Rapid field and laboratory methods for measuring plant available water capacity and water retention curves

DNRME Technical Note 2017

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These methods are to be used when collecting soil samples for laboratory analysis by the DNRME science team in Toowoomba. Please contact us before proceeding to discuss sampling strategies and procedures. We are not a commercial laboratory. Any analysis undertaken must be linked to a collaborative research project.

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List of terms

BD – bulk density

DP – drainable porosity

DUL – drained upper limit

LLcrop – crop lower limit

LL15 – 15 bar theoretical lower limit

PAW – plant available water

PAWC – plant available water capacity

SAT – saturation

TP – total porosity

WRC – water retention curve

Overview

This document provides a practical overview of the methods used by the Toowoomba DNRME science team to estimate the Plant Available Water Capacity (PAWC) and Water Retention Curve (WRC) of a soil. Details of sample collection and processing methods as well as the calculation and application of each descriptor are provided in the following sections.

PAWC and WRC are useful soil physical characteristics. The first quantifies the capacity of a soil to store water, and the second, how freely available this water is for plant uptake. There are three main ways we use these descriptors:

1. Agronomic decision making – determining the PAWC or 'bucket size', as well as the Plant Available Water (PAW) or 'how full the bucket is' provides useful information about the soil-water-plant dynamics of a soil. This is invaluable in agronomic decision making that rely on information about the amount of stored water in a soil, e.g. fallow stored moisture available for planting, irrigation amount required to fill a soil water deficit,
2. Electromagnetic induction (EMI) methods – EMI can be used to estimate the total amount of water in a soil profile. This amount includes both the available water (for plant use – PAW) and the unavailable water that is beyond the extraction capability of a plant. If soil/site specific PAWC information is available, then the PAW proportion of the total amount of soil water can be defined. EMI maps can then be expressed as a percent of the PAWC to improve the general interpretation of the moisture status of the soil,
3. Modelling the soil water balance – PAWC and WRC descriptors are used to parameterise agronomic and soil water balance models such as HowLeaky, APSIM-SoilWat, APSIM-SWIM and HYDRUS. PAWC data is also required for some decision support tools such as CliMate and Yield Prophet. Soil water balance simulations and potential yield estimates from these models and decision support tools can be significantly improved by using direct measurements of PAWC rather than generic soil type or local values.

There is abundant reference material available on this topic on the internet, e.g. Soil Matter (Dalgliesh & Foale 1988); GRDC project update 'Methods and tools to characterise soils for plant available water capacity (North Star)' (Verburg et al. 2016). Reference texts include 'Soil Physical Measurement and Interpretation for Land Evaluation' (McKenzie et al 2002).

Over the past 20 years CSIRO, in collