from 314 mm to 471 mm in WY3 (Figure 5.38). As well as an increase in moisture storage range in WY2, the wetting and drying pattern of the profile also changed and showed more rapid increases and decreases in response to rainfall. The soil moisture storage also showed multiple peaks and troughs at different times of the year which reflected the almost linear cumulative rainfall over the years.

The soil moisture content at each depth reflects the change in soil moisture storage over time. The widest range of moisture contents was initially measured in the topsoil (0.15 m) with little variation at lower depths (Figure 5.39). Toward the end of WY1 the range of moisture contents recorded increased at 0.8 m depth and by the end of WY2 the range of moisture content at all depths had increased. The moisture content near the bottom of the profile (1.35 m depth) remained above 30% moisture until mid-September 2009. After this time, the moisture content near the bottom showed a repeated pattern of moisture increases and decreases, suggesting moisture moved to this depth in the profile but also that the plant roots were active in rapidly extracting the moisture. The moisture content remained below the laboratory measured field capacity on the as constructed cores.

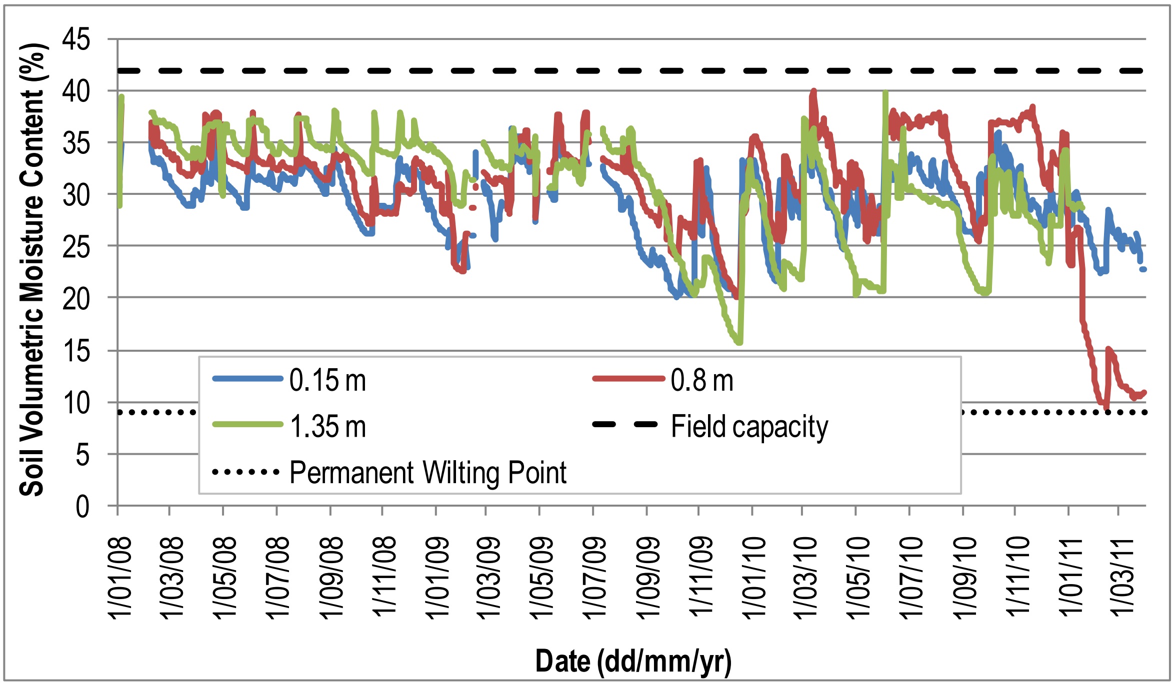

Figure 5.39 Average Daily Volumetric Soil Moisture Content at Three Depths in Phytocap at Lismore Waste Facility

The drainage measured from the soil profile was less than 5% of the rainfall received, with the total volume recorded < 100 mm over the 3 year period (Table 5.11). Drainage was measured by tipping bucket and dosing siphon over the trial period. During WY1, the tipping bucket was the primary measuring device for drainage and then in November 2008 the dosing siphon was installed as a backup to ensure data were recorded even if one device developed a fault. However, during 2009, issues were discovered with both the tipping bucket and the dosing siphon and resulted in discrepancies in the drainage recorded (Figure 5.40).

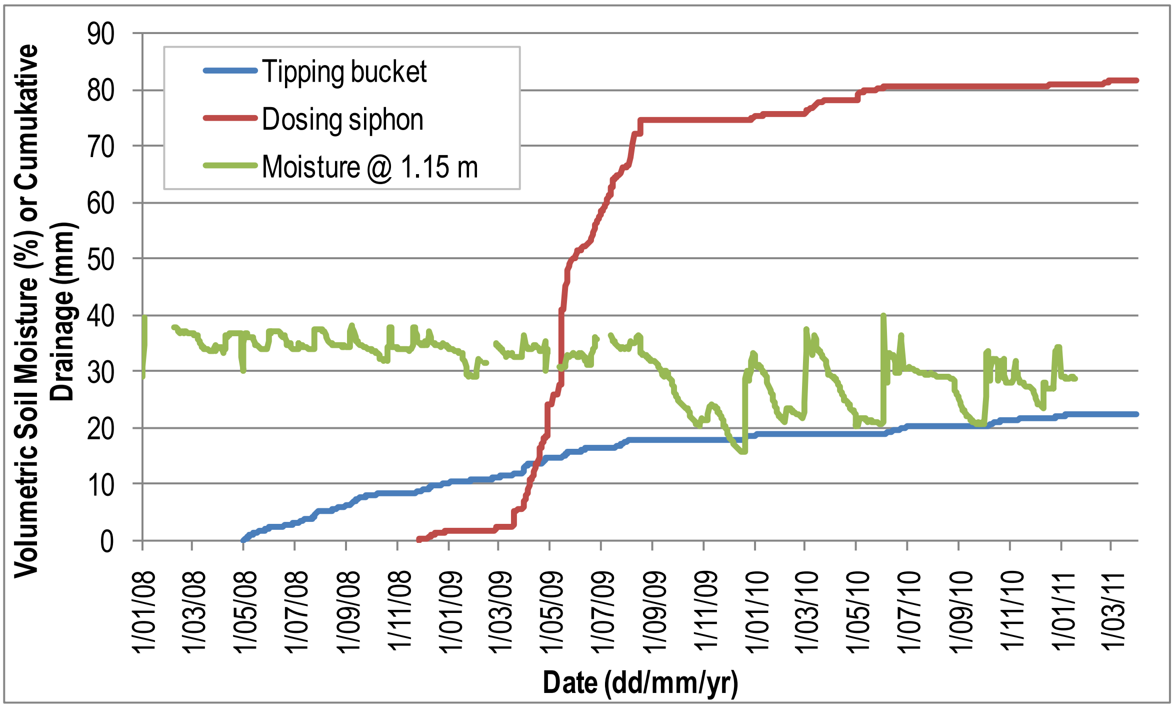

Figure 5.40 Average Daily Volumetric Soil Moisture Content at 1.15 m Depth and Cumulative Drainage Measured by Tipping Bucket and Dosing Siphon at Lismore Waste Facility

The tipping bucket inlet screen became blocked with iron precipitate resulting in reduced or no flow to the tipping bucket; however, the system was designed that if drainage filled the inlet funnel it overtopped to the dosing siphon. However, air entrapment in the dosing siphon resulted in the device siphoning when only partially full. These faults would have resulted in the tipping bucket underestimating the drainage for some periods while the dosing siphon would have overestimated the drainage. The issue is that it is difficult to determine for which periods which device was providing accurate data. As a result, the drainage data are presented as a range for WY2. In WY3, the dosing siphon reported drainage when the soil was dry suggesting that the interface had developed a fault and hence only the tipping bucket data were used.

The drainage measured by the tipping bucket from May 2008 to August 2009 showed a linear increase, with an average rate of 0.04 mm drainage/day (Figure 5.40). Once the dosing siphon had been repaired in February 2009, the cumulative drainage also increased linearly but at a higher rate of 0.47 mm/day. From September 2009 both devices showed a decrease in the rate of drainage and rather than the drainage continually seeping from the base of the lysimeter, drainage only occurred when the moisture content at the base of the profile increased. However, even during this period, there are differences in the magnitude and timing of drainage.

Drainage may occur through any soil profile when moisture flows through preferential flow paths and/or as the moisture flows through the mesopores and micropores in the soil mass and past the base of the profile. Prior to September 2009, the drainage seeped from the base of the Lismore soil profile almost continuously and the higher moisture content (near field capacity) suggested that cracking had not occurred (Figure 5.40). After September 2009 the soil dried and preferential flow paths may have formed leading to “short circuiting” of the soil mass and drainage, especially given the higher clay content and plasticity of the soil used in the phytocap.

Comparison of the timing of drainage measured from the profile with the change in moisture content near the base of the profile does not support the “short circuiting” theory. Drainage was recorded after the moisture content increased, as shown by examples from December 2009 and October 2010 (Figure 5.41). In 2009, drainage decreased before the moisture content near the bottom had decreased. This may be an artefact of the accumulation of precipitate reducing flow into the tipping bucket device as the same response was not observed in 2010. Overall, the drainage and soil moisture patterns suggest that moisture moved through the soil mass and through preferential pathways.

5.4.1 Lysimeter vs Control Plot

Comparison of the moisture content measured in the lysimeter with the control showed there are differences near the base of each of the profiles (Figure 5.42). The moisture content in the lysimeter remained relatively constant over WY1 while the moisture content in the control plot varied between 30% and 40% volumetric moisture. The pattern in the control plot is consistent between the upslope and downslope location but the cause of the variation is not evident. However, as the main difference between the two plots is the influence of landfill gas, it can only be assumed that this is the cause of the difference.

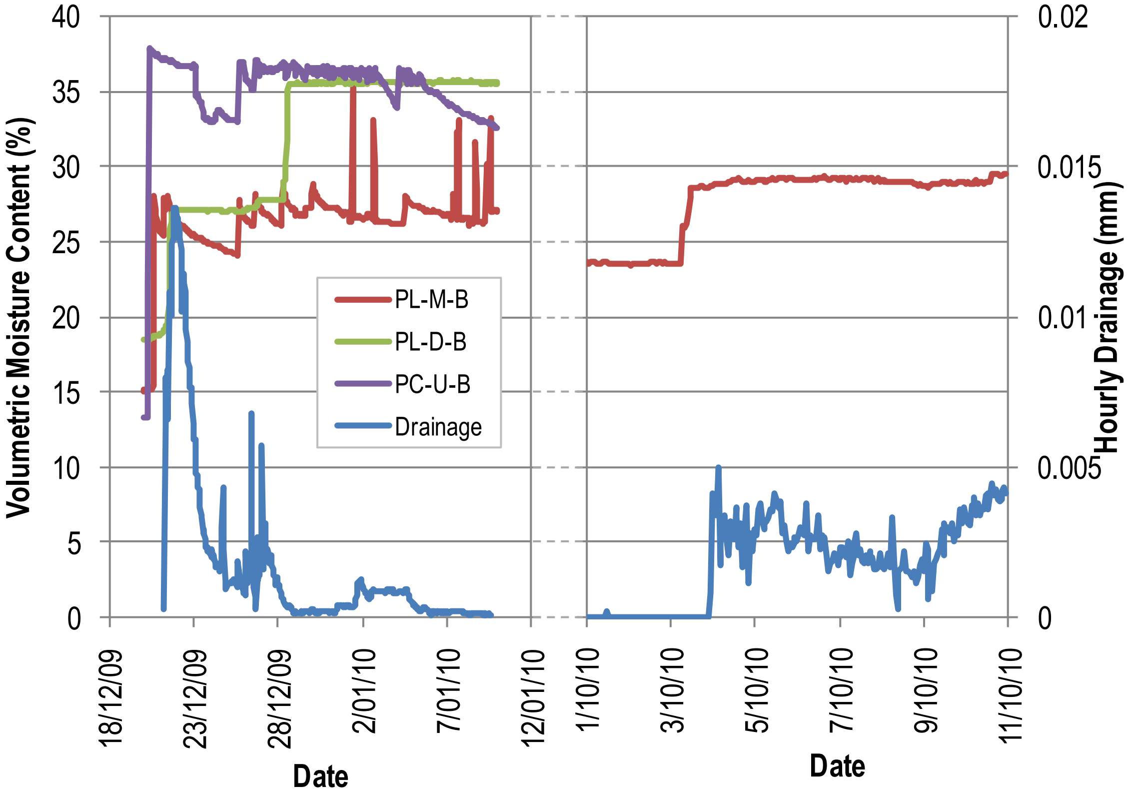

Figure 5.41 Hourly Drainage and Moisture Content Measured Near the Base of the Profile (1.15m) in the Lysimeter Midslope (PL-M-B) and Downslope (PL-D-B) and in the Control Plot Upslope (PC-U-B) at Lismore Waste Facility

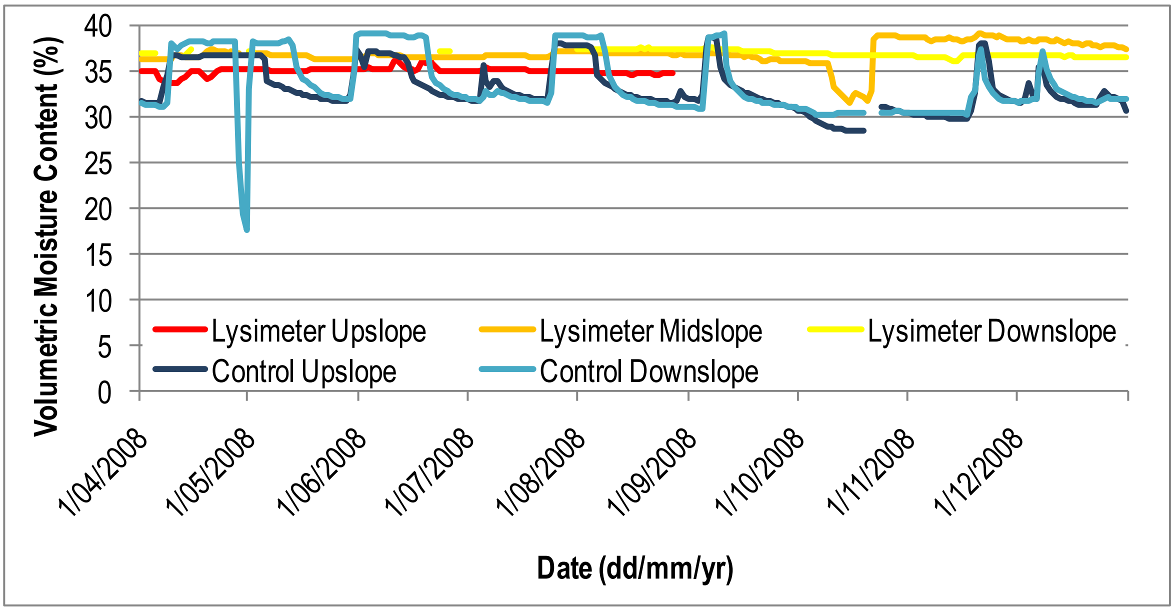

Figure 5.42 Volumetric Moisture Content at 1.15 m Depth in the Lysimeter and Control Plot at Lismore Waste Facility

The temperature measurements at the bottom of the profile also showed differences between the lysimeter and control plots (Figure 5.43). The temperature was higher in the control plot than the lysimeter plot. Again, these differences are indicative of the interaction with the decomposing waste mass on the final cover soil.

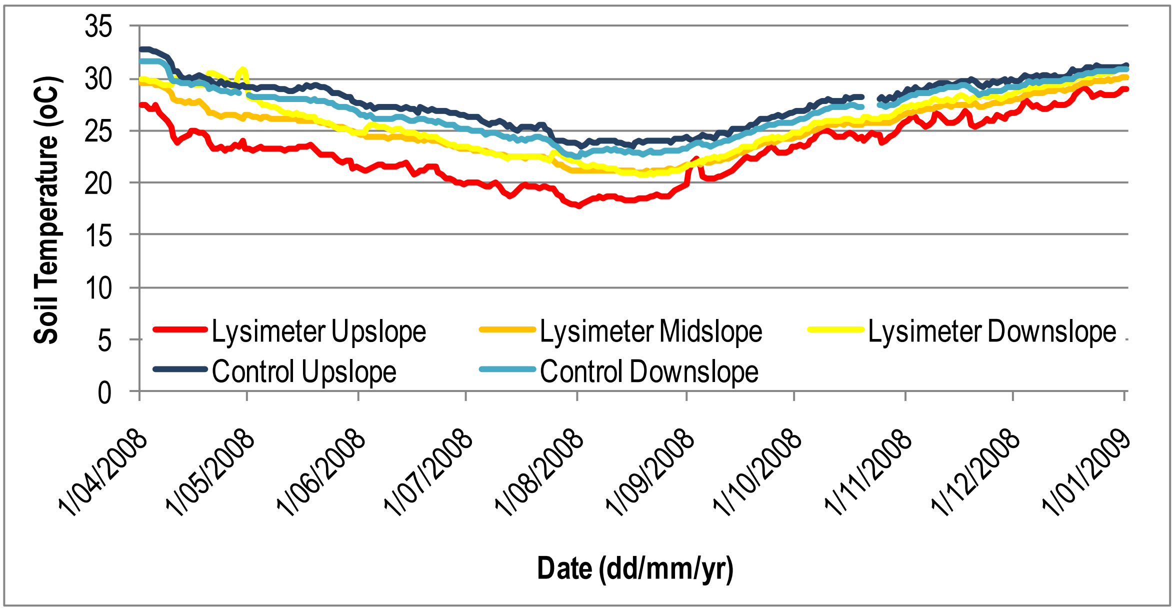

Figure 5.43 Soil Temperature Measured at 1.15 m Depth in the Lysimeter and Control Plot at Lismore Waste Facility

Differences were evident between the lysimeter and control plot. As the moisture content varied in the control plot and not in the lysimeter plot, the effect of this on drainage is not known but as the moisture content was lower in the control plot than the lysimeter plot for more of the time, the drainage from the control may have been lower and hence it is unlikely that the lysimeter has underestimated the drainage compared to the control plot. Benaud (2011) noted there were no differences in plant heights between the lysimeter and control plot, which suggests the rooting depths may have been similar.

5.4.2 Summary

The rainfall during the trial ranged from wetter than average to drier than average and included flooding events. The average temperatures were similar to long-term averages with daily extremes tending to be warmer than expected from on long-term averages.

The phytocap water balance showed that the majority of precipitation was lost as evapotranspiration and that in the Lismore environment, runoff was relatively high. Drainage was < 5% of rainfall received and the drainage pattern altered during the second year, which was most likely related to plant roots extracting water from deeper in the profile. In addition, although preferential cracking was expected from this clayey soil, measurements have suggested that drainage predominantly occurred through flow within the soil mass.

5.5 Perth Site

At Henderson Waste Recovery Park data collection commenced in October 2007 from the phytocap lysimeter and control area. The runoff and drainage measurement devices were installed on 15 February 2008. Dosing siphons were installed as backup for runoff and drainage on 7 – 8 April 2009.

For the Perth site, substitute rainfall data were available from a nearby trial site from May 2008 to December 2010 (Phillips, pers. comm., 2011), providing a nearly complete rainfall record. After data validation and substitution, rainfall and soil moisture were recorded on > 95% of occasions. Prior to the installation of the dosing siphons, i.e. in WY1, the runoff and drainage measurements were recorded on 56% and 88% of occasions, respectively, with the flow meter interface removed for repair from 15 August to 14 November 2008. Drainage data from 28 May – 10 July 2008 were interpolated as "best guess" substitution, based on the soil moisture content near the base of the profile remaining relatively high over the period and the occurrence rain throughout this period. The estimated drainage was 16.9 mm and it is considered that drainage could be up to 3 times higher than this estimate. After the installation of the dosing siphon the data record is considered accurate. Data Interruptions of more than a few days occurred from 28/5 – 4/6/08, 1 – 7/4/09, 26/11 – 1/12/09, 25/2 – 3/3/10 and 25 – 28/11/10.

The climate at Henderson is temperate with distinct hot and dry summer, also known as a Mediterranean climate. Rain usually commences in April or May and hence the weather year commences in April. Data collection has allowed collation of data into three weather years: WY1 from April 2008 to March 2009; WY2 from April 2009 to March 2010; WY3 from April 2010 to March 2011.

5.5.1 Trial Weather

The weather recorded over the trial included very wet and very dry conditions. The long-term average rainfall for the site is 791 mm/yr. In WY1, the rainfall was 1,027 mm, which is above average and close to the maximum annual rainfall recorded for the area of 1,037 mm. In WY2 and

WY3, the rainfall was 530 mm and 443 mm, respectively, which is below the long-term average rainfall and also below the minimum rainfall based on the long-term historical data.

Above average annual rainfall in WY1 was as a result of above average rainfall in April, July, September and November, with April rainfall three times higher than average and the highest rainfall since 1957 for April (Figure 5.44). The high rainfall in April 2008 was due to one large rainfall event on 31 March/1 April, when 54 mm was recorded in 24 hours. On 15, 18 and 23 July 2008, daily rainfall exceeded 20 mm and included rainfall exceeding 9 mm/hr with 21 mm/hr recorded during the rain event on 23 July.

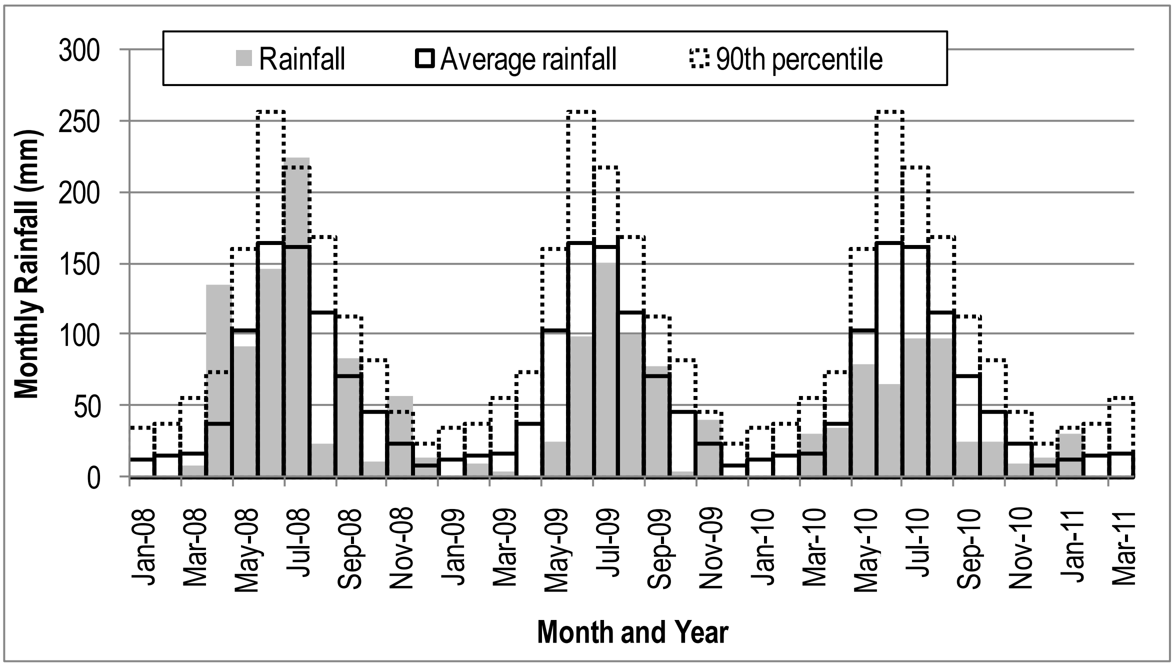

Figure 5.44 Measured Monthly Rainfall at Henderson Waste Recovery Park Compared with Long-term Average and 90th Percentile Rainfall

The monthly rainfall in WY2 was below average for the first 5 months and in WY3, the monthly rainfall was below average in all months except December and January (Figure 5.44). In WY2, no rain was received for 66 consecutive days from December to February. In WY3, a similar pattern was also observed with no rain for 64 days from November to January.

Irrigation was applied to the lysimeter plot in 2008 and 2009 to improve plant survival. Irrigation volumes were not recorded on site and hence the addition can not be included in the water balance. Periods of irrigation are evident within the record as shown by soil moisture content increases in the absence of rainfall. However, as irrigation was only applied during summer months when evaporative demand was high, the impact of the irrigation on the overall water balance, particularly drainage, is likely to be low. Irrigation was only applied to the lysimeter and not to the control area and hence comparison of these data sets in Section 5.5.3 will indicate the magnitude of the impact on the overall water balance.

The average daily temperature for each month over the trial period was similar to long-term averages (Figure 5.45). The exceptions were in October and November 2008 and September 2009 when the site average maximum daily temperature was over 2 °C cooler than the long-term average. In November 2010 and February 2011 the site average minimum and maximum temperatures were 3 °C warmer than the long-term average with the average minimum daily temperature remaining 2 °C higher than average in March 2011.

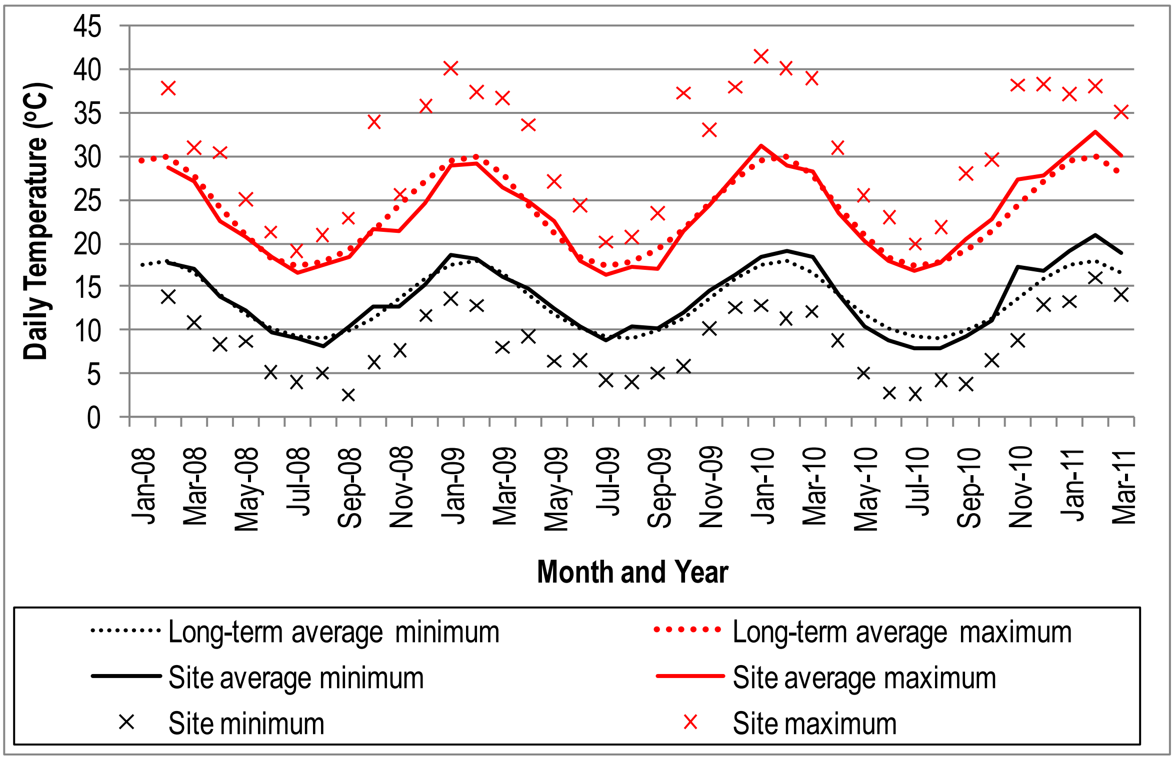

Figure 5.45 Long-term and Site-Measured Average and Extreme Minimum and Maximum Daily Temperatures for Henderson Waste Recovery Park

The extreme temperatures tended to be near average or warmer than average. Over the three year monitoring period, 39 days would be expected to be > 35 °C based on the long-term average. From the data measured over the trial period, 53 days were recorded over this temperature, suggesting additional heat stress on plants and soil evaporation may have occurred over the trial period compared to longer term averages. The temperatures recorded > 40 °C and < 2 °C were as expected from long-term averages at 3 days and 0 days, respectively.

Over the trial period, initially wet and slightly cooler weather of WY1 became the drier weather of WY2 and then drier and slightly warmer in WY3.

5.5.2 Phytocap Water Balance

The water balance was measured in the phytocap for three years. The rainfall decreased in each year and hence it is difficult to separate the changes over time from the changes related to lower rainfall (Table 5.12). Evapotranspiration accounted for > 80% of precipitation, which was the largest loss. Runoff, change in storage and drainage varied and accounted for 2 – 23% of the water balance, with the change in storage showing a progressively drying pattern.

Table 5.12 Measured Phytocap Water Balance for Henderson Waste Recovery Park

	Measured Water Balance (mm) for Weather Year		
	WY1 (April 2008 – March 2009)	WY2 (April 2009 – Mar 2010)	WY3 (April 2010 – March 2011)
Precipitation	1026.8	530.4	442.8
Evapotranspiration (calc)	818.1 (80%)	495.2 (93%)	381.2 (86%)
Runoff	16.7(2%)	22.0 (4%)	68.5 (15%)
Change in storage	-40.5 (-4%)	-52.1 (-10%)	-17.1 (-4%)
Drainage	232.5 (23%)	65.4 (12%)	10.2 (2%)

The rainfall pattern shows a distinct seasonal pattern with rainfall occurring over the winter months and little or no rainfall over the summer months (Figure 5.46). This seasonal pattern is also reflected in the runoff, moisture storage and drainage. Runoff has increased over the monitoring period which is an unexpected result as the increase in vegetative cover would be expected to reduce runoff through decreasing raindrop impact from interception of rainfall and also increased infiltration. However, the runoff measurement has potential inaccuracies from the poor resolution, "noisy" data and faulty interface associated with the flow meter, which was particularly evident in the data for WY1. A dosing siphon was installed in 2009; however, the siphon recorded runoff events in the absence of rainfall and hence its accuracy is also uncertain.

Rainfall intensity can also be a factor in runoff. In WY2, the median and mean rainfall rates were 0.4 mm/yr and 1.0 mm/yr, respectively with a maximum of 20.6 mm/yr. In WY3, the median and mean rainfall rate was higher at 0.6 mm/yr and 1.1 mm/hr, respectively with a lower maximum of 11 mm/hr. Histogram analysis of the distribution of the rainfall for the two years showed that in WY3, there were more rainfall hours that were 4 – 6 mm/hr, 8 – 10 mm/hr and > 10 mm/hr (Figure 5.47) compared with WY2. In WY3, rainfall was > 4 mm for 23 hours, while in WY2 there were 17 hours.

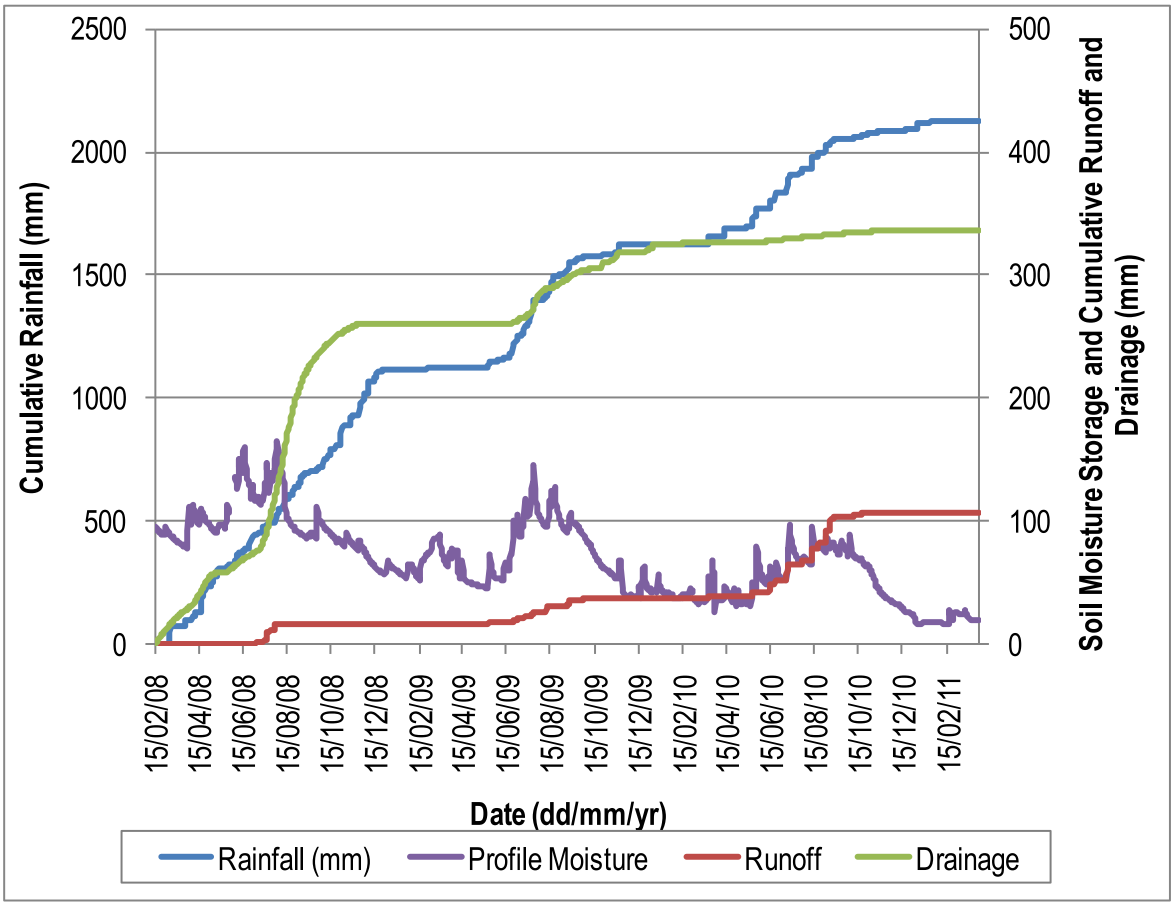

Figure 5.46 Cumulative Rainfall, Runoff and Drainage and Average Daily Profile Moisture Storage of Phytocap at Henderson Waste Recovery Park

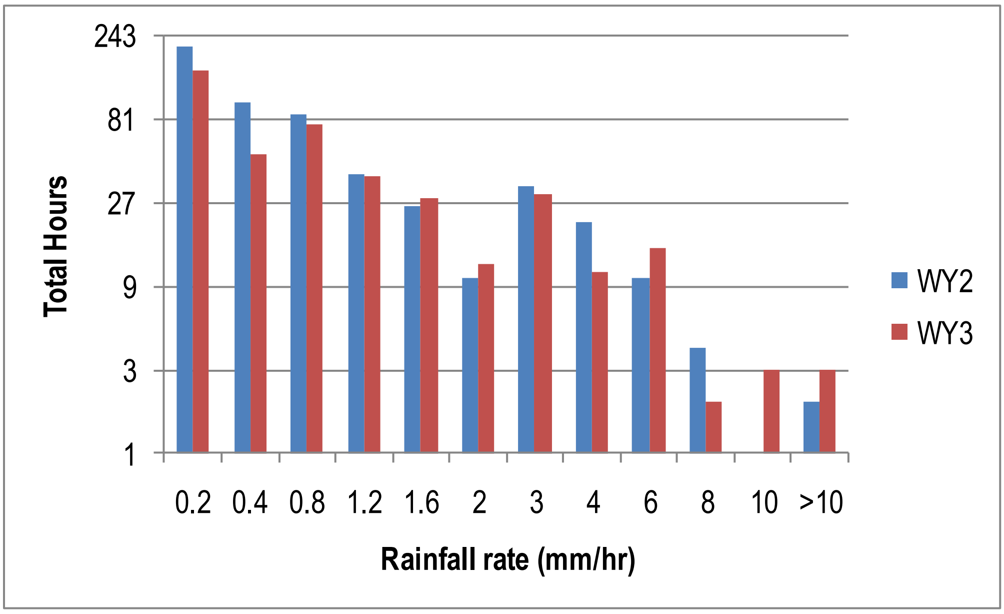

Figure 5.47 Hourly Rainfall Histogram for WY2 and WY3 at Henderson Waste Recovery Park

[Note: Logarithmic Y-axis]

Though the total annual rainfall and number of rain days was less in WY3 than WY2, the greater number of hours with higher intensity rainfall may explain the higher runoff.

Another explanation for the increase in runoff may be related to the drying soil profile. The Swan Coastal plain sands have been reported to become hydrophobic when dry and hence the further establishment of vegetation reducing the soil moisture but not yet achieving canopy closure combined with the cessation of summer irrigation may be increasing the length of time the soil remains hydrophobic and thus increased the surface runoff. The soil profile moisture was lower in WY3 than WY2 (Figure 5.46) suggesting the surface soil would have also been drier and hence this may be another factor causing higher runoff in WY3. Further data collection would show if runoff decreased once canopy closure occurs or the profile moisture content increases.

The soil moisture storage decreased each year (Table 5.12) with the highest and lowest profile moisture contents decreasing in each successive year (Figure 5.46). This pattern was also reflected in the moisture content measured at each depth (Figure 5.48). The decreasing rainfall over the three years is likely to be a major cause of this decreasing moisture content.

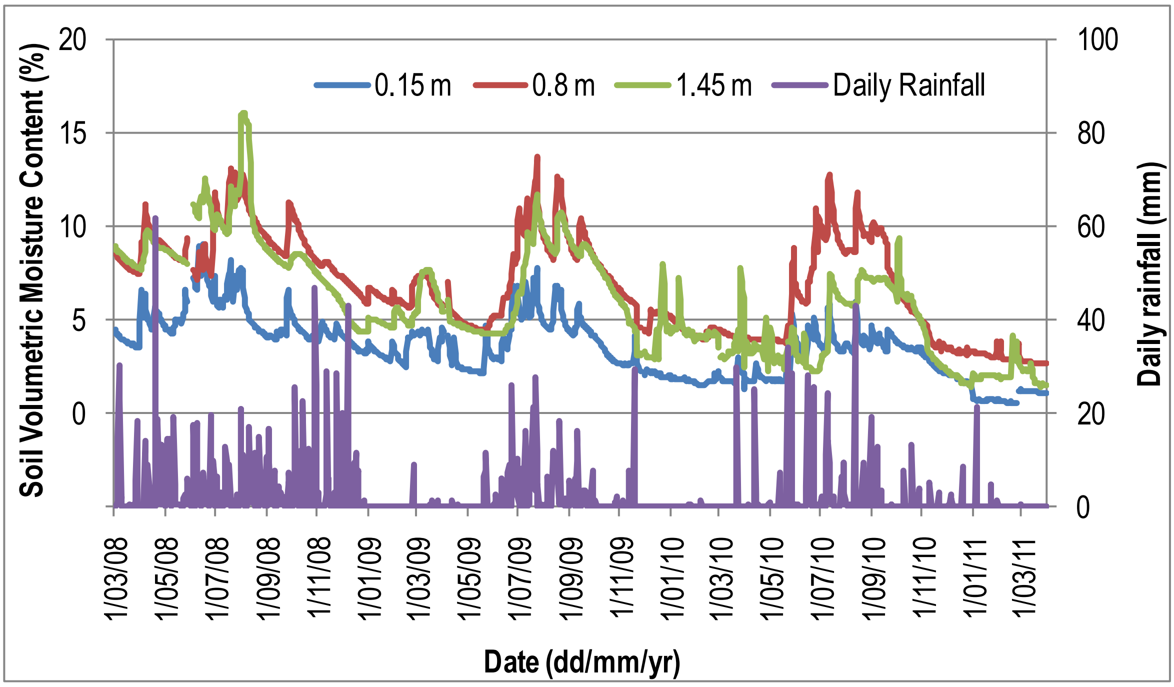

Figure 5.48 Average Daily Volumetric Soil Moisture Content at Three Depths in Phytocap and Daily Rainfall at Henderson Waste Recovery Park

Increased transpiration may also be a factor in the decreasing moisture content. From Figure 5.48, comparison of the moisture contents measured at 0.8 m depth showed the moisture content appeared to decrease more rapidly in September/October 2010 than in 2009. After 7 days of no rain, the soil moisture content was 7.7% at 0.8 m depth on 10/10/09. After 16 days and no further rain, the moisture content had decreased to 6.83%, i.e. a reduction of 0.9%. Over a similar period in 2010 commencing on 22/9/10 and no rain in the preceding 10 days, the moisture content was 7.7% and decreased to 6.25% over 16 days. This suggests that plant roots were extracting moisture from this depth to a greater extent in 2010 than in 2009.

The other trend of note that may also indicate increased transpiration is increased lag time between the increased moisture content at 0.8 m depth being transmitted to the 1.45 m depth interval (Figure 5.48). In WY1, the wetting front can be seen to move rapidly through the profile with a short lag time between increased moisture content at the 3 measurement depths. In WY2, the commencement of rainfall in winter showed a longer lag time between increased moisture through the profile, which increased further in WY3. The delay in the moisture movement through the profile can be explained by increasing plant transpiration and the growth of roots deeper in the soil profile. It can also be explained by less frequent more intense rainfall as occurred in WY3 compared to WY2 (Figure 5.47 and Figure 5.48).

The drainage measured from the phytocap has decreased over time. Due to the decrease in rainfall and the peak moisture contents over the period it is unknown to what extent the increased plant growth over the monitoring period is having on the drainage. There was no apparent change over time in lag time between rainfall events and drainage commencing or the drainage rate increasing to suggest other influences on the decreased drainage other than decreased rainfall.

5.5.3 Lysimeter vs Control Plot

The moisture content measured near the base of the lysimeter compared to the control showed no consistent pattern of difference (Figure 5.49). The moisture content measured at the downslope position in the lysimeter showed a marked increase in moisture content in August 2008 and although this was possibly caused by a restriction to flow out of the lysimeter, it is not an indication of systematic differences between the lysimeter and control plot. Increased moisture content in the lysimeter from January to March 2009 was likely to be caused by irrigation undertaken to aid vegetation establishment. The increased moisture content suggests that the drainage may have occurred due to irrigation but drainage measurements over this period totalled 0.8 mm and hence were insignificant compared to the total drainage measured.

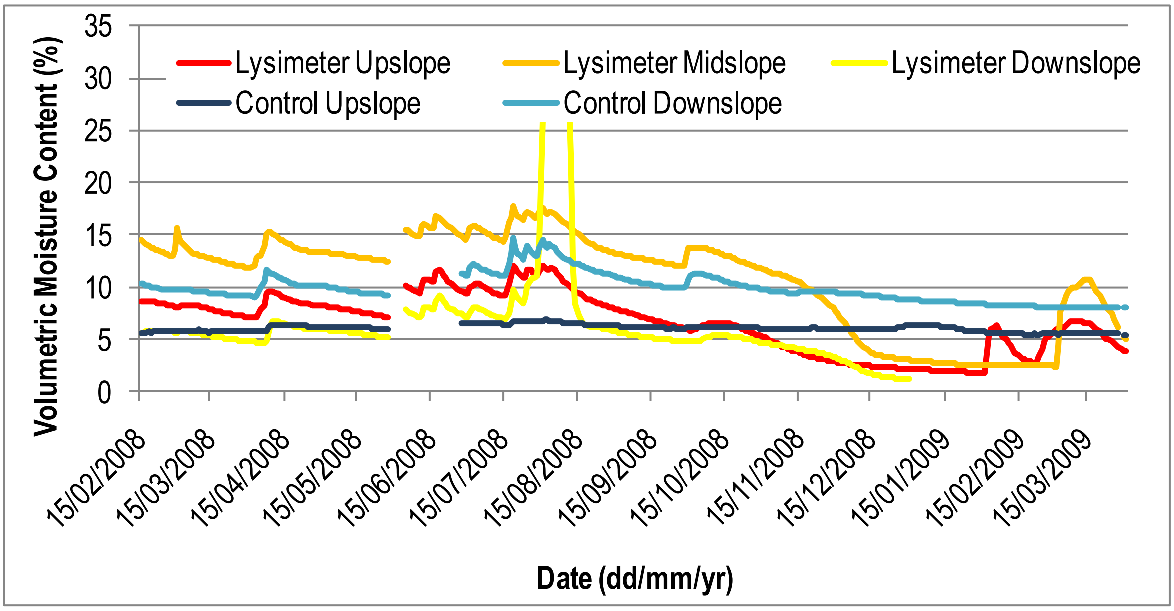

Figure 5.49 Average Daily Volumetric Moisture Content Measured near the Base of the Profile (1.45 m) at Each Location in the Phytocap at Henderson Waste Recovery Park

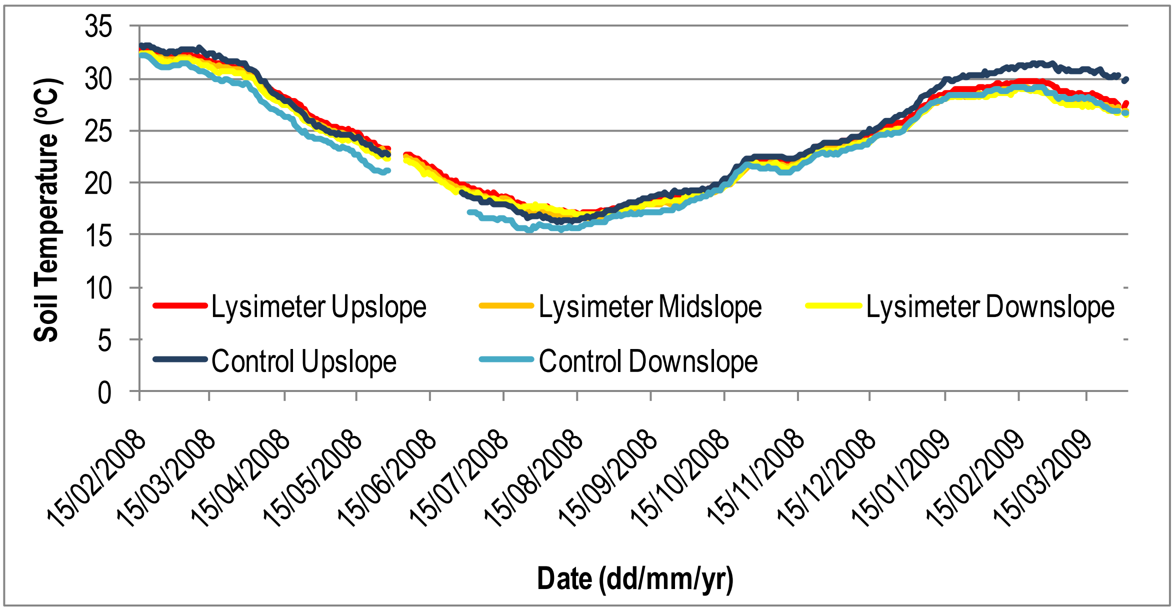

Figure 5.50 Average Daily Soil Temperature near the Base of the Profile (1.45 m) at Each Location in the Phytocap at Henderson Waste Recovery Park

The soil temperature near the base of the lysimeter showed seasonal variation but no pattern of difference between the temperature within the lysimeter and outside the lysimeter (Figure 5.50). The soil temperature at the upslope position in the control area showed greater temperature fluctuation than the other sensors but the cause of this is unknown. Although landfill gas rises through the path of least resistance there is no reason to expect this to be near the top of the control and it would be expected for the difference to be more evident in winter when the difference between the temperature of the waste mass and the ambient temperature is the greatest.

Overall, there was no apparent difference in soil moisture content or temperature near the base of the phytocap profile suggesting that the underlying waste mass is unlikely to be affecting or contributing to the waste balance within the phytocap.

5.5.4 Summary

The water balance of the phytocap at the Perth site was strongly influenced by the sandy soil. The decreasing rainfall over the trial period was the dominant influence over the water balance results and other factors, such as increased plant transpiration and soil structural changes, were not clearly evident in the monitoring results. Drainage was measured in all years, even when the rainfall decreased to 443 mm.

5.6 Trial Site Comparison

The water balance from the trial sites showed that, as expected, evapotranspiration is the largest loss of precipitation. At all trial sites, evapotranspiration through the final cover was greater than 79% of rainfall. The highest evapotranspiration occurred at the Townsville and Lismore sites where the average daily temperatures are higher, rainfall occurs during the season of maximum plant growth and the vegetation included trees and shrubs in the phytocap.

At the southern sites, the evapotranspiration was highest at the Melbourne site and lowest at the Perth site. The available moisture at the Melbourne site was higher than Adelaide and combined with the higher rainfall, moisture was not as limited in the Melbourne profile and the addition of trees and shrubs increased the ability of the vegetation to remove the stored moisture. The Perth site had the lowest evapotranspiration, with the exception of WY1 when evaporation from the nearly bare soil surface would have been the dominant component. The very sandy soil had reduced moisture storage capacity and drained rapidly. In addition, although trees, shrubs and grasses were sown, the grasses did not establish and the trees and shrubs established slowly (Benaud, 2011).

Evapotranspiration was higher in the phytocap than the conventional cap in most years. The exception was the Adelaide site in WY3 and WY4, which was caused by plant die-back in the phytocap lysimeter. The higher phytocap evapotranspiration was also more evident at the Melbourne and Townsville sites where the phytocap vegetation included trees and shrubs while the conventional cap was only grasses. The difference between the phytocap and conventional cap evapotranspiration was also greater during wetter years when the greater transpirative potential of the trees and shrubs became evident.

Despite problems with measuring runoff, the data indicated that runoff decreased over time, with the exception of the Perth site. In the final year of measurement, runoff was < 1% of precipitation but was 2% and 9% at the northern sites. Runoff tended to be higher in the conventional caps than the phytocaps.

As expected, the soil moisture storage and variation in moisture content changed over the trial period. Initially, the soil moisture storage showed little variation and changes in moisture content were predominantly seen in the upper layers of the profile. After the first 1 – 2 years, the range and rate of change of soil moisture storage increased and the variation in moisture content was observed at all depths at all trial sites, with the exception of Perth. This indicated that at most sites the plant roots had extended through the depth of the profile.

The compacted clay barriers constructed at the trial sites dried in the first year after placement (Figure 5.51). In following years, the moisture content increased and decreased in the clay barrier showing that the layer was permeable. Linear shrinkage measured for the clay barriers indicated that the materials were non-expansive and had a low-medium potential for volume change. The monitoring data provided indirect evidence that cracks had formed in clay barrier from this desiccation. As the clay became wetter, the data suggest that the cracks reduced in size, which is consistent with the low to medium potential for volume change. At Townsville, the compacted clay barrier was shallow and hence greater variation in moisture content was measured. At the Melbourne and Adelaide sites, the barrier was placed deeper in the profile and the seasonal variation was reduced.

Lateral flow was measured from the clay barrier interface in the conventional caps at all sites. In some years lateral flow was higher than drainage but in other years the lateral flow was less. The higher lateral flow occurred predominantly in years when the soil moisture content increased gradually through the profile, which most likely allowed the clay to swell and cracks to seal before a larger wetting front moved through the profile. Higher or similar drainage to lateral flow occurred when the moisture moved through the soil rapidly and before the clay had wet. This was most evident in Townsville due to the seasonality of rainfall, higher rainfall intensity, greater linear shrinkage of the clay material and shallower depth to the barrier than the southern sites.

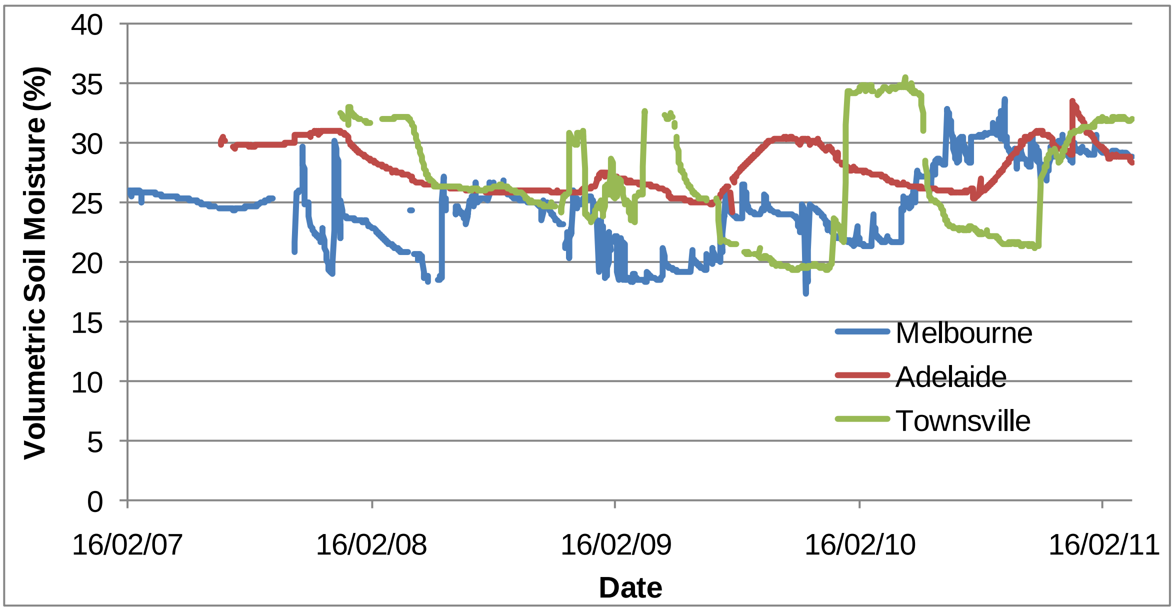

Figure 5.51 Volumetric Soil Moisture Content over Time in the Compacted Clay Barrier at Three Trial Sites

The generation of lateral flow from the compacted clay barrier suggests that drainage is reduced. However, in the larger-scale of a landfill, this lateral flow may become drainage if preferential settlement compromises the continuity of the clay layer or if the lateral flow ponds on deformations or at the toe of batter slopes and slowly seeps through the barrier. The generation of lateral flow requires additional site management to collect and treat this water as stormwater runoff.

Drainage was reduced in the phytocaps at the sites once the vegetation had established. Drainage accounted for < 6% of rainfall at Adelaide, Melbourne and Lismore and < 12% in Townsville. Higher drainage was measured in Perth; however, the vegetation was still establishing through to the end of 2010 (Benaud, 2011). The drainage through the cover was not only dependent on the amount of rainfall received but on the frequency of rainfall over months and the season. Successive wet months of near or above average rainfall resulted in higher drainage than a similar volume of rainfall falling either over a shorter period, such as a few days or one month, or falling over a longer period such as over a year. The timing of rainfall was also an important factor in the occurrence of drainage. In Townsville rainfall of 1,964 mm resulted in 6 mm drainage while in Melbourne rainfall of 1,451 mm resulted in 28 mm drainage. The reason for this is likely to be caused by the coincidence of higher rainfall and warmer temperatures in Townsville which resulted in higher evaporative and transpirative potential. In Melbourne, more rain fell during winter when temperatures are low and evapotranspirative demand was lowest.

Drainage in the conventional caps occurred when the clay was dry, suggesting that preferential flow paths formed and allowed the water to "short circuit" through the clay. The exception was Townsville where the drainage was higher when the clay layer was wetter for an extended period. The shallow depth of the barrier in this profile is likely to have resulted in greater changes in the clay layer due to more frequent wetting and drying cycles and plant root intrusion.

Comparison of the drainage in the phytocap and conventional cap shows that in some years the phytocap performs better than the conventional cap, while in other years the conventional cap performs better in reducing drainage. In general, the phytocap performed better than the conventional cap where rainfall was strongly seasonal and tended to be more intensive storms and where the clay barrier was shallower in the profile.

Overall, the impact of lysimeters on preventing the potential influence of methane oxidation on the water balance appeared to be negligible. Differences between the lysimeter and control plots were noted at Melbourne and Lismore but these differences were not significant. Michaels (2010) reported differences between the lysimeter and control plots at Wollert in Victoria; however, this landfill recirculates leachate which was not practiced at any of the sites used in this study.

6. Water Balance Modelling Calibration

Water balance models are one of the tools available to aid in the prediction of capping performance over the longer term of the landfill maintenance period, often a 50 year period. A number of authors (see Section 2.3) have noted that the accuracy of an uncalibrated water balance model, i.e. one that has not been calibrated against field data, can be an order of magnitude. The accuracy of the water balance model can be improved by verifying the performance against field data.

This chapter compares the predictions from the water balance modelling with the field data over the trial period, i.e. 2007 to 2011 using the Adelaide data. The modelling is presented in a progressive manner, with water balance predictions based on preliminary laboratory results and soil texture, i.e. the modelling presented in Section 4.1, then progresses to water balance prediction based on soil hydraulic properties collected from representative soil samples taken during construction, i.e. the data presented in Table 4.1, and finally the water balance predictions from a model calibrated using field data. These three scenarios are referred to as “Design”, “Construction” and “Calibration” modelling, respectively. The Design modelling was undertaken in 2006 while subsequent modelling based on construction parameters and field data were undertaken in 2011 and 2012. The comparison and calibration using the WAVES model and field collected data will be used to assess the effectiveness of the selected water balance model, i.e. WAVES, in predicting the performance of final covers for landfill and to compare the accuracy of water balance predictions based on varying knowledge.

6.1 Modelling Inputs

The assumptions used by the WAVES model to resolve the carbon and water balances are described in detail by Zhang and Dawes (1998). The user provided modelling inputs used in the WAVES modelling were:

- Climate data from 1/1/2007 to 29/08/2012 were sourced from the weather station on-site, with missing data substituted using the daily climate data interpolated for the site (based on coordinates -35.2 °S; 138.5 °E). Irrigation applied in July/August 2009 was included as precipitation;
- Soil hydraulic input was based on Broadbridge and White (1988) hydraulic functions, as recommended for use in the WAVES model. The properties required to generate an

hydraulic lookup files are saturated hydraulic conductivity (K_{sat}), saturated volumetric moisture content (θ_s), dry volumetric moisture content (θ_d), macroscopic capillary length (λ_c) and a shape parameter (C). The values used for each scenario, being Design, Construction and Calibration, are shown in Table 6.1.

Table 6.1 Topsoil and Subsoil Hydraulic Properties Input to Broadbridge and White (1988) Hydraulic Functions

Property	Phytocap Soil Hydraulic Properties Input to WAVES Modelling					
	Design		Construction		Calibration	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
K_{sat} (m/d)	0.16428	0.1135	0.16416	0.11232	0.44	0.11232
θ_s (vol/vol)	0.429	0.352	0.46	0.42	0.46	0.42
θ_d (vol/vol)	0.09	0.09	0.09	0.08	0.08	0.12
λ_c (m)	0.3	0.3	0.1	0.05	0.05	0.05
C	10	10	1.02	1.02	1.02	1.02

- The total profile depth was 1.5 m and consisted of 0.3 m topsoil over 1.2 m subsoil in all scenarios;
- Vegetation was based on a mixed stand of warm season (C4) and cool season (C3) grasses. During the Design and Construction modelling scenarios, the vegetation was modelled as two separate layers in WAVES, with the C4 grass input as the overstorey and the C3 grass as the understorey. For the modelling undertaken for Calibration, this was simplified to one vegetation layer as individual growth parameters were not measured for the C3 and C4 grasses in the field and observation suggested the C3 grasses may have formed a larger proportion of grasses than the C4 grasses.

The parameters entered into the WAVES model for each vegetation type (i.e. C3 or C4 grass) were altered between the Design modelling and Construction modelling as a better understanding of native vegetation growth patterns and the vegetation input parameters of the WAVES model was gained by the author over the intervening period from literature review and observations. Vegetation parameters were again varied for the Calibration scenario to force modelled soil moisture changes to better reflect field measured changes. The leaf area index (LAI), which is calculated by the WAVES model, for each scenario is shown in Figure 6.1.

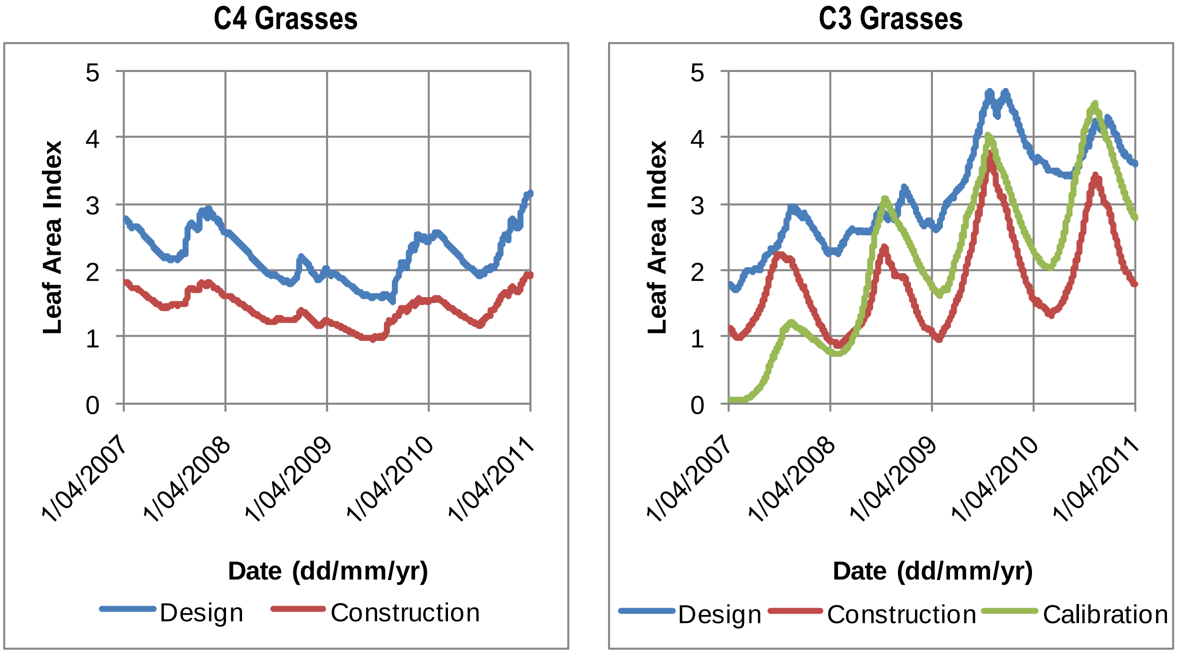

Figure 6.1 Leaf Area Indices Estimated for C4 Grasses (left) and C3 Grasses (right)

6.2 Design Modelling

“Design” modelling was used to develop a soil profile for the field trial which would allow some drainage in most years and was based on laboratory data from recompacted cores and generic soil hydraulic properties for the soil textural group of the material, as published by Dawes *et al.* (1998) and shown in Table 6.1. The long term modelling was presented in Section 4.1 and covered the period from 1957 to September 2006, i.e. prior to the monitoring trial. The Design modelling was updated, as described herein, to reflect the prevailing weather conditions over the trial period.

6.2.1 Water Balance

The water balance predicted varied over the trial period with annual precipitation (P) ranging from 361 mm in Weather Year 2 (WY2) to 708 mm in WY3 (Table 6.2). The greatest loss of precipitation was via evapotranspiration (ET) which was predicted to range from 278 mm to 515 mm. When viewed as a percentage of precipitation (presented in brackets in Table 6.2), the ET was predicted to be highest in WY1 decreasing to WY3 and then increasing over WY4. Interception (I) was also lowest as a percentage of rainfall in WY3, showing the effect on vegetation predicted by WAVES after the below average rainfall experienced in WY2. Overall, the percentage of precipitation predicted to be returned to the atmosphere via I and ET was 90%.

The runoff (R) was predicted to be 0 mm, which reflects the modelling simplification of evenly distributing rainfall over the duration. Drainage (D) was predicted to range from 16 mm to 90 mm over the trial period, which represents 4 – 15% of precipitation received. The change in soil moisture storage (ΔS) accounts for almost none of the precipitation received.

Table 6.2 Summary of Water Balance over Trial Period for Design Scenario

	Predicted Annual Volume (mm/yr) (% Precipitation)				
	WY1 Apr 07 – Mar 08	WY2 Apr 08 – Mar 09	WY3 Apr 09 – Mar 10	WY4 Apr 10 – Mar 11	TOTAL
P	473	361	579	708	2121
I	62 (13%)	67 (18%)	82 (14%)	103 (14%)	313 (15%)
ET	381 (81%)	278 (77%)	408 (70%)	515 (73%)	1582 (75%)
R	0	0	0	0	0
D	35 (7%)	16 (4%)	88 (15%)	90 (13%)	230 (15%)
ΔS	-3 (-1%)	0 (0%)	1 (0%)	0 (0%)	-2 (0%)

6.2.2 Comparison with Field Measurements

The losses in the water balance measured in the field trials were runoff, drainage and soil moisture content. The drainage and soil moisture content are useful parameters for comparison with the modelling data due to their reliability and sensitivity. Comparison of the Design modelling with the field data shows disparity in the predicted and measured data. The Design modelling predicts drainage would occur every year, while drainage was measured from the phytocap in WY3 and WY4 only. The drainage is predicted to commence in March/April and continue into spring, with occasional, short events in summer (Figure 6.2). In comparison, the field data recorded 2 drainage events which commenced later in the year (August/September), continued for a shorter time (≤ 3 months) and were less intense at < 0.5 mm/day.

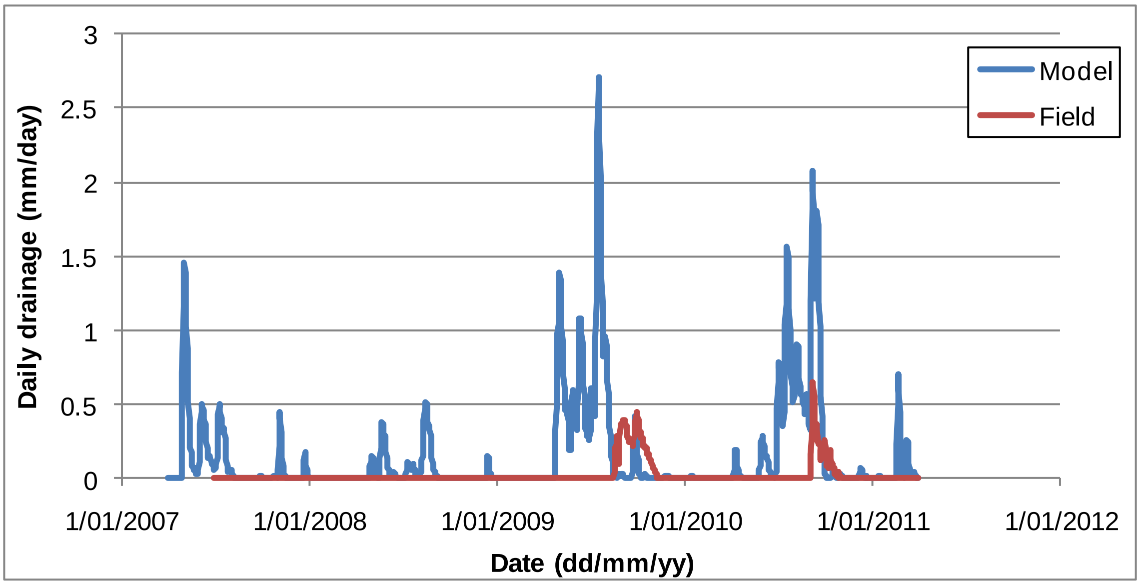

Figure 6.2 Daily Drainage from Field Measurements and Design Modelling Predictions

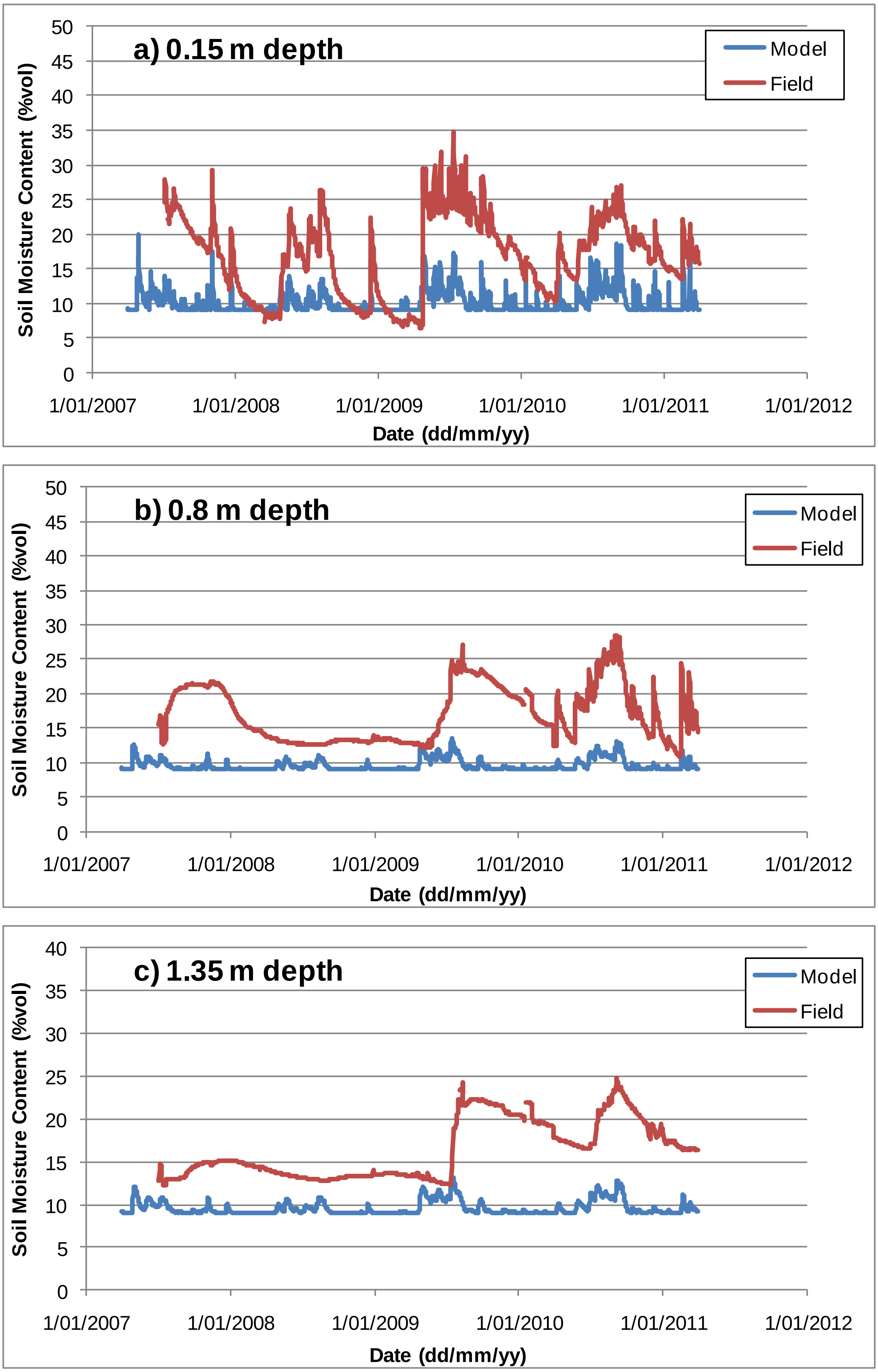

Figure 6.3 Soil Moisture Content from Field Measurements and Design Modelling Predictions at 3 Depths

The disparity between the modelled and field measured drainage is caused by poor prediction of moisture movement through the profile. Comparison of the soil moisture content predicted by the model with the average moisture measured at three depths within the profile (0.15 m, 0.8 m and 1.35 m) shows the model overestimates the unsaturated hydraulic conductivity resulting in moisture moving rapidly through the profile before the soil has become moist (Figure 6.3).

Overall, the Design modelling was a poor predictor of the movement of moisture through the profile. Though the Design model predicted better plant growth, as indicated by the LAI, the drainage was higher and the soil moisture moved rapidly through the profile as unsaturated flow.

6.3 Construction Modelling

The "Construction" modelling scenario reflects the level of knowledge after construction of the test sections and after the literature review was substantively completed. Comparison of the soil hydraulic inputs for the Design and Construction scenarios (Table 6.1) shows only minor changes in the saturated hydraulic conductivity and wet and dry moisture contents. The main change in the soil input parameters for this scenario was from better understanding of the shaping parameter 'C' in the Broadbridge-White hydraulic model. White and Broadbridge (1988) reported on the application of their hydraulic model and found that C tended to be between 1 and 2, with recompacted cores and poorly structured materials with a sharp wetting front tending towards 1, while well-structured clay soil with a longer wetting front tended to be closer to 2. The Design model used a 'C' parameter of 10 in order to lessen the steepness of the soil water retention curve without understanding that such a high value would result in a long wetting front not typical of sandy soil as used in the Southern Waste Depot trial.

The plant parameters were also varied for the Construction scenario. Following the literature, more realistic estimates of leaf area indices (LAIs) for grasses tended to be 1 – 2 as compared to the design scenario where LAIs were predicted to be 2 – 4. To achieve the lower LAI, the maximum carbon assimilation rate of the grasses was halved and the temperature range for growth of the C3 grasses was lowered. These changes were based on generic data provided by Dawes *et al.* (1998) who defined "low", "medium" and "high" values for vegetation inputs for a number of species, including C3 and C4 grasses. Effectively the "high" values chosen in the design scenario were replaced with "low" or "medium" values. The best combination of values to achieve the LAIs was determined heuristically.

6.3.1 Water Balance

The water balance predicted varied over the trial period with annual precipitation (P) ranging from 361 mm in weather year 2 (WY2) to 708 mm in WY3 (Table 6.3). The greatest loss of precipitation was via evapotranspiration (ET) which was predicted to range from 309 mm to 617 mm. When viewed as a percentage of precipitation (presented in brackets in Table 6.3), the ET was predicted to be highest in WY1 and then remain steady over the following years, accounting for 87% of precipitation received. The volume of rainfall intercepted increased over the trial period but when viewed as a percentage of precipitation received accounted for 10 – 11% in most years. Interception (I) was also lowest as a percentage of rainfall in WY3, showing the effect on vegetation predicted by WAVES after the below average rainfall experienced in WY2. Overall, the percentage of precipitation predicted to be returned to the atmosphere via I and ET was 97 – 100%, which is greater than the design scenario, which averaged 90%.

Table 6.3 Summary of Water Balance over Trial Period for Construction Scenario

	Predicted Annual Volume (mm/yr) (% Precipitation)				
	WY1 Apr 07 – Mar 08	WY2 Apr 08 – Mar 09	WY3 Apr 09 – Mar 10	WY4 Apr 10 – Mar 11	TOTAL
P	473	361	579	708	2121
I	49 (10%)	52 (15%)	64 (11%)	73 (10%)	239 (11%)
ET	432 (91%)	309 (86%)	495 (86%)	617 (87%)	1853 (87%)
R	0	0	0	5 (1%)	5 (0%)
D	0	0	7 (1%)	10 (1%)	17 (1%)
ΔS	-6 (-1%)	0	11 (2%)	3 (0%)	8 (0%)

The runoff (R) was predicted to be 0 mm with the exception of WY4 when 5 mm was predicted to occur on 14 July 2010 in response to 22 mm rainfall. Drainage (D) was predicted to range from 0 mm to 10 mm over the trial period, which represents ≤ 1% of precipitation received. The change in soil moisture storage (ΔS) was greatest in WY3 when irrigation was applied and also following a very dry year where the growth of C4 grasses was relatively low, as indicated by the LAI remaining below 1.5 (Figure 6.1).

The water balance predicted for the Construction scenario was markedly different from the Design scenario, though the input parameters appeared to be similar. The Construction scenario predicted lower interception and drainage and higher ET and runoff than the Design scenario. This suggests that WAVES is sensitive to the sharpness of the soil moisture wetting front and the rate and seasonality of plant growth.

6.3.2 Comparison with Field Measurements

Comparison of the field collected drainage and soil moisture content with the Construction modelled data shows disparity in the predicted against the measured data. Drainage was measured in the field in WY3 and WY4, totalling 20 mm/yr and 11 mm/yr respectively (Table 5.2). The Construction modelling predicted drainage only occurred in WY3 and WY4 but under predicted the volume drainage in WY3 at 7 mm, while in WY4 modelling predicted similar drainage to that measured with 10 mm predicted.

Though the total volumes of drainage measured and predicted were within an order of magnitude, the timing of the drainage is markedly different (Figure 6.4). In the field, drainage commenced in WY3 in August and in WY4 in September and ceased in November in both years and the maximum flow rate was 0.5 mm/day. In comparison, the Construction modelling scenario predicted drainage commenced in September of WY3 and continued through to the end of WY4. The maximum drainage was predicted to be over 2 mm/day while on the majority of days after drainage commenced the modelled drainage was < 0.1 mm/day. The lack of parity in magnitude and timing of drainage suggests that the similar prediction of total drainage in WY4 was not due to the accuracy of the model.

Comparison of the soil moisture content predicted by the model with the average moisture measured at three depths within the profile (0.15 m, 0.8 m and 1.35 m) shows good correlation between the timing of moisture peaks at all three depths (Figure 6.5). In the topsoil, the model tended to overestimate the wet end moisture content of the soil and predicted more rapid reduction in moisture

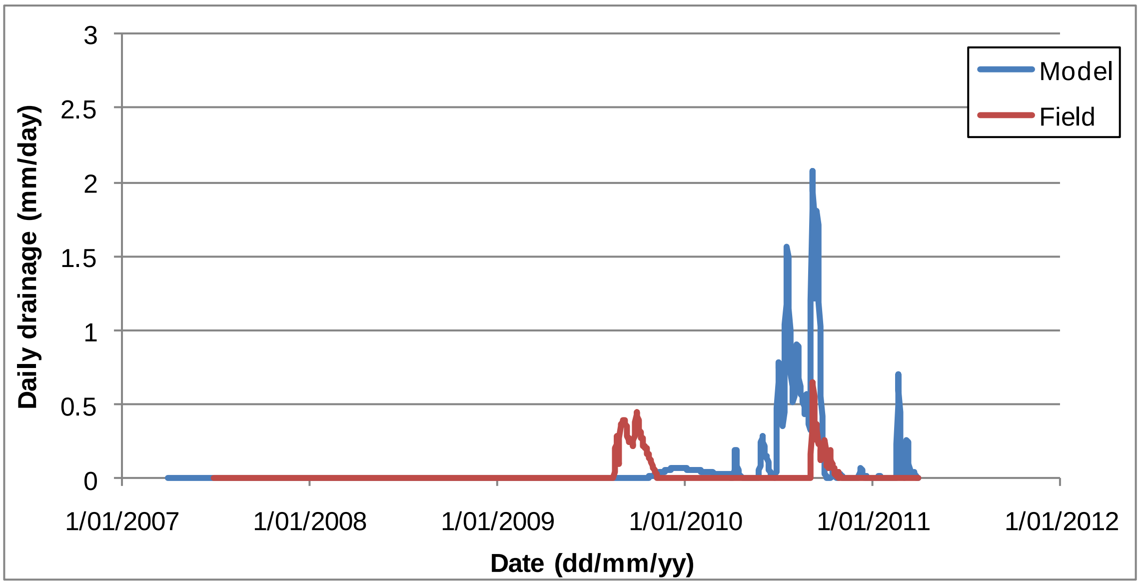

Figure 6.4 Daily Drainage from Field Measurements and Construction Modelling Predictions

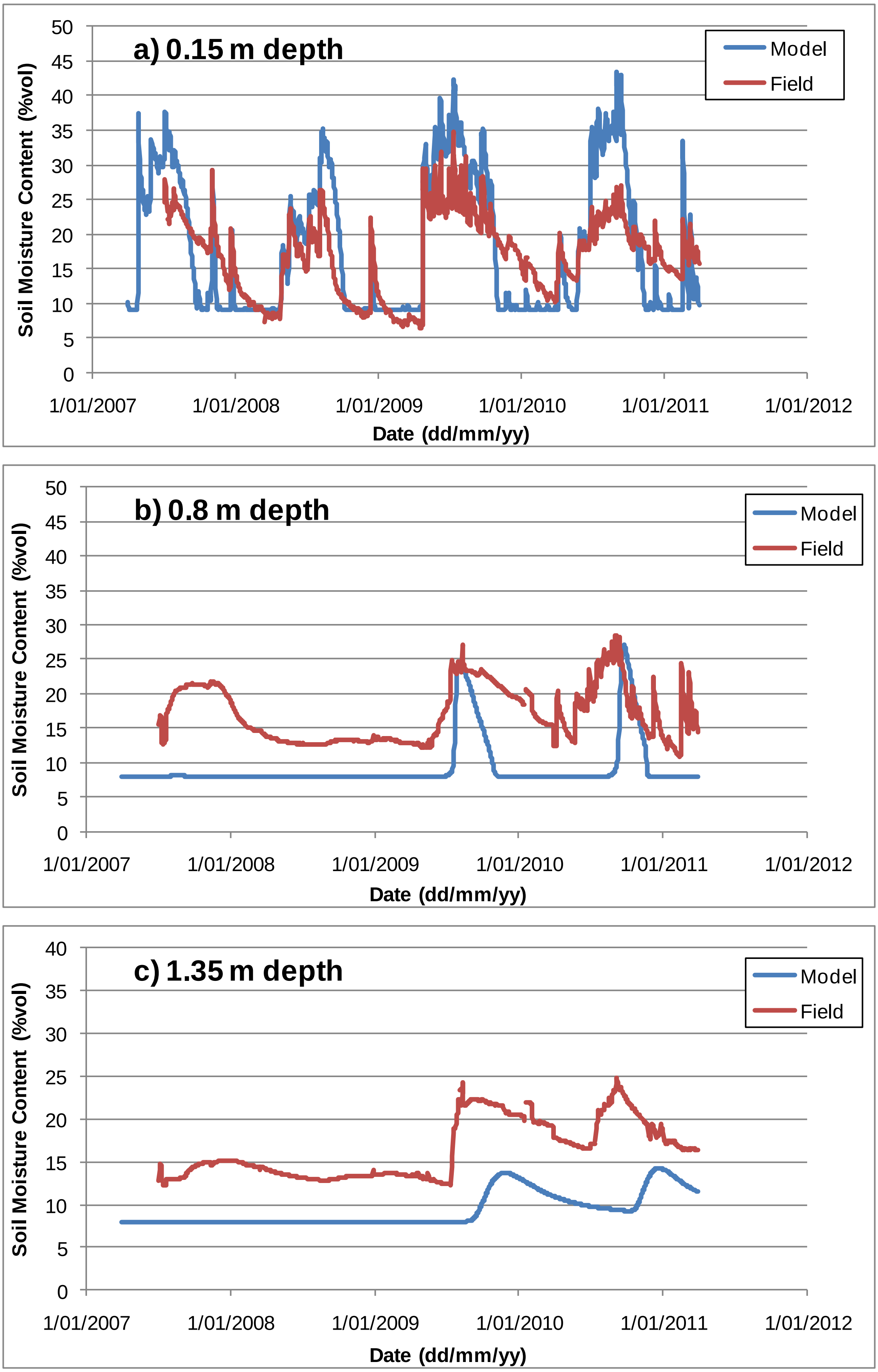

Figure 6.5 Soil Moisture Content from Field Measurements and Construction Modelling Predictions at 3 Depths

content than measured. This may be explained by vegetation establishment in WY1 and vegetation re-establishment after herbicide damage in WY3 and WY4. In WY2, the rate of moisture reduction is similar between the measured and predicted values.

The moisture content predictions at 0.8 m depth were similar in maximum moisture content but the moisture content reduced more rapidly in the modelled scenario than the field, which would be due to the recovering vegetation. The model also predicted a drier profile than was measured in the field.

Toward the base of the profile, the minor differences between the measured and predicted values in the overlying layers became magnified. The greater moisture retention predicted in the topsoil leads to reduced moisture movement and hence delayed and reduced increases in moisture in the deeper profile. Correlating the increase in moisture content with the drainage also shows that the modelling predicted drainage commenced almost as soon as the moisture content of the deep profile increased, while in the field, drainage was measured once a sustained moisture increase occurred but ceased once the moisture content decreased but the soil was still moist.

Overall, the Construction modelling was a better predictor of the movement of moisture through the profile than the Design modelling and showed similar moisture trends over time, and could predict the years in which drainage was likely to occur. However, the model does not accommodate external influences on vegetative growth, such as herbicide damage, which affected the ability to more accurately predict the field measured values. Also, the model was still unable to accurately reflect the timing, flow rate and volume of drainage as measured in the field.

6.4 Calibration Modelling

The Calibration scenario involved refining the vegetation parameters and soil parameters to account for field observations and measurement. Only minor changes were required from the estimates used in Construction modelling to fit the field validation. Altering the plant growth properties was required to provide better estimation of the field measured values. As individual plant growth parameters were not measured to provide input data for C3 and C4 grasses and based on a higher proportion of C3 grasses planted and established on site, the vegetation inputs were simplified to one vegetative layer. The optimal temperatures for growth, specific leaf area and leaf mortality were varied from Construction modelling.

The modelling for Calibration was also undertaken after more experience in using the WAVES model. At Design, modelling was undertaken quickly and with limited assessment of the output as profile depths were required for the impending construction. Subsequent modelling was undertaken with greater levels of knowledge and with increasing experience in using the model and selecting and modifying the input, particularly plants. WAVES assumes that permanent vegetation is established from commencement of modelling, as it was developed for catchment modelling where the vegetation is mature. By changing the initial soil and plant conditions it was possible to delay plant growth and force the model to "grow" the plants from mid-2007, as shown in Figure 6.1. This appeared to result in a better prediction of moisture content during mid-2007.

6.4.1 Water Balance

The water balance predicted varied over the trial period with annual precipitation (P) ranging from 361 mm in Weather Year 2 (WY2) to 708 mm in WY3 (Table 6.4). The greatest loss of precipitation was via evapotranspiration (ET) which was predicted to range from 345 mm to 616 mm. When viewed as a percentage of precipitation (presented in brackets in Table 6.4), the ET was predicted to be highest in WY2 and then remain steady over the following years, accounting for 88% of precipitation received. The volume of rainfall intercepted increased from WY1 to WY2 as the plants established and then remained relatively constant at around 6 – 7% of precipitation received. Overall, the percentage of precipitation predicted to be returned to the atmosphere via I and ET was 89 – 103%, which is similar to the Construction scenario, with the exception of WY1.

Table 6.4 Summary of Water Balance over Trial Period for Calibration Scenario

	Predicted Annual Volume (mm/yr) (% Precipitation)				
	WY1 **Apr 07 – Mar 08**	**WY2** **Apr 08 – Mar 09**	**WY3** **Apr 09 – Mar 10**	**WY4** **Apr 10 – Mar 11**	**TOTAL**
P	473	361	579	708	2121
I	7 (1%)	24 (7%)	38 (7%)	48 (7%)	117 (6%)
ET	416 (88%)	345 (96%)	495 (86%)	616 (87%)	1872 (88%)
R	0	0	0	7 (1%)	0
D	57 (12%)	0 (0%)	39 (7%)	31 (4%)	129 (6%)
ΔS	-6 (-1%)	-9 (-2%)	6 (1%)	5 (1%)	-3 (0%)

The runoff (R) was predicted to be 0 mm with the exception of WY4 when 7 mm was predicted to occur on 14 July 2010 in response to 22 mm rainfall. Drainage (D) was predicted to range from 0 mm to 57 mm over the trial period, which represents ≤ 12% of precipitation received and averaged 6%. The change in soil moisture storage (ΔS) was greatest in WY3 and WY4 after the wet winter, which in WY3 was partly created by irrigation. The growth pattern and water balance do not show a large response to the dry WY2, which may be a reflection of the growth cycle of the plants and the incidence of rainfall, i.e. though most months in WY2 were below average, in August, i.e. the month when the plants are starting to transpire and grow after the cold winter, the rainfall received was above average (see Figure 5.1).

The water balance predicted for the Calibration scenario was different from the Construction scenario, though the soil input parameters, with the exception of hydraulic conductivity were similar. The Calibration scenario predicted lower interception, similar ET and runoff but higher drainage and a drying soil profile compared with the Construction scenario. This shows that WAVES is sensitive to the plant growth parameters, as would be expected.

6.4.2 Comparison with Field Measurements

Comparison of the field collected drainage with the Calibration modelled data shows some similarities between the measured and predicted drainage in WY3 and WY4 (Figure 6.6). However, the model predicted drainage occurred in WY1 which was not recorded in the field. This discrepancy may be an artefact of the lysimeter construction. The subgrade and drainage net (including the geofabric surrounds) at the base of the lysimeter were placed dry and hence would need to become moist or saturated before drainage could be expected to occur.

Drainage was measured in the field in WY3 and WY4, totalling 20 mm and 11 mm respectively (Table 5.2) while the model predicted 39 mm and 31 mm, respectively (Table 6.4). Though the model overestimated cumulative drainage, the magnitude of the daily drainage events was similar to the measured drainage (Figure 6.6).

The ability of the model to predict the commencement of drainage was variable. In both the measured and modelled data, drainage increased rapidly after commencing. In WY3, drainage commenced in mid August for both the measured and modelled data. In WY4 drainage was predicted to commence 6 weeks later than measured. Though the model predicted drainage relatively accurately in WY3, this is the year that the vegetation growth was checked by herbicide application and hence accuracy in prediction in this year may not be reflective of the longer term conditions.

One of the largest discrepancies between the measured and modelled data is the cessation of drainage. In WY3 and WY4, drainage ceased in November, while the model predicted drainage continued from 2009 through to 2011 with small volumes predicted through late summer to early winter. For the measured data, drainage reduces linearly until it ceased while in the modelling drainage reduced at a decreasing rate from the maximum.

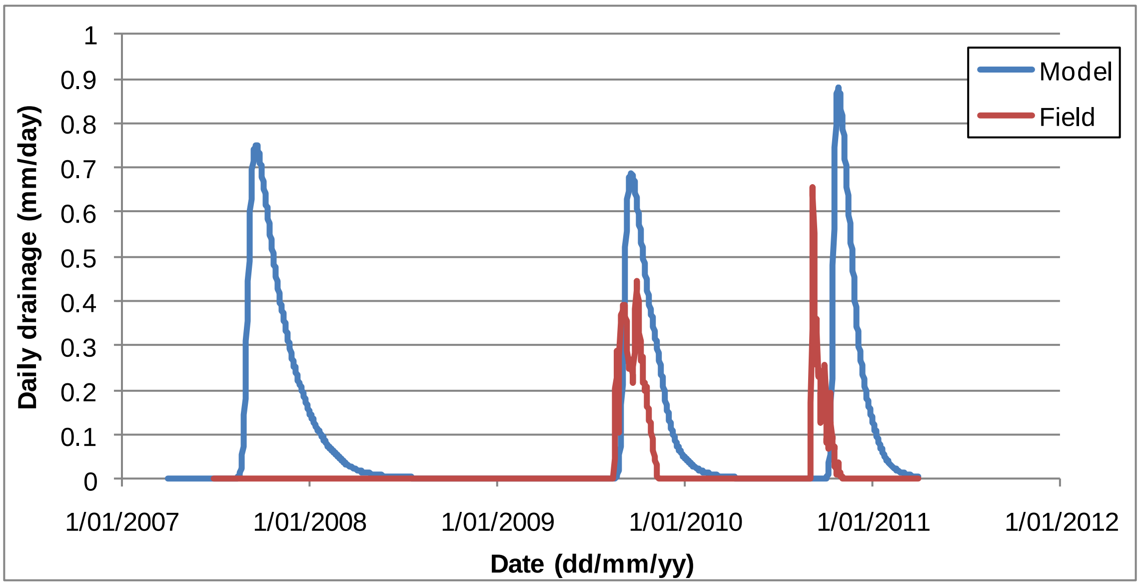

Figure 6.6 Daily Drainage from Field Measurement and Calibration Modelling Predictions

Linear reduction and exponential reduction in drainage are possible depending on the interface at the base of the profile. Where there is a capillary break, drainage can be expected to cease suddenly once the moisture content of the material reaches field capacity. A capillary break in the lysimeter is formed between the basal layer and the drainage net but has been assumed to represent the landfill environment where a capillary break may form between the soil cap and the waste mass. Where there is no impediment to continued moisture movement the rate drainage reduces is likely to be exponential due to unsaturated flow. The boundary conditions allowed in the WAVES model are either “drainage” or “ground water” as capillary breaks are rare in nature and WAVES was developed for catchment modelling not landfills. No method was found to force the WAVES model to predict a linear reduction in drainage as changing the permeability factor of the boundary or adding an artificial thin coarse layer both still resulted in exponential reduction in drainage.

The moisture content measured in the field and that predicted by the Calibration model show difficulty in accurately reflecting the moisture movement through the soil (Figure 6.7). In WY1, the topsoil (0.15 m) moisture was predicted to decrease more rapidly than measured but peaks were similar. In WY2, the topsoil moisture content was relatively accurately modelled. Through WY3 and WY4, the peaks in moisture were accurately modelled but the soil dried more rapidly than measured. It is likely that this is related to the model still predicting vegetative growth during this period though this was not the case in the field.

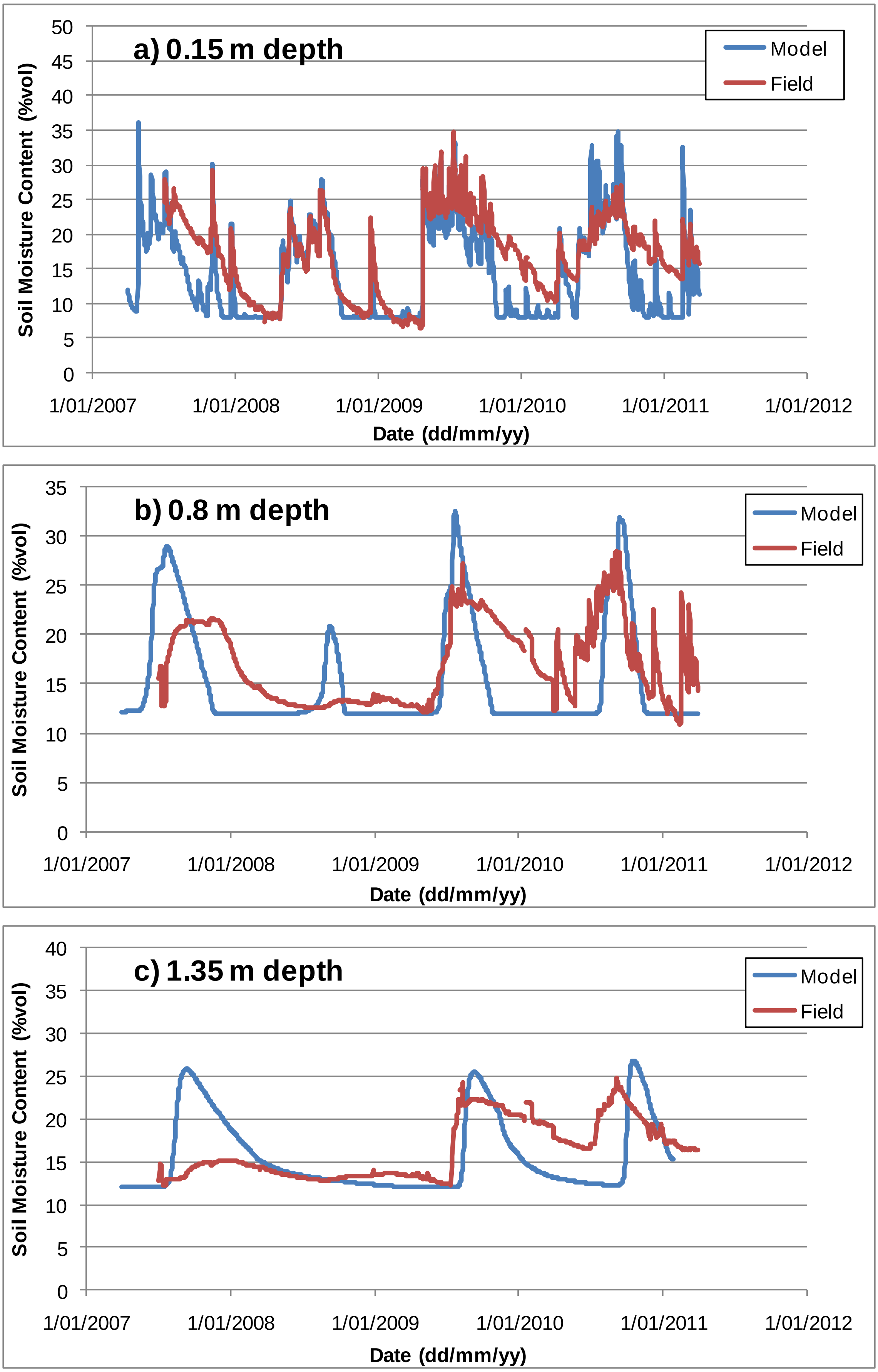

Figure 6.7 Soil Moisture Content from Field Measurements and Calibration Modelling Predictions at 3 Depths

In the middle of the profile (0.8 m depth), the model predicted moisture moved through the profile in all years; however, moisture was only measured at this depth in WY1, WY3 and WY4 (Figure 6.7). The moisture measured in WY3 and WY4 is likely to be caused by the die back of plants which resulted in a wetter profile at all depths. The reduced plant growth conditions in WY3 also affected the deeper soil. The model is able to predict the moisture increase in WY3 but is delayed in the prediction in WY4, which would partly as a result of the model predicting the plants would remove moisture from the subsoil over summer.

Overall, the Calibration modelling was the best predictor of the occurrence of drainage and moisture movement but was still not highly accurate. The WAVES model assumes that the permanent vegetation is established, which was not the case in WY1, and that plant growth is affected by weather and soil conditions only, which was not the case in WY3 after plants were damaged by herbicide application. In combination with the dry conditions experienced in WY2, which resulted in moisture movement only detected by the upper moisture sensor, these factors have led to difficulties in calibrating the model and also results in uncertainty as to the long-term accuracy of a model which does correlate to these field conditions.

6.5 Conclusions

The modelling undertaken for the Design scenario was poor due to lack of soil physical properties and poor understanding of the model. The measured properties from the Construction modelling were not greatly different from the Design properties; however, the main difference between the inputs were the macroscopic capillary length (λ_c) and the shaping factor (C). The different parameters in the Construction modelling were chosen based on further information gained from literature reviews on the use of the WAVES model and possibly modeller experience.

The accuracy of the modelling for the Construction and Calibration scenarios was improved by measured soil hydraulic properties. However, the modelling was still inaccurate due to the impact of influences not included in the model, such as the plant establishment phase and herbicide damage. A longer monitoring phase would be required to overcome these limitations.

The accuracy of the drainage predictions was also affected by a difference in the rate of drainage predicted in the field compared to the WAVES model. As discussed in Section 6.4.2, the field data showed that drainage reduced linearly from the daily maximum to cessation; however, the modelling predicted an exponential reduction. Where there is a capillary break between the cap and the waste, this may lead to drainage being overestimated by the model, which for design purposes can be used to increase the safety factor. However, for a waste mass that contains a large proportion of soil or is highly compacted, this break may not be present and hence the modelling may be more accurate.

The greatest value of the WAVES model is the explicit modelling of plant growth. Most water balance models, particularly those used for landfill design, do not include this feature and assume plant growth is insensitive to weather and soil conditions. This does create difficulties in modelling accuracy as the information available to characterise the vegetation is limited and the modelling performance is highly sensitive to vegetative performance.

The overall performance of the WAVES model in predicting the water balance through a landfill cover is unclear from the data analysed. The impact of influences external to the modelling inputs and the field data limitations, particularly the lack of plant growth data and additional depths for measuring moisture content, makes it difficult to assess for this case. Further work is required to assess the WAVES model, but it is likely that it could be a useful tool in designing phytocaps in Australia’s variable climatic conditions due to the explicit plant growth modelling.

7. Soil Hydraulic Changes at the Laboratory and Small Plot Scale

Changes in soil properties for the compacted clay covers have been documented by many authors (see Section 2.4). However, less emphasis has been placed on measuring the changes which may occur in the phytocap over time. Literature in the soil science field suggests that these changes can and do occur in all soil. Soil hydraulic changes over time are likely to occur in the constructed covers due to changes in:

- bulk density, which can be caused by settlement from self-weight and rainfall;
- pore size distribution which can result in larger pores formed by plant root growth and meso-fauna channels (e.g. from worms, ants, termites and insect larvae, etc.);
- particle aggregation and disaggregation which can occur after wetting and drying cycles.

These changes can act together to increase or decrease bulk density, moisture retention and/or hydraulic conductivity. They can also counteract each other to result in little or no change. The relative magnitude of each influence will be important in determining whether the soil hydraulic properties, which are important in the water balance, are affected. Laboratory and small plot trials were undertaken to assess the direction of change which may occur in the hydraulic conductivity due to settlement and plant growth.

7.1 Trial Aims

The aim of the trials was to measure any change in saturated hydraulic conductivity which may occur from repeated wetting and drying of the soil materials used at the Adelaide trial site. Changes in these parameters can suggest the development of soil structure and repeated wetting and drying cycles were used to represent the natural cycles that occur in the soil. The laboratory trials were used to investigate the influence of wetting and drying cycles on selected soil physical properties. The small plot trials were used to include the influence that plant roots (and possibly soil fauna) may have on the properties which control water flow in the profile.

7.2 Methodology

The three soil materials used in the Adelaide trial site were selected for further testing due to their availability, differing properties and lack of shrink-swell potential (see Table 4.1 for further details).

These materials have been referred to as the topsoil, subsoil and clay and were used in the field trial to produce a phytocap (0.3 m topsoil over 1.2 m subsoil) and a conventional cap (0.1 m topsoil over 0.8 m subsoil over 0.9 m clay).

7.2.1 Laboratory Trials

A flexible membrane (as used in triaxial testing) was inserted into a compaction mould B (i.e. metal cylinder of approximately 100 mm internal diameter and 115 mm height) and stretched over the ends of the mould. Soil was compacted inside the mould in three layers to the required density, with the surface of each layer roughened prior to placement of the next layer to prevent lamination. In the case of the topsoil and subsoil the required density was 85% maximum dry density and for the clay was to > 95% maximum dry density at equivalent moisture content, measured as described by Standards Australia (2003b). After the soil was partially wet, saturated hydraulic conductivity was measured as described by Standards Australia (2001b). The soil core and permeability apparatus are shown in Figure 7.1.

After steady-state infiltration was measured, the core was disconnected from the water supply. The top plate was removed and the soil, mould and base plate were weighed to calculate saturated moisture content. The specimen, including the base plate, was then placed in the oven at 30 – 40 °C for > 2 weeks. The sample was then reweighed (as shown in Figure 7.1, left) before wetting up and retesting the saturated hydraulic conductivity. This was repeated 3 – 4 four times on 3 replicates of each soil type.

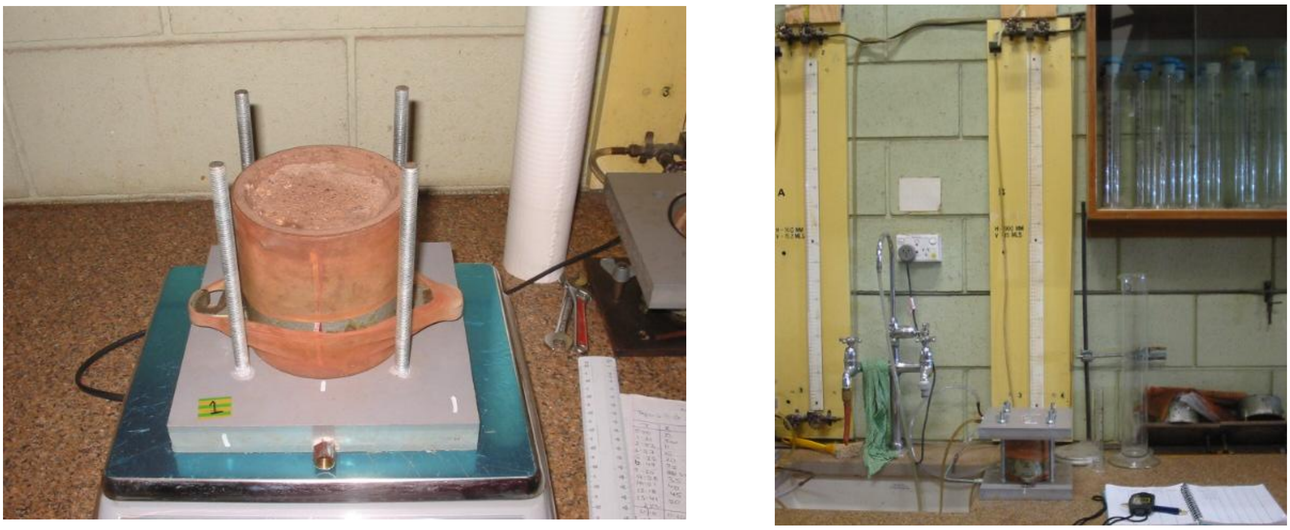

Figure 7.1 Laboratory Trial Recompacted Soil Core and Permeability Apparatus

7.2.2 Small Plot Trial

In January 2008, 8 large wooden boxes, 1 m^2 x 1.5 m deep, were used to create 4 small plot replicates each of the phytocover and conventional cover used in the Adelaide trial site (Figure 7.2). The base of the boxes was shaped with sand to drain towards a drainage hole and then the base and sides were lined with building plastic (including piercing the plastic at the drainage hole). Compaction of the clay barrier was achieved using a vibratory compactor and ramming using a crowbar or similar to compact moisture conditioned clay to the highest density possible. The barrier was constructed in 4 – 5 lifts rather than the usual 3 lifts to ensure compaction throughout the lift. The subsoil and topsoil layers were placed by a front-end loader and raked as required. Native grasses (as used in the field trial) were planted in the in the boxes in May 2008 and drip irrigation installed.

Figure 7.2 Construction of Small Plot Trial Boxes (top left) with Clay Compacted using a Vibratory Pad (top right) then Subsoil and Topsoil Tipped into Boxes (bottom left) followed by Planting (bottom right)

Figure 7.3 CSIRO Disc Permeameter (left) and Removing Undisturbed Core (right) from Box Trial

Irrigation was applied initially to establish the native grasses. To simulate more rapid wetting and drying cycles, irrigation was applied to all boxes approximately monthly from December 2008 to May 2009 until drainage was observed. This usually required approximately 3 days of irrigation. Irrigation ceased from May 2009 and boxes were exposed to natural rainfall events from May 2009 to April 2012.

Testing of one replicate of each cap type occurred on three occasions:

- December 2008, 11 months after construction and while plants would be actively growing at the beginning of summer;
- May 2009, 16 month after construction, after 6 artificial wetting cycles and just prior to winter;

A CSIRO disk permeameter was used to measure field-saturated hydraulic conductivity and undisturbed cores were taken for calculation of dry density of the topsoil, subsoil and clay in one replicate of each cover (Figure 7.3). Large core samples were also taken from the same depth as disk permeameter measurement. These cores were intended to be analysed for saturated hydraulic conductivity in the laboratory using a large flexible membrane permeameter; however, on-going issues with maintaining pressure and isolating the soil cores from the confining water in the apparatus prevented these cores from being tested.

For each replicate, the field saturated volumetric moisture content, dry bulk density, sorptivity and saturated hydraulic conductivity were measured or calculated at three depths in the phytocap and conventional cap at the topsoil surface, within the subsoil and in the compacted clay barrier.

7.3 Results

7.3.1 Laboratory Results

The three topsoil replicate samples were compacted to an initial dry density of 1.41 – 1.48 t/m^3 and the initial saturated hydraulic conductivity was measured as 6 × 10^{-7} to 1.5 × 10^{-6} m/s. Changes in the saturated hydraulic conductivity were noted after the first drying cycle with the saturated hydraulic conductivity of two replicates increasing by an order of magnitude (Figure 7.4). The remaining replicate also increased by an order of magnitude but this was more gradual. By the 5th wetting cycle the saturated hydraulic conductivity of the three replicates was similar ranging from 8.5 – 9.5 × 10^{-6} m/s. This increase occurred though the soil slumped 2 – 5 mm after the first drying cycle, which resulted in an increase in bulk density to 1.48 – 1.54 t/m^3, i.e. <0.1 t/m^3, as summarised in Table 7.1.

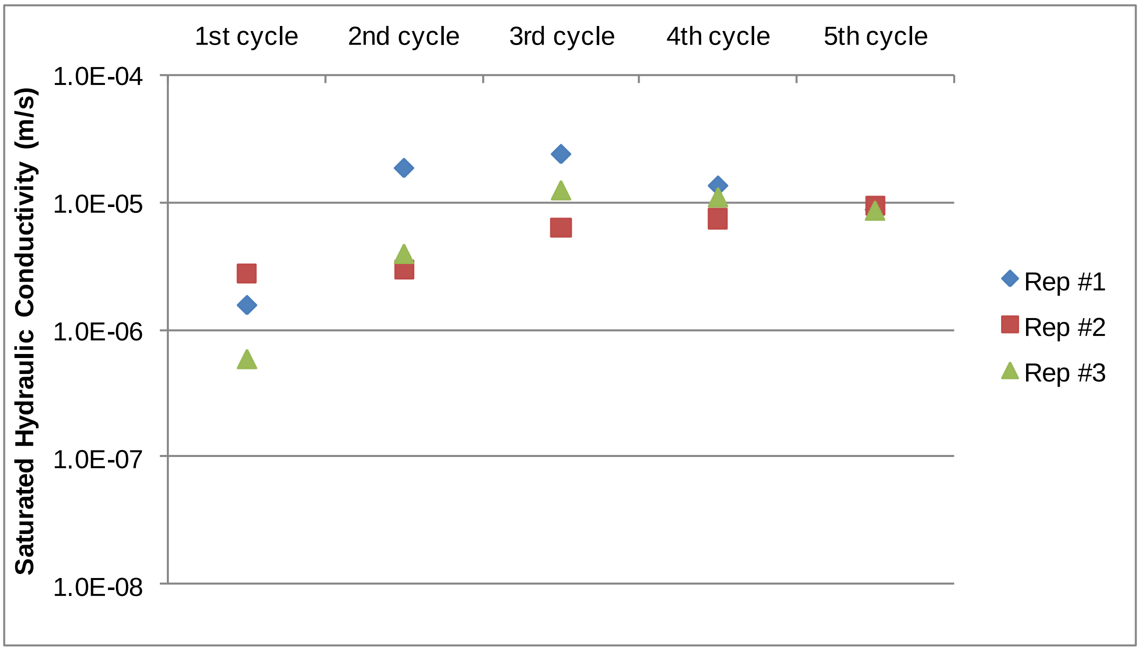

Figure 7.4 Topsoil Saturated Hydraulic Conductivity of 3 Replicate Recompacted Cores after Successive Wetting and Drying Cycles

The increasing trend in saturated hydraulic conductivity was not observed in the saturated volumetric moisture content. Overall, the average saturated moisture content remained relatively unchanged after the 5th wetting cycle (Figure 7.5), i.e. around 40% moisture. The decrease in saturated moisture content after the first drying cycle was negatively correlated with the change in dry density with a larger decrease in saturated moisture associated with a greater increase in density (Table 7.1). Unlike saturated hydraulic conductivity, the variability in the saturated moisture content was greater at the end of the experiment than at the beginning.

Table 7.1 Calculated Dry Density Before and After First Wetting and Drying Cycle

	Rep #1	Rep #2	Rep #3
Initial Dry Density (t/m^3)	1.41	1.48	1.47
Height slump after first drying cycle (mm)	5	4	2
Dry density after slumping (t/m^3)	1.48	1.54	1.50

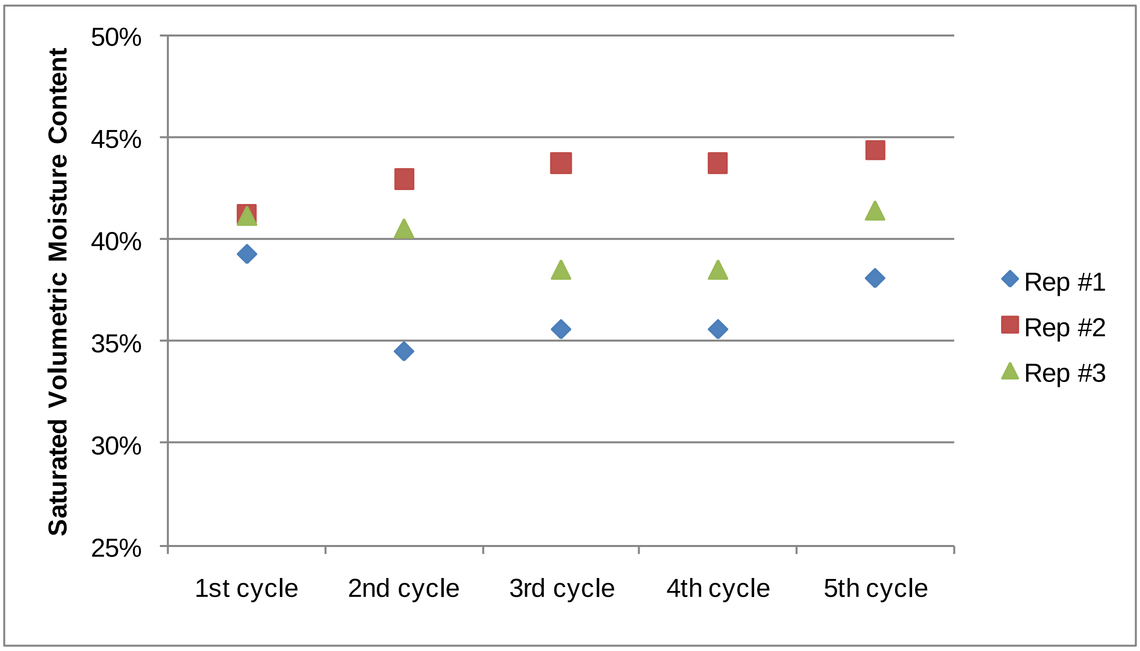

Figure 7.5 Topsoil Saturated Volumetric Moisture Content after Repeated Cycles of Wetting and Drying

The three subsoil replicate samples were subjected to 3 wetting and 2 drying cycles. The subsoil was compacted to 1.49 – 1.52 t/m^3 initially with a saturated hydraulic conductivity of 4.1×10^{-8} to 1.7×10^{-7} m/s. Over the three cycles the saturated hydraulic conductivity initially decreased slightly and then reverted to similar to initial conductivity (Figure 7.6). No slumping of the subsoil cores was observed and hence dry density would have remained similar to that calculated when the cores were prepared. The saturated moisture content tended to decrease over the cycles, though remained variable (Figure 7.7).

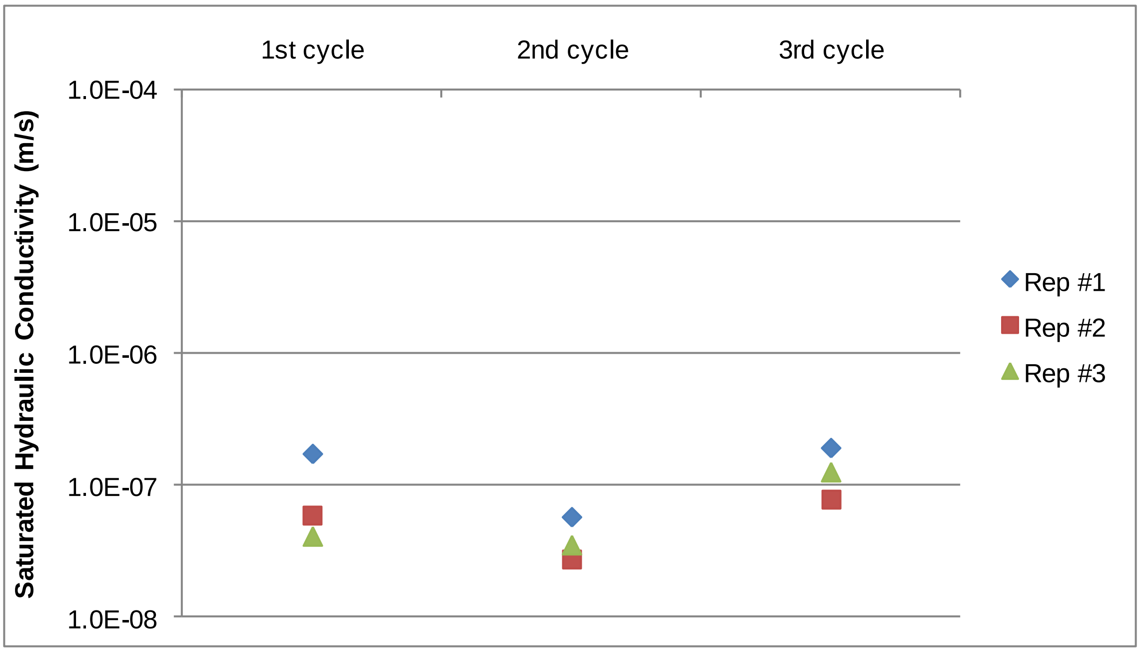

Figure 7.6 Subsoil Saturated Hydraulic Conductivity of 3 Replicate Recompacted Cores after Successive Wetting and Drying Cycles

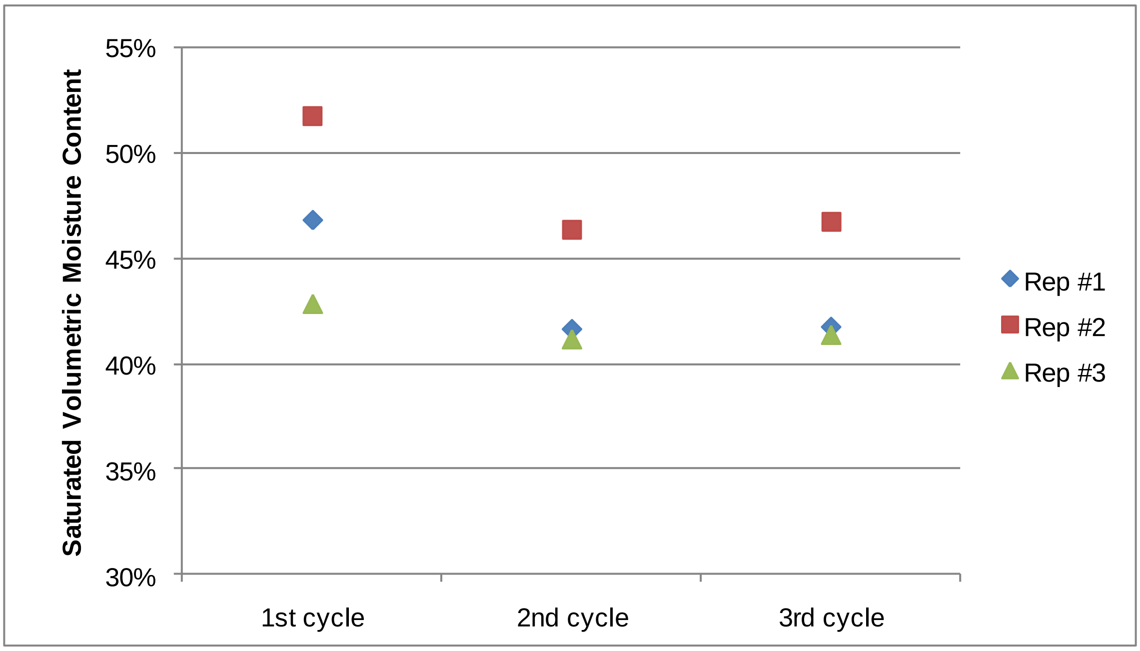

Figure 7.7 Subsoil Saturated Volumetric Moisture Content after Repeated Cycles of Wetting and Drying

The clay testing in the laboratory was abandoned due to a number of difficulties. The first run measured saturated hydraulic conductivity of 2.3×10^{-7} to 6.5×10^{-8}. After drying, the samples were placed in water to rewet. However, after weeks of saturation the samples were not wet and no drainage was recorded through the sample even when a 3 m pressure head was applied. Dissection of the cores showed fungus or mould had grown in the sample and hence, even if readings were recorded, they would not be reflective of field conditions. Further, although cracking was observed of the cores, the cores were saturated and tested under confined conditions and hence increases in volume could not occur. This constraint meant results were unlikely to be reflective of field conditions and hence further testing was abandoned.

7.3.2 Field Results

The vegetation was observed to establish in all the phytocap trial boxes and the conventional cap trial boxes, as shown in photographs taken at sampling (Figure 7.8). Observations showed that the phytocap boxes slumped by approximately 0.2 m in the first year while the conventional cap slumped < 0.1 m. Excavation of the profile showed that the main compaction occurred in the subsoil with the topsoil maintaining thickness over time, as evident in the profile photos taken in 2012 (Figure 7.8).

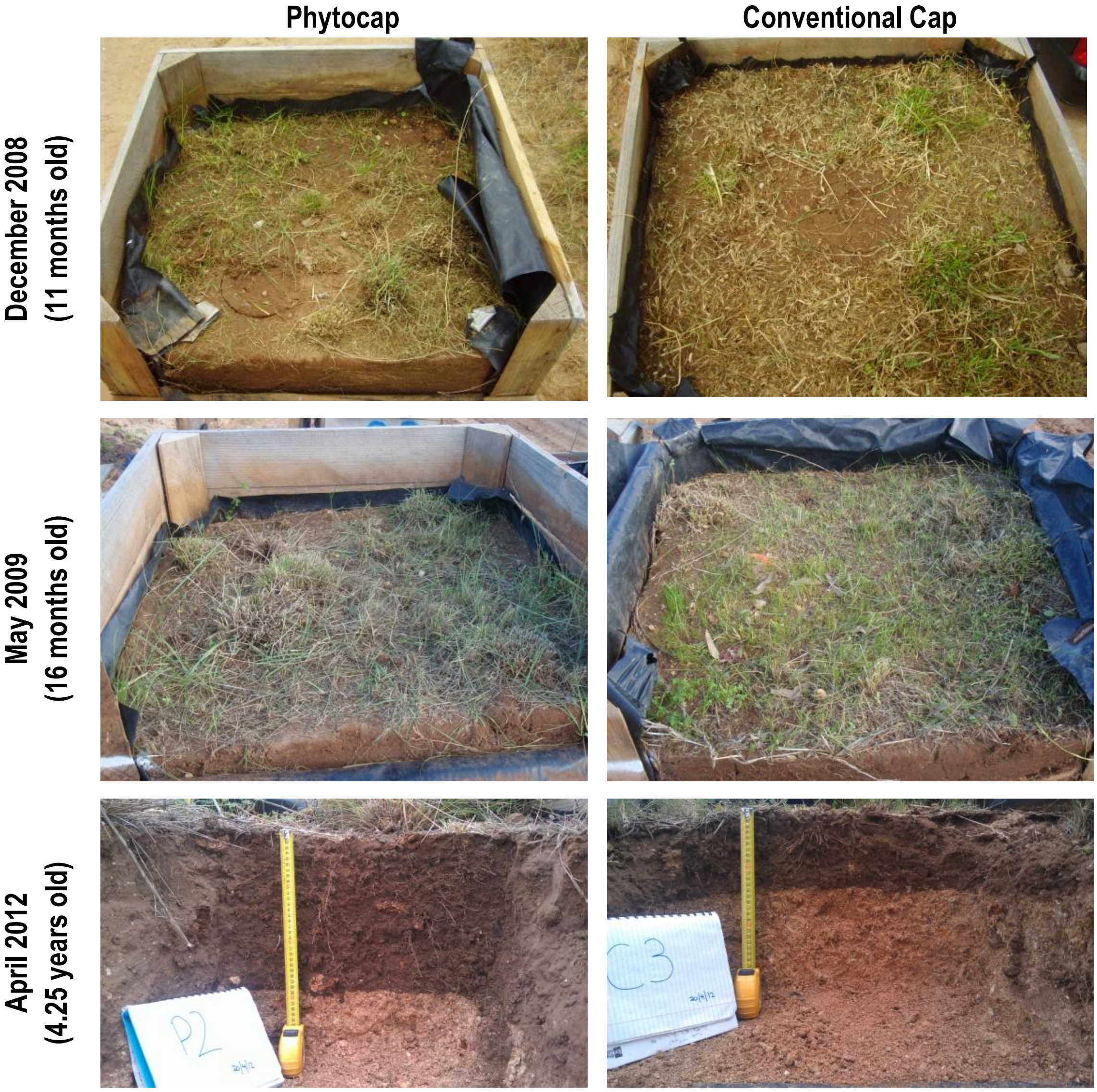

Figure 7.8 Vegetation Trimmed from Surface of Trial Boxes in December 2008 and May 2009 and Surface Profile Exposed in April 2012

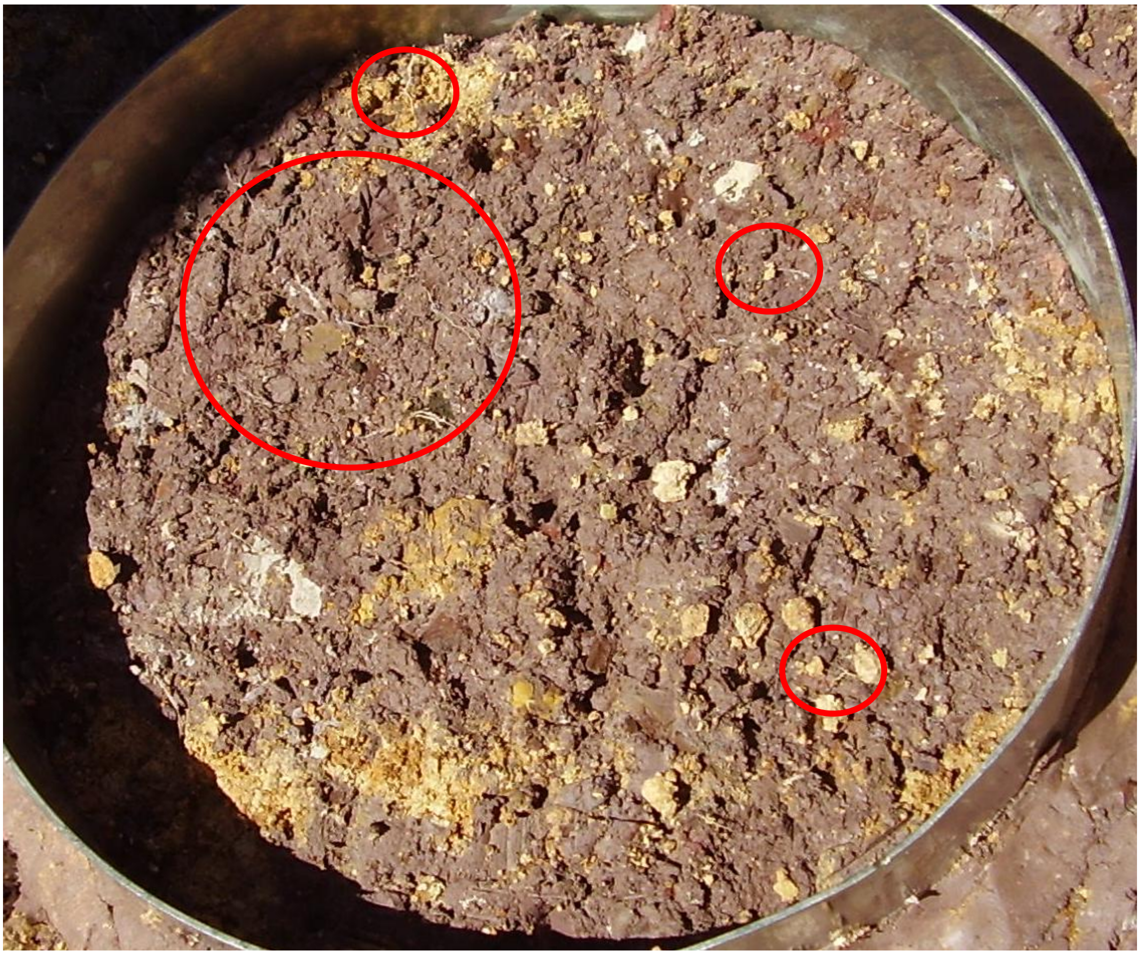

Figure 7.9 Fine Roots (circled) Growing in the Clay Barrier in December 2008

- April 2012, 4.25 years after construction and after 6 artificial wetting and drying cycles and 4 natural wetting and drying cycles.

Roots were observed to over 1 m in both the phytocap and conventional cap boxes 11 months after planting, i.e. in December 2008. Fine roots, 1 – 2 mm thick, had penetrated into the compacted clay barrier, as shown in Figure 7.9.

Disc permeameter results were calculated for all occasions. The moist state of the boxes from applied irrigation facilitated rapid attainment of steady state conditions which can result in difficulties in determining sorptivity; however, on all but one occasion, sorptivity was able to be determined.

The field saturated soil moisture content was measured after the permeability test was finished. Over time the field saturated moisture content has increased in the topsoil for both the phytocap and the conventional cap from 40% to 50 % (Figure 7.10). The field saturated moisture content of the subsoil at around 400 – 500 mm depth did not show any trend with time, remaining around 50% for both the phytocap and the conventional cap. Deeper in the subsoil of the phytocap, the field saturated moisture content increased from 11 months after construction to 16 months after construction, i.e. near the beginning of summer to the beginning of the following winter. However, at the commencement of winter 3 years later the field saturated moisture content had decreased to 45% volumetric moisture content.

The compacted clay barrier volumetric soil moisture content remained unchanged over the testing period at 53 – 56%. It should be noted that the initial moisture content of the conditioned clay is on average 32 – 35% volumetric moisture content, based on a 21% gravimetric moisture placed at a dry density of 1.57 to 1.72 t/m^3 (i.e. the bulk density measured in December to 95% density ratio). So although no changes in the field saturated moisture content were observed, the moisture content of the compacted clay had increased in the first 11 months.

The dry bulk density of the phytocap soil materials tended to increase in the topsoil and deeper subsoil but tended to decrease in the middle of the profile. Measurements of layer thickness were taken during each sampling event and showed that the topsoil thickness reduced by a few centimetres while the majority of the 0.2 m decrease in profile depth occurred in the subsoil. The dry density measured suggested further that the increase in compaction occurred lower in the profile whilst the upper subsoil experienced a decrease in density.

In the conventional cap, the dry bulk density of the topsoil exhibited a similar pattern to the phytocap. However, in the subsoil of the conventional cap the density increased rather than decreased. The subsoil measurements were taken at 500 mm depth in the conventional cap which was deeper than the phytocap. During December 2008, one measurement was taken on the upper surface of the conventional cap subsoil, i.e. 100 mm depth, which had a density of 1.3 t/m^3. The density of the compacted clay varied from 1.53 – 1.57 t/m^3 after 11 months or more of wetting and drying, which was equivalent to a density ratio of 86 – 88% and less than the target placement density of ≥ 1.7 t/m^3 (i.e. ≥ 95% maximum dry density).

The sorptivity of the soil is a measure of the rate at which the soil absorbs water via capillarity and dominates during early infiltration. The sorptivity is deducted from the steady state infiltration rate to calculate the saturated hydraulic conductivity. Sorptivity can vary in the soil depending on size and connectivity of the pores and is also an indication of the sharpness of the wetting front. For the topsoil and subsoil, no consistent trend is evident between the phytocap and conventional cap with

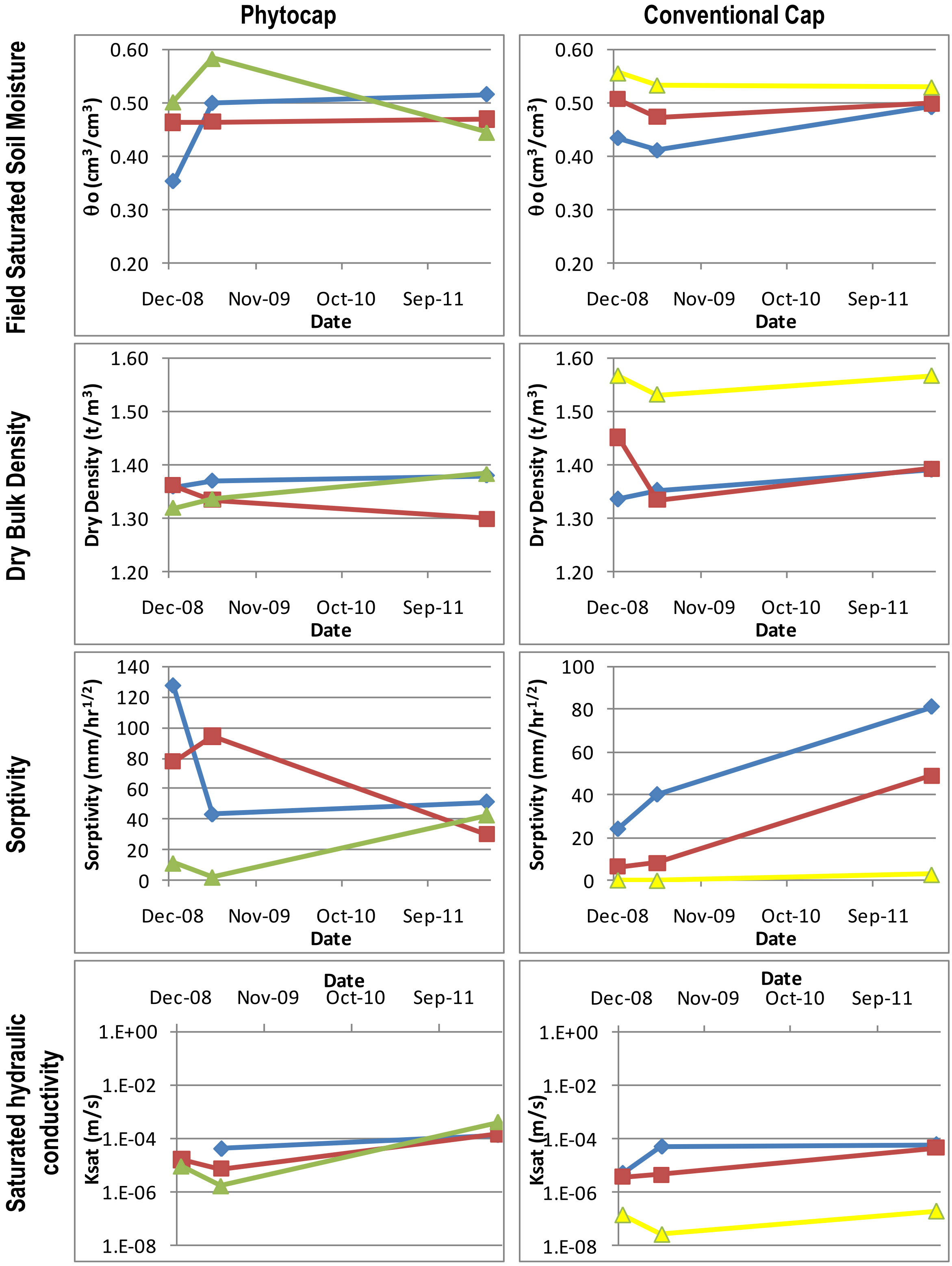

Figure 7.10 Box Trial Temporal Trends for Topsoil (◆), Subsoil at 300 – 500 mm depth (■) and Subsoil at 800 mm depth in the Phytocap (▲) or Compacted Clay at 900 mm depth in the Conventional Cap (△)

the phytocap suggesting a decrease in sorptivity and the conventional cap an increase. The sorptivity of the compacted clay barrier increased by an order of magnitude from ≤ 0.26 mm/hr½ to 2.8 mm/hr½ by 2012 but further testing would be required to determine if this is significant.

The saturated hydraulic conductivity (K_{sat}) of the topsoil and subsoil material increased by an order of magnitude from December 2008 to April 2012, resulting in a K_{sat} of approximately 1×10^{-4} m/s. The compacted clay barrier showed no trend over time and varied from 3×10^{-8} to 2×10^{-7} m/s (i.e. 0.1 – 0.7 mm/hr). However, this is 1 – 2 orders of magnitude greater than the saturated hydraulic conductivity targeted at placement of 1×10^{-9} m/s.

7.4 Discussion

The laboratory experiments were designed to replicate the field conditions but without the influence of plant growth and soil fauna. The topsoil density in the laboratory experiment was initially 1.4 – 1.5 t/m^3 but increased to over 1.5 t/m^3 after the first wetting and drying cycle. The topsoil density in the field was 1.3 – 1.4 t/m^3 but only a small change in thickness was recorded. The subsoil dry density also was higher in the laboratory tests than the field tests. Even after compaction was observed in the field, the dry density was 1.3 – 1.4 t/m^3, whilst in the laboratory experiments the material was compacted to 1.5 t/m^3. The laboratory experiments were compacted to the equivalent of 85% maximum dry density as it was assumed that this would be close to the field density. However, this has been shown to be incorrect for soil material subjected to natural compaction. Regardless of the difference in density, similar patterns were observed in the laboratory and field experiments.

Over time the saturated hydraulic conductivity of the topsoil and subsoil materials increased but was not necessarily accompanied by an increase in saturated moisture content. It was hypothesized that the wetting and drying cycles would increase the proportion of larger diameter pores which would increase saturated hydraulic conductivity and increase the saturated moisture content, presuming no change in dry density. In the laboratory experiment, the dry density of topsoil cores increased (due to slumping) which should have resulted in decreased saturated hydraulic conductivity and saturated moisture content. However, the saturated hydraulic conductivity increased and the saturated moisture content remained unchanged. This suggests that the increase in saturated hydraulic conductivity was more likely to be related to increased pore connectivity rather than increased pore diameter.

The difference in saturated hydraulic conductivity between the laboratory and field experiments was approximately an order of magnitude increase (i.e. the soil became more permeable when saturated) for both the topsoil and subsoil. In the laboratory experiments, successive wetting and drying resulted in a saturated hydraulic conductivity of 1×10^{-5} m/s and 1×10^{-7} m/s for the topsoil and subsoil respectively. In the field experiments, the saturated hydraulic conductivity measured after successive wetting and drying cycles was approximately 1 × 10^{-4} m/s for both the topsoil and subsoil. This difference between the laboratory and the field would be partly related to the difference in density noted above but could also be related to the influence of plant roots, particularly for the subsoil where the change was greater.

The compacted clay barrier showed signs that its integrity was compromised over the monitoring period. During irrigation of the conventional cap boxes, drainage was observed to commence before the phytocap boxes but then to cease, which would be indicative of cracks having formed in a dry clay layer and then as the moisture content of the clay increased, the clay swelled reducing or removing cracks through the layer. Changes in the compaction of the clay barrier are also evident from the penetration of roots through the barrier and the increase in field saturated moisture content seen in December 2008, 11 months after construction. The greatest changes in the compacted clay barrier must have occurred during the 11 months from construction to first sampling as few changes were recorded after this time.

7.5 Conclusions

The saturated hydraulic conductivity was affected by successive wetting and drying cycles with a greater increase when plants were also grown. No change in saturated moisture content was observed which suggests that the increase in saturated hydraulic conductivity was not due to an increase in pore size diameter but was more likely to be related to increased connectivity as observed by the measured increase in sorptivity of the compacted clay barrier.. Changes in the saturated hydraulic conductivity and density in the compacted clay barrier occurred within the first 11 months after construction.

One of the assumptions made as a rule of thumb is that the natural field condition of soil is equivalent to 85% of maximum dry density. However, these experiments have shown that this assumption may not hold true and that the “real” field density may be closer to 70 – 75% maximum dry density. This range of densities correlates to the findings of Michael (2010) that the optimum field density for water use of many species was around 77% of maximum dry density.

8. Summary and Conclusions

8.1 Summary

The Australian Alternative Cover Assessment Program aimed to determine whether phytocaps can meet performance criteria for landfills more cost effectively and sustainably than conventional covers. The sustainability of the covers has been partially assessed by monitoring the water balance parameters (excluding evapotranspiration) of phytocaps and conventional caps at trial sites in 5 states for 3 – 4 years. The aims of this PhD were to quantify drainage, compare the phytocaps and conventional caps and determine if changes in the water balance parameters are related to changes in soil properties over time.

8.1.1 Drainage

The drainage from phytocaps and conventional caps was measured and represented a relatively small proportion of the rainfall received at most sites, as discussed for each site in Chapter 5. At the Adelaide, Melbourne and Lismore sites, the annual drainage was ≤ 6% of precipitation for the phytocaps and conventional caps and annual drainage was ≤ 11% of precipitation at the Townsville site. Annual drainage was higher at the Perth site (2 – 23% of precipitation) due to poor initial establishment of grasses and slow establishment of trees and shrubs over the monitoring period.

The phytocap drainage was a similar order of magnitude to the drainage measured from the conventional cap, with lower drainage from the phytocap in some years and lower from the conventional cap in other years. In the southern states (the Adelaide and Melbourne sites), the drainage from the conventional cap was higher than the phytocap in years when the clay had dried over summer and winter rains resulted in a rapid wetting front through the profile (refer Figures 5.9 and 5.18). Conversely, the conventional caps performed better than the phytocap when slow wetting of the clay barrier occurred, which was inferred to be caused by the desiccation cracks swelling prior to sufficient moisture being available to result in drainage. In the latter scenario, lateral flow was generally higher. However, as the continuity of the clay barrier can be compromised by differential settlement, lateral flow may become drainage.

The drainage from the phytocap was generally less than the conventional cap at the Townsville site (Section 5.3.4). The compacted clay barrier at this site was shallow, at 300 mm below the surface compared to the southern sites where the barrier was 500 mm or 900 mm below the surface. This shallower depth combined with the lower slope on this site may have resulted in a perched water table above the clay barrier and thus higher drainage.

Water balance modelling is a better predictive tool for determining the suitability of a phytocap for a particular site than simple indicators, such as the P:PET ratio, as it incorporates climatic seasonal variation, soil properties and plant water use. The modelling comparison undertaken for the Southern Waste Depot trial site showed the importance of determining the changes in the soil hydraulic properties of the phytocap over time to improve the accuracy of water balance modelling (Section 6.3.2). In marginal sites, field trials could be used to calibrate the model to improve the accuracy. As shown with the Adelaide trial site, it is important to determine the soil hydraulic properties once plants have established and are actively growing to ensure the water balance data can be accurately predicted and extrapolated over the longer term (Section 6.4.2).

8.1.2 Rainfall and Cap Drainage

The largest influence on the hydraulic performance of the phytocaps and conventional caps was the seasonality of rainfall. The average annual PET:P ratio suggested by Hauser and Gimon (2001) for each of the sites is calculated in Table 3.2. Based on this ratio, the Adelaide and Perth sites (with ratios > 1.5) were expected to have performed better than the other sites. Conversely, the Lismore site with high annual rainfall and relatively low PET was expected to perform poorly. However, comparison of annual drainage from the sites in years of similar rainfall showed that the Adelaide and Perth sites did not perform as well as expected. In Adelaide and Perth, the rainfall is strongly winter dominant and falls when the PET is lowest and the plants are not actively growing. In Lismore the rain falls throughout summer when PET is highest and plants are actively growing. This shows that the PET:P ratio is not a valid indicator of the opportunity for a site to utilise a phytocap in Australia and that this is an oversimplification of phytocap design. As summarised in the following sections, because the water balance is also affected by vegetation and soil, these factors need to be included when assessing phytocap potential.

8.1.3 Vegetative Influence on the Water Balance

Besides the direct influence of climate on the water balance, the major changes measured in the water balance after the first year of the trial period can be related to vegetation survival and growth. The evapotranspiration rate increased as the vegetation established and the soil moisture storage variation approached the laboratory measured minima and maxima as roots penetrated through the profile. At the Adelaide site, after the vegetation died back the moisture content in the lower profile did not decrease over summer, as would be observed with active vegetative growth, and drainage was measured in the following winter (Figure 5.4). However, as the vegetation re-established, the moisture content at depth began to decrease again. This showed that the vegetation is critical in minimising drainage at this site but also that the vegetation is able to regenerate within 18 months. Although the die-back at the site was caused by herbicide application, a similar response could occur following fire or other catastrophic events. Unfortunately, these catastrophic events are not easily included in current water balance models, which affects their ability to predict short term water balance.

Trees and shrubs had an important role in removing more moisture than grasses alone and from deeper in the profile. These factors combined to result in less drainage measured from caps with trees and shrubs than with grasses alone (Section 5.3.4). This relationship was not as clear in Melbourne where the clay barrier deeper in the profile of the conventional cap sometimes resulted in less drainage from the grass covered conventional cap compared to the trees and shrubs included in the phytocap (Section 5.2.3).

Zhang *et al*. (2001) showed that treed communities and grasslands have similar evapotranspiration for sites with an average annual rainfall < 500 mm. The 5 trial sites all have an average annual rainfall > 500 mm/yr and hence difference in evapotranspiration can be expected. In Australia, the high rainfall variability will influence the proportion of time the soil moisture conditions are limiting in each year. During wetter years, even in semi-arid and arid sites, moist soil conditions will result in other factors, such as leaf area index, becoming more important (Zhang *et al.*, 1999). For a phytocap, the design needs to consider the range of climatic conditions to provide a robust design which will meet its objectives (Section 2.2) in the majority of years and not only on average.

At the Perth site (Section 3.5), the trees and shrubs included in the vegetation mix did not perform better than the Adelaide site (Section 5.1), which was also sandy soil but was planted to only native grass. The relatively high drainage measured from the Perth cap showed the importance of including grasses in the plant mixture and ensuring they establish to minimise drainage while the trees and shrubs establish more slowly. The Melbourne site was also a sandy soil but was ameliorated with compost which improved moisture holding capacity of the soil and in turn reduced drainage. The addition of an ameliorant at the Perth site may have aided plant establishment, increased moisture holding capacity and hence reduced the drainage through the profile.

8.1.4 Soil Physical Changes Influence on the Water Balance

Changes in the soil hydraulic properties were evident from the changed water balance response to rainfall in the conventional covers but not to the same extent (if at all) in the phytocaps. The compacted clay barrier dried within the first year of construction (Figures 5.9, 5.18 and 5.30) and subsequently drainage was measured at all sites and lateral flow reduced. In addition, the timing of drainage and lateral flow and changes in clay moisture content suggested that the compacted clay barriers had developed preferential pathways, most likely due to desiccation cracks in the clay (Figures 5.10, 5.10 and 5.31).

The clay at the Townsville site had the highest linear shrinkage potential of the 3 sites which, when combined with the shallower placement depth, appeared to have hastened the change in soil physical properties of the clay layer. The drying and cracking of the compacted clay barrier resulted in an increase in the field permeability at Vantassel Street Landfill over the monitoring period (Section 5.3.3). Drainage from the Adelaide and Melbourne site occurred when the clay was relatively dry and hence the same trend was not observed in these field data. However, the saturated hydraulic conductivity had increased from 1×10^{-9} m/s to 2×10^{-7} m/s after 4 years in the small plot trial conducted using the Adelaide soil materials. The Melbourne clay has higher clay content than the Adelaide soil but lower linear shrinkage and hence it is not known to what extent a similar change would occur in the Melbourne clay barrier.

The overall comparison of the phytocap and conventional cap suggests that the phytocap is likely to be more sustainable than the conventional cap. The phytocap has remained in a similar condition to at-placement and has continued to operate as expected, with improvements in drainage minimisation as the vegetation has established. In addition, repairs to the phytocap can be affected more easily than the conventional cap by increasing soil thickness, adding soil ameliorants or changing the plant composition, as examples. The conventional cap did not continue to act as a barrier to moisture movement and the influence of preferential flow paths on drainage is less predictable than the matrix flow associated with the phytocap. Furthermore, the inclusion of trees and/or shrubs on the phytocap results in increased evapotranspirative potential than the “grass only” capacity of the conventional caps, due to limited rooting depths.

8.2 Recommendations for Future Research

This PhD project has investigated the water balance over 3 – 4 years at the selected trial sites. Little structural development was evident on the phytocap over the time period and longer term trials are essential for fully assessing the sustainability of this capping system. Further research by destructively sampling the control areas adjacent to the lysimeter plots would aid in understanding the changes that have occurred and separating these from the influence of vegetation establishment. Also, longer term monitoring of field trial sites to collect data once vegetation was fully established, particularly sites with trees and shrubs, would aid in calibrating the WAVES model and providing more detailed vegetation input values.

The trial monitoring was predominantly over the period in which the vegetation was establishing. This research showed that vegetation had a major impact on the water balance during this period. However, as the plant community reaches a climax, the changes in the soil moisture content range may become fixed. On-going research is required to assess whether there are any other changes in the water balance parameters associated with development of the vegetative community.

The impact of varying and improving the phytocaps could also be investigated, particularly for the Perth site. Resowing grasses, adding mulch or incorporating compost into the topsoil would affect the water balance of the cover and aid in determining if such a sandy profile can be used as a phytocap. This information is important in determining the suitability of phytocaps for the Perth region as the Swan Coastal Plain is predominantly sand with limited clay deposits. Other areas in Australia, such as parts of south east South Australia which were formed from a receding beach front, would also benefit from this research.

The ability of phytocaps to control infiltration rather than prevent it also lends this technology for use with bioreactors and with the emerging philosophy of sustainable landfilling. This philosophy promotes the controlled infiltration of moisture into the waste to promote decomposition and hence increase the waste stability in a shorter timeframe and hence keep the environmental impacts within the service life of the landfill. This philosophy is fundamentally different from the current “dry tomb” approach, which aims to prevent drainage (and hence leachate) but with the much slower release of contaminants from the waste can result in environmental impact from this release occurring after the base liner has outlived its service life. Further research into the application of phytocaps for controlling and not just preventing drainage would also aid the long term sustainability of landfilling as a disposal pathway for waste products.

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Appendix A

CS229 Calibration and Field Data

A.CS229 Calibration and Field Interpretation

Soil suction, the largest component of which is matric potential, has been measured in the field using gypsum blocks and tensiometers. The disadvantages of these methods for the A-ACAP trial were the limited measurement range and slow response time of both instruments as well as the short lifespan of gypsum blocks in an aggressive environment, as can be experienced on a landfill, and the high labour requirement to maintain tensiometers (Munoz-Carpena *et al.*, undated). Campbell Scientific sells the CS229 matric potential sensor which uses heat dissipation from a thermocouple through a ceramic outer to measure suction of the surrounding media, e.g. soil. These sensors require individual equilibration due to differences in the pore size distribution, and hence moisture retention, of the ceramic outer. Flint *et al.* (2002) and Campbell (2006) used soil moisture retention equipment, such as suction tables and pressure plate apparatus, to calibrate 3-6 sensors in the laboratory; however neither author reported on the field performance of these sensors.

The A-ACAP trial installed CS229 sensors with an adjacent moisture content sensor (MP406) in all trial sites. This resulted in a total of 120 sensors requiring calibration. Given the limited number of sensors which could be calibrated at one time (estimated as 6-8 sensors/batch) and the length of time required to calibrated the sensors at a 5 moisture potentials (estimated at 3 months/batch), calibration would have required almost 4 years to complete. It was evident that a bulk method of calibration would be required to correspond to the construction timetable.

A.1 Laboratory Calibration

The CS229 sensor contains a thermocouple surrounded by a ceramic cylinder which was then cabled to an ICT proprietary interface so it could communicate with the logger. The sensor reports temperature difference (ΔT) which is related to the soil's matric potential. The ΔT reported by each sensor needs to be calibrated against a known matric suction. As the calibration is curvilinear, it is necessary to undertake the calibration at various suctions. Campbell (2006) recommends measuring the ΔT at air dry, saturation and 5 data points, 4 points between 20 kPa and 500 kPa and one point at > 1,000 kPa.

CS229 sensors were calibrated in batches of 30 sensors using large plastic containers filled with warm, deaerated water first and then placed in successive soil mixes with increasing soil suction (Figure 1, top left). While equilibrating, the sensors were placed in a constant temperature room and

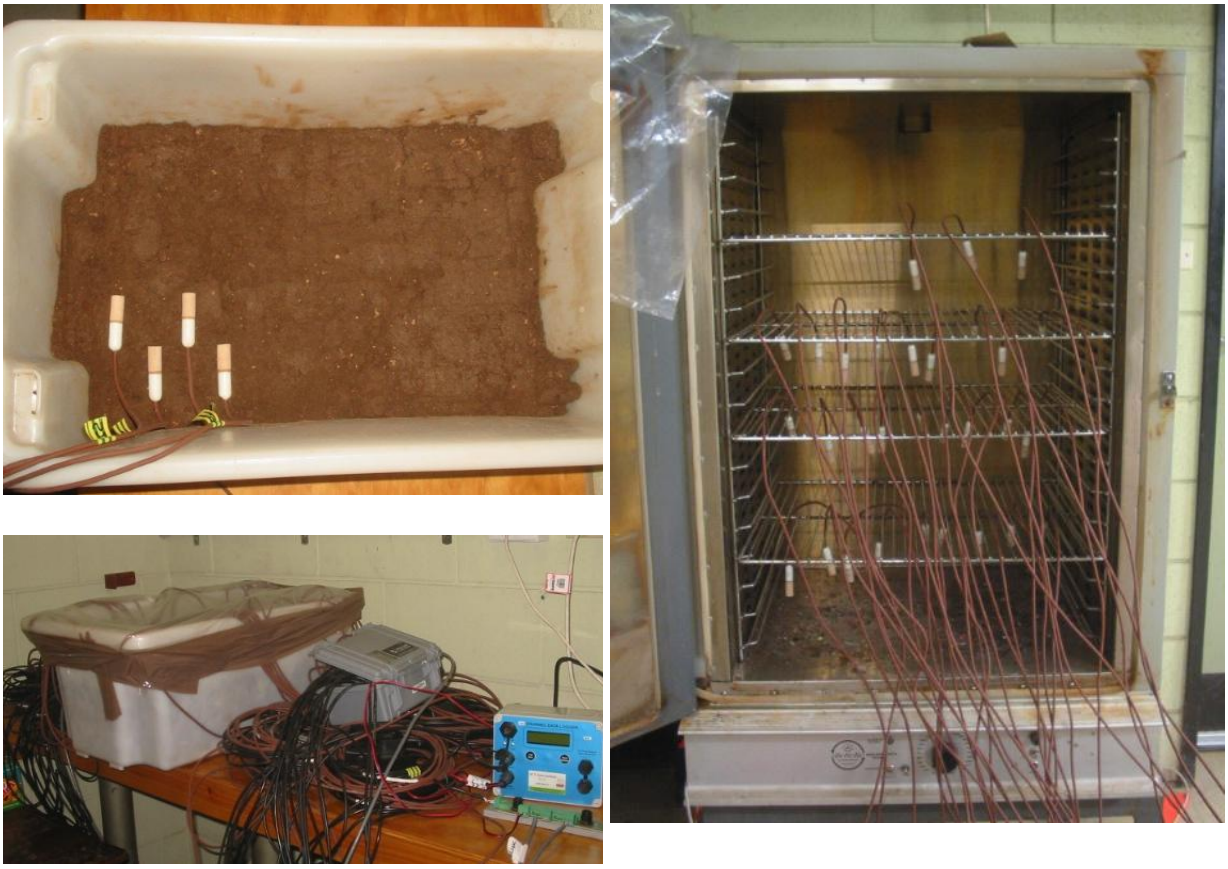

Figure 1 **Placement of CS229 Sensors in Bulk Soil (top,left) and Equilibration in Constant Temperature Room (top,right) and Placement in Oven to Determine T_d.**

plastic sheeting used to prevent moisture loss (Figure 1, bottom left). Soil moisture content was determined at each sensor location once the sensor had equilibrated and soil suction measured on selected samples. To achieve air-dry, the sensors were hung from racks in an oven set at 35 – 40 °C (Figure 1, right). The oven was sealed with plastic bags to assist in maintaining temperature. Sensors were equilibrated until constant ΔT for 24 hours was recorded. For wetter suctions and air-drying, this process took 2 – 7 days, while at the drier suctions equilibration required weeks.

Five soil mixes were created for the sensor calibration. Topsoil from the Adelaide trial sites was moisture conditioned to five different soil suctions, which were nominally 10 kPa, 30 kPa, 300 kPa, 500 kPa and 1500 kPa. The moisture content associated with the nominated suctions was determined from the soil moisture characteristic curve (Figure 2). It should be noted that this curve was derived using gravimetric moisture content and not volumetric moisture content to reduce the variability from including bulk density. Air-dry soil was mixed with water and allowed to cure for 24 hours. Soil was stored in double plastic bags between calibration tests to reduce moisture loss.

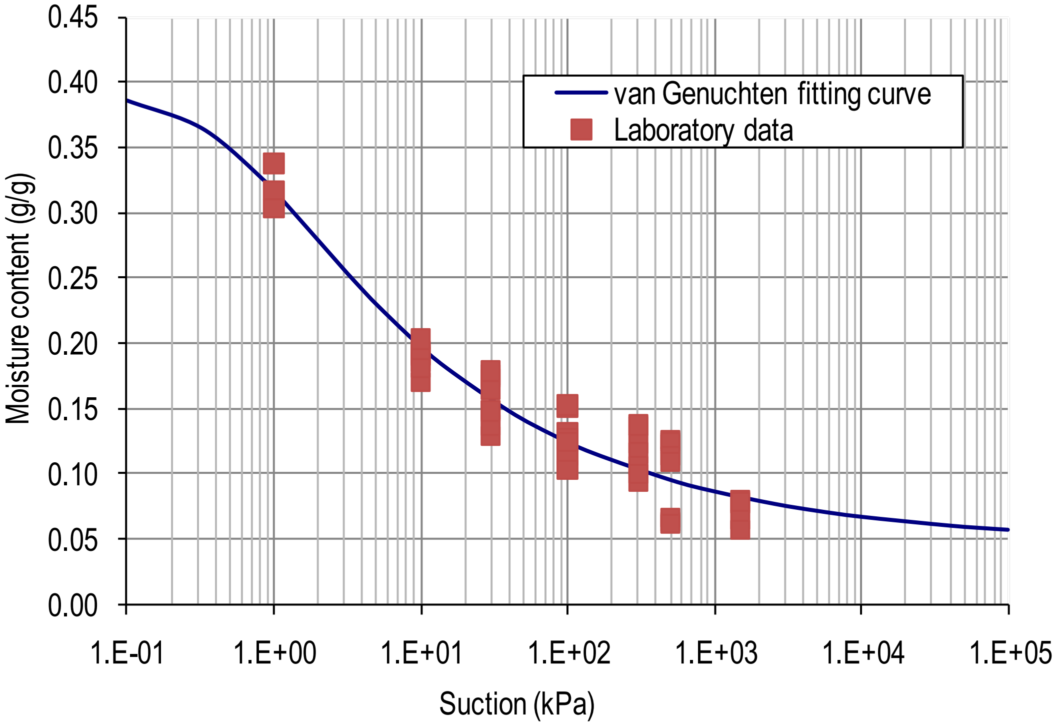

Figure 2 **Soil Moisture Characteristic Curve for CS229 Calibration Soil**

Preparation for soil calibration tests involved placing the material in two lifts and each lift was compacted using a metal plate to the approximate field dry density of 1.5 t/m^3. Thirty sensors were placed horizontally on the first lift and pushed into the underlying soil to ensure good contact before the second lift was placed and then compacted. After the readings had equilibrated, the sensors were carefully excavated and soil within 1 cm of the ceramic outer was sampled for moisture content and suction (selected samples) analysis.

Soil suction was measured using a WP4 Dewpoint PotentiaMeter (Decagon, 2007). Initially soil suction samples were taken for all sensor locations; however, the stated accuracy of the WP4 at suctions from 0 – 300,000 kPa is +/- 100 kPa, which was greater than the difference between the moister soil mixes and resulted in variable results, as shown in Figure 3 for Soil 1 (nominally 10 kPa). Instead, the soil moisture content measured at each sensor location was converted to suction using the van Genuchten (1980) function derived for the soil and shown in Figure 2. The measured moisture content and temperature rise recorded for the sensors from the Adelaide site are shown in Table 1. The values measured were similar to the values reported by Campbell (2006).

The method described by Flint *et al.* (2002) was used to provide a calibration curve for converting the measured ΔT to soil suction. The equations are based on the van Genuchten moisture function as

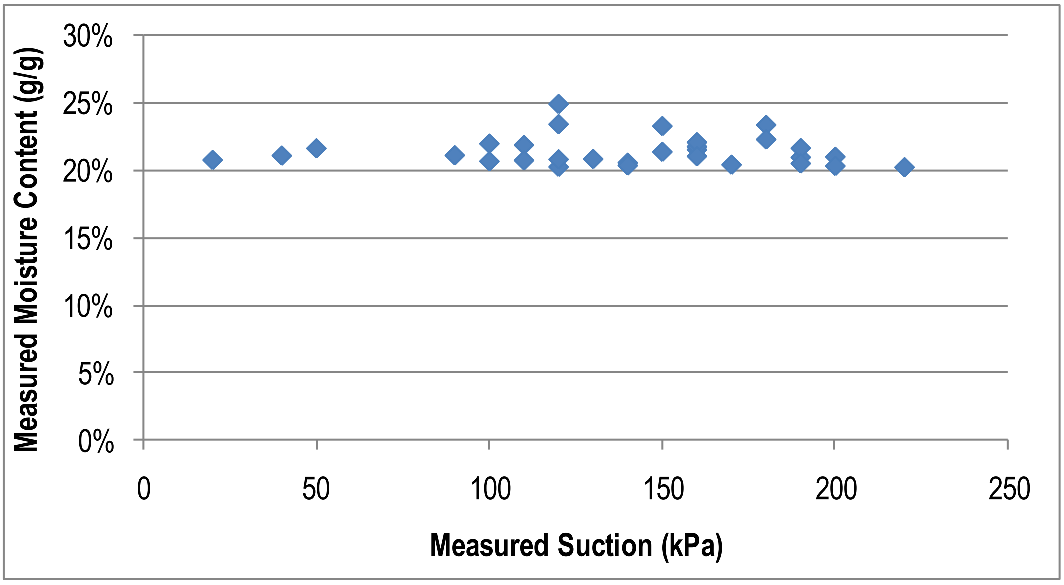

Figure 3 **Measured Suction and Moisture Content at 30 Locations in Soil Mix 1**

shown in the equations below. The Excel Solver add-in was used to refine the estimation of the equation parameters.

$$T^* = \frac{\Delta T_d - \Delta T}{\Delta T_d - \Delta T_w}$$ ....Equation 1

Where,

T^* is dimensionless temperature rise

ΔT_d is the temperature change for a dry ceramic

ΔT is the temperature change measured in the medium

ΔT_w is the temperature change for a fully saturated ceramic

$$\Psi = \Psi_o \left(T^{*\,-1/m} - 1\right)^{1/n}$$ ....Equation 2

Where,

Ψ is suction of the medium

Ψ_o is air entry value

T^* is dimensionless temperature rise, calculated in Equation 1

m and n are fitting parameters

The values calculated for the CS229s installed at the Adelaide site are shown in Table 2 with an example of the fit shown in Figure 4. Similar values and ranges were obtained for other trial sites.

Table 1 Calibration Data for CS229 Sensors Installed at Adelaide Trial Site

Location [a]	Interface ID	Tw	SOIL 1		SOIL 2		SOIL 3		SOIL 4		SOIL 5		Td
		ΔT (°C)	θ_v (%)	ΔT (°C)	θ_v (%)	ΔT (°C)	θ_v (%)	ΔT (°C)	θ_v (%)	ΔT (°C)	θ_v (%)	ΔT (°C)	ΔT (°C)
PL-U-T	SMM71001	2.399	20.7	2.438	16.7	2.917	11.9	5.394	8.0	6.096	4.2	6.280	6.796
PL-U-M	SMM6C108	1.399	22.0	1.413	16.6	1.556	13.4	2.085	8.6	3.073	4.0	3.399	3.718
PL-U-B	SMM6C087	1.225	20.5	1.242	17.5	1.361	13.0	1.831	8.3	2.645	3.7	2.950	3.193
PL-C-T	SMM6C097	1.314	20.5	1.337	17.1	1.477	13.7	1.978	8.9	2.926	4.0	3.276	3.558
PL-C-M	SMM6C078	1.228	20.7	1.238	16.5	1.356	12.2	1.836	8.4	2.728	4.0	3.026	3.283
PL-C-B	SMM6C079	1.618	21.3	1.608	16.8	1.741	13.1	2.278	8.2	3.388	4.0	3.691	3.955
PL-D-T	SMM6C099	1.181	21.8	1.187	17.4	1.248	13.3	1.751	8.7	2.730	4.1	3.015	3.271
PL-D-M	SMM6C094	1.227	21.6	1.238	16.5	1.338	11.7	1.835	8.3	2.682	4.6	3.021	3.272
PL-D-B	SMM6C100	1.251	20.2	1.284	17.9	1.439	13.0	1.897	8.2	2.755	4.5	3.041	3.300
PC-U-T	SMM6C077	1.283	23.3	1.345	17.4	1.429	13.2	1.871	9.3	2.751	4.2	3.058	3.303
PC-U-M	SMM6C051	1.118	20.4	1.124	17.5	1.245	12.8	1.733	8.6	2.672	4.0	2.968	3.226
PC-U-B	SMM6C101	1.650	22.3	1.657	17.2	1.770	12.9	2.239	8.2	3.080	4.2	3.515	3.791
PC-D-T	SMM6C074	0.964	23.4	0.965	16.9	1.022	13.3	1.481	8.5	2.358	4.3	2.604	2.801
PC-D-M	SMM6C091	1.654	20.8	1.676	18.4	1.875	13.5	2.414	8.2	3.467	4.1	3.837	4.128
PC-D-B	SMM6C085	1.729	20.3	1.751	16.3	1.866	13.1	2.471	8.2	3.543	4.0	3.885	4.169
CL-U-T	SMM6C096	1.735	21.6	1.783	17.6	1.965	12.8	2.489	9.5	3.752	3.8	4.127	4.438
CL-U-M	SMM6C104	1.171	21.0	1.174	16.4	1.287	12.4	1.805	7.9	2.753	3.9	3.095	3.372
CL-U-B	SMM6C055	1.560	21.0	1.573	17.4	1.685	13.0	2.136	8.2	3.001	4.1	3.311	3.559
CL-C-T	SMM6C057	1.240	20.9	1.248	16.7	1.324	13.2	1.848	8.1	2.817	4.4	3.116	3.344
CL-C-M	SMM6C069	1.333	21.5	1.309	17.7	1.466	13.0	1.950	8.6	2.937	4.1	3.285	3.568
CL-C-B	SMM6C068	1.434	20.6	1.445	16.9	1.546	13.9	2.065	7.9	3.027	4.1	3.368	3.642
CL-D-T	SMM6C107	1.391	21.9	1.375	17.2	1.451	14.7	2.100	8.1	3.295	4.4	3.675	4.023
CL-D-M	SMM6C075	1.314	20.8	1.323	16.9	1.476	12.8	1.927	8.5	2.712	3.7	3.031	3.315
CL-D-B	SMM6C065	1.727	23.3	1.769	16.9	1.918	13.8	2.536	9.2	3.702	4.1	4.189	4.526
CC-U-T	SMM6C102	1.435	20.2	1.453	16.2	1.663	12.8	2.170	8.0	3.288	3.9	3.602	3.898
CC-U-M	SMM6C070	1.113	20.3	1.118	16.5	1.318	12.8	1.748	8.8	2.694	3.9	2.958	3.191
CC-U-B	SMM6C080	1.346	24.9	1.388	16.9	1.557	12.8	2.045	8.0	2.896	4.7	3.168	3.403
CC-D-T	SMM6C060	1.270	21.7	1.357	16.9	1.578	14.6	2.150	9.6	3.242	4.3	3.606	3.896
CC-D-M	SMM6C106	1.117	21.0	1.135	16.8	1.224	14.3	1.664	11.6	2.546	3.8	2.808	3.030
CC-D-B	SMM6C103	1.438	21.1	1.449	18.0	1.550	13.8	2.041	8.5	3.001	4.1	3.329	3.606

[a] Location Codes format is “test section-location-depth” being ‘PL’ Phytocap Lysimeter, ‘PC’ Phytocap Control, ‘CL’ CCL Lysimeter, ‘CC’ CCL Control; ‘U’ upslope, ‘C’ centre, ‘D’ downslope; ‘T’ top, ‘M’ middle ‘B’ bottom

Table 2 Calibration Parameters for CS229s Installed at Adelaide Trial Site

Location	Interface ID	Wet ΔT	Dry ΔT	Air Entry	Fitting Parameters	
		(Tw)	(Td)	(Ψo, cm)	(n)	(m)
Mean		1.393	3.686	209.8	2.477	0.1903
Standard Deviation		0.279	0.716	56.5	0.471	0.0593
Coefficient of Variation*		20%	20%	27%	19%	31%
PL-U-T	SMM71001	2.399	6.796	126.1	3.352	0.1437
PL-U-M	SMM6C108	1.399	3.718	172.9	2.374	0.1757
PL-U-B	SMM6C087	1.225	3.193	179.3	2.519	0.1583
PL-C-T	SMM6C097	1.314	3.558	159.8	2.702	0.1598
PL-C-M	SMM6C078	1.228	3.283	335.4	2.164	0.2434
PL-C-B	SMM6C079	1.600	3.955	278.4	2.200	0.2356
PL-D-T	SMM6C099	1.181	3.271	278.4	2.227	0.2424
PL-D-M	SMM6C094	1.227	3.272	176.8	2.247	0.1500
PL-D-B	SMM6C100	1.251	3.300	177.8	2.245	0.1812
PC-U-T	SMM6C077	1.283	3.303	157.5	2.314	0.2180
PC-U-M	SMM6C051	1.118	3.226	240.2	2.866	0.1716
PC-U-B	SMM6C101	1.650	3.791	179.3	2.498	0.1350
PC-D-T	SMM6C074	0.964	2.801	318.4	2.157	0.2784
PC-D-M	SMM6C091	1.654	4.128	141.8	2.803	0.1350
PC-D-B	SMM6C085	1.729	4.169	186.7	2.552	0.1632
CL-U-T	SMM6C096	1.735	4.438	285.4	2.394	0.1914
CL-U-M	SMM6C104	1.171	3.372	232.3	2.983	0.1320
CL-U-B	SMM6C055	1.560	3.559	189.1	2.432	0.1614
CL-C-T	SMM6C057	1.240	3.344	184.2	2.896	0.1446
CL-C-M	SMM6C069	1.300	3.568	228.5	2.456	0.1911
CL-C-B	SMM6C068	1.434	3.642	134.2	3.415	0.0994
CL-D-T	SMM6C107	1.370	4.023	243.1	2.194	0.2052
CL-D-M	SMM6C075	1.314	3.315	189.2	2.786	0.1434
CL-D-B	SMM6C065	1.727	4.526	212.8	1.605	0.3099
CC-U-T	SMM6C102	1.435	3.898	216.4	2.497	0.1719
CC-U-M	SMM6C070	1.113	3.191	259.6	3.024	0.1904
CC-U-B	SMM6C080	1.346	3.403	257.9	1.184	0.3607
CC-D-T	SMM6C060	1.270	3.896	136.9	1.857	0.2833
CC-D-M	SMM6C106	1.117	3.030	265.4	2.392	0.2002
CC-D-B	SMM6C103	1.438	3.606	149.7	2.978	0.1327

* Coefficient of Variation calculated as $c_v{}^* = (1 + {}^{1}/_{4N})\frac{st.dev.}{mean}$

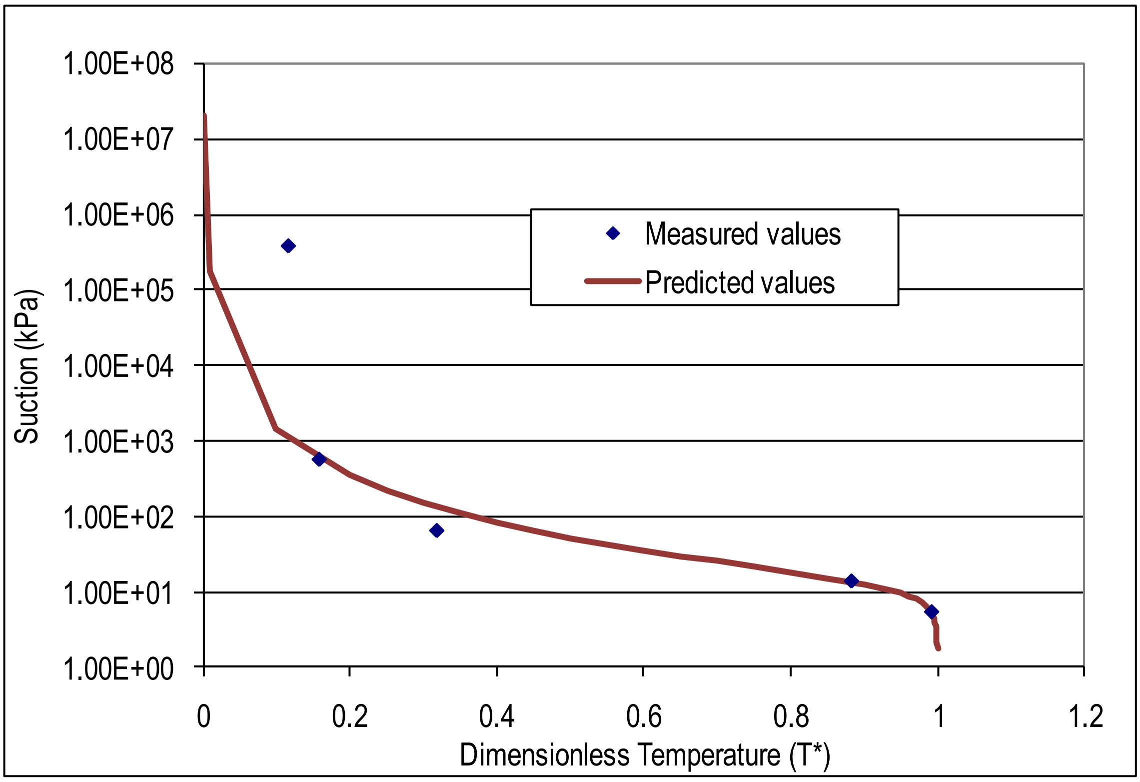

Figure 4 **Fitting Curve for CS229 Calibration. Phytocap Lysimeter – Upslope – 0.15 m Sensor Shown**

A.2 Field Data

CS229 data were collected at all trial sites; however, after 12 – 18 months, the readings from most sensors became erratic and then sensors failed, as discussed for the soil temperature readings in Section 5. It is not known if the cause of this failure was the CS229 sensor or the interface.

The field data from Southern Waste Depot from July 2007 until December 2008 are presented herein as an example of the issues encountered with the soil suction measured by the CS229 sensors. The field data were converted to dimensionless temperature (T*) and then to suction using the equations shown above; however, the calibration resulted in unrealistic values of suction. From the example shown in Figure 5, it can be seen that the soil is predominantly drier than permanent wilting point (1.5×10^{-3} kPa) for the majority of time at all depths. The calculated suctions are not realistic and unlikely to reflect field conditions. Also, the graph appears to show that at suctions greater than 1×10^{-7} kPa the calculation is less accurate, resulting in “noise” in the resultant suction.

Though the soil suction calculated from the calibration curves were not realistic, the CS229 sensors did react to changes in soil moisture. Comparing the dimensionless temperature (T*) with the soil

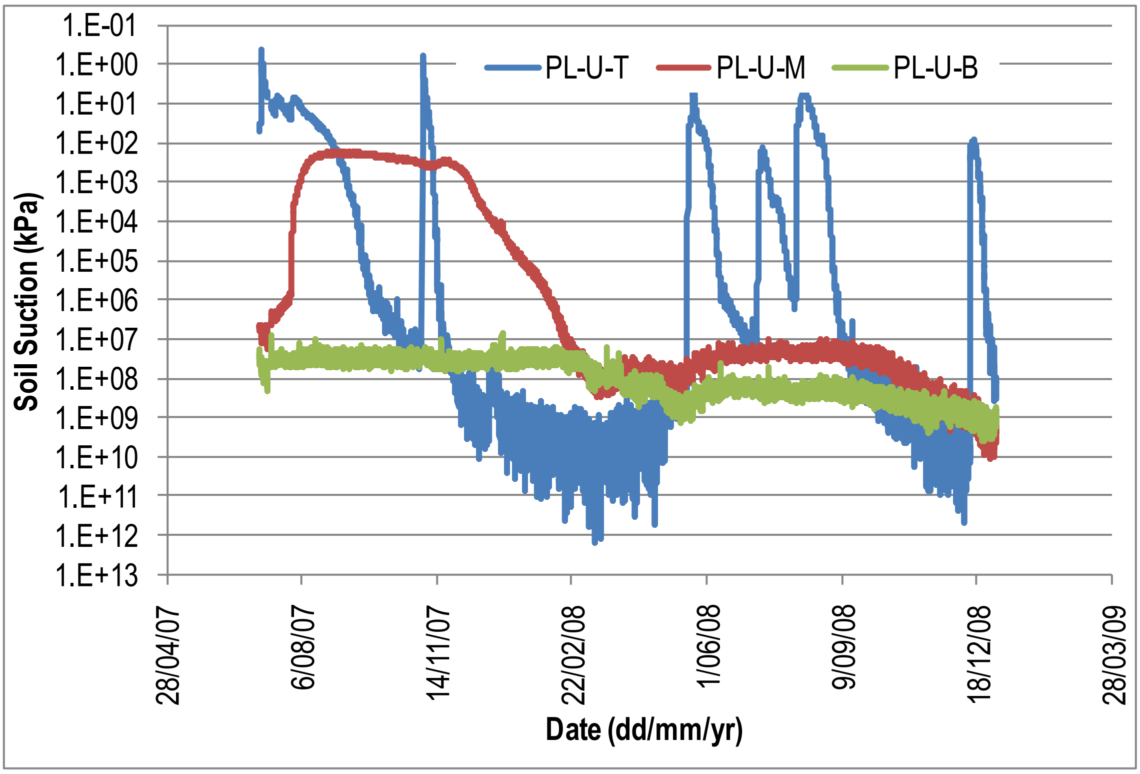

Figure 5 **CS229 Data Converted to Soil Suction for the Three Depths at "Phytocap Lysimeter – Upslope" Location**

moisture content shows a similar pattern between the two (Figure 6). However, as shown in a number of sensors at the sites, after installation in the field, the sensor reported temperature changes which were less than the saturated value (Tw) and greater than the dry value (Td). This is shown in Figure 6, where the dimensionless T is greater than 1, i.e. wetter than saturation for some sensors and for others is less than 0, i.e. drier than air-dry.

Closer examination of the soil suction compared to the soil moisture content changes and to the rainfall events shows the CS229 is slow to equilibrate to a rapid moisture front and hence moisture loss has occurred before the sensor has equilibrated with the surrounding soil. This effect can be shown most clearly in the data from the "Phytocap Lysimeter – Upslope" location (Figure 7, left). Two peaks are present in the moisture and suction data in August and December 2008. In August the preceding conditions were moister and additional rain fell on the following days compared to December when the rainfall was a relatively isolated event (Figure 8). Over both events, the CS229 sensor did not record a peak until almost 2 days after the event. In August, this may have been over 5 days but the influence of subsequent rainfall events makes the exact correlation difficult to determine.

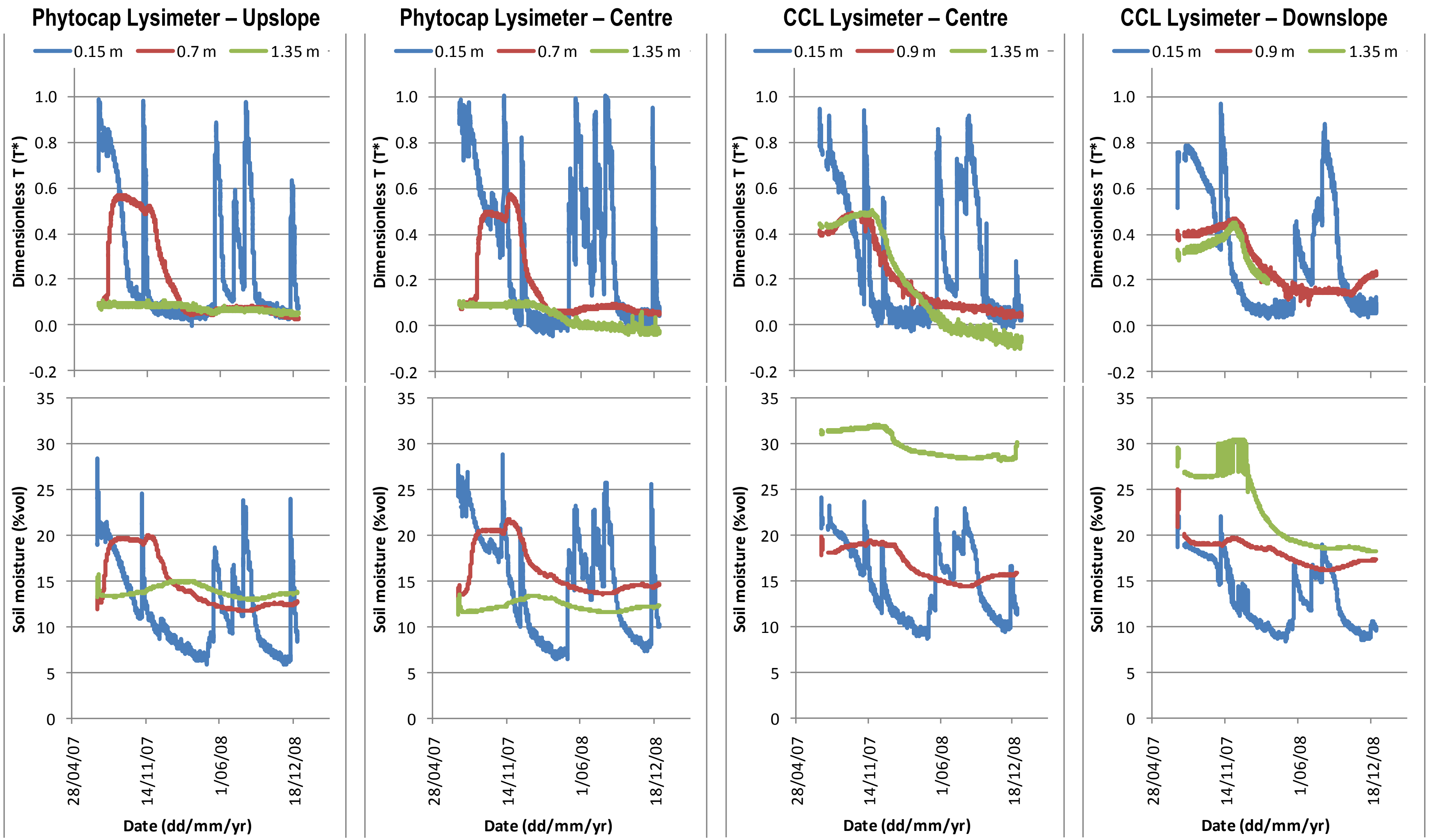

Figure 6 Converted CS229 Readings and Soil Moisture with Depth for Selection Locations at Southern Waste Depot

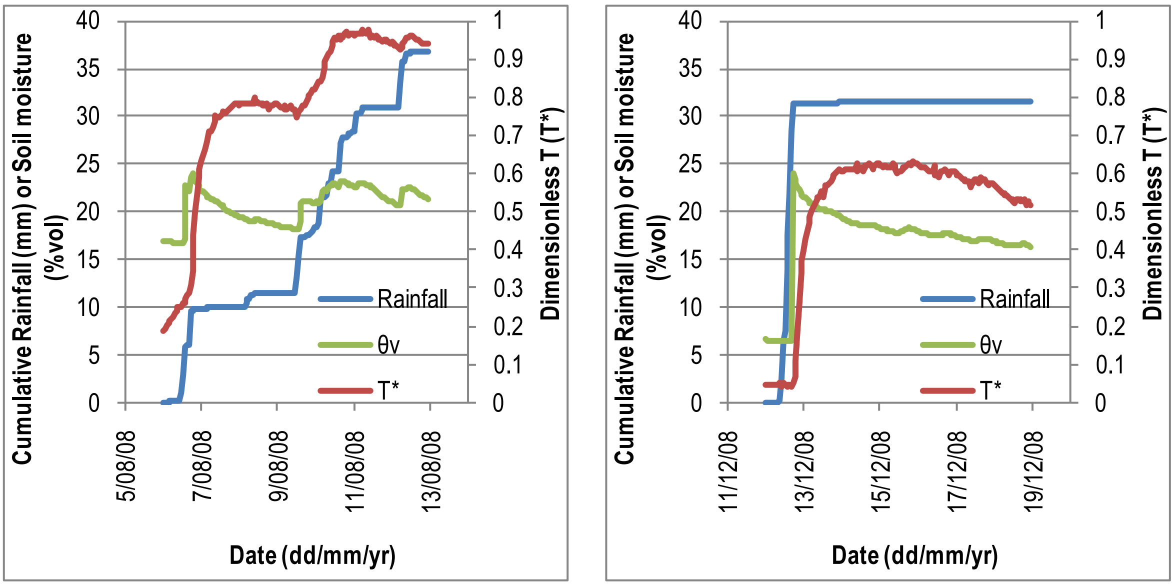

Figure 7 August and December 2008 Rainfall Events and Measured Changes in Soil Moisture (θv) and Suction (T*)

The maximum suction recorded by the CS229 sensor was higher in August than December, though the maximum soil moisture content recorded for both events was similar at 24%. This change in relationship between the soil moisture and suction can suggest a change in the moisture characteristic curve, which would be caused by soil structural improvements (e.g. aggregation, macropore formation). This is unlikely to be the cause for the difference over the short time frame of 4 months. Instead, the slow equilibration time of the CS229 would result in the high evapotranspiration from the surface soil during summer removing moisture before the CS229 had equilibrated, thus resulting in a lower maximum.

A.3 Conclusions

The CS229 sensors were unable to be calibrated using bulk laboratory methods used herein. The calibration relies on determining the dry and saturated temperature changes for each ceramic but after placement in the field, higher saturated and lower dry values were achieved than in the laboratory. The fitting curves for the sensors resulted in variable parameters but these were within expected coefficients of variation for field values of 20-30%. As noted by Campbell (2006), the sensitivity of the CS229 at low suctions (10-20 kPa) is reduced and higher suctions (> 500 kPa) are determined with a loss of accuracy. This loss of accuracy may exacerbate the difficulties in calibrating the sensors using the bulk method described herein. The slow equilibration time of the CS229 sensors would also make field-calibration (i.e. using field data to determine the calibration curve) difficult.

If the CS229 sensors could have been calibrated for this study, the issue of slow equilibrium time could have resulted in incorrect findings on potential structural change, particularly as the first two years at the Adelaide site were dominated by drought. Regardless of all this, the longevity of the sensors/interfaces resulted in limited reliable data being collected to enable assessment of longer term trends. The malfunctioning of the soil suction sensors was not resolved as to whether the issue was with the CS229 sensor or with the ICT interface.

A.4 References

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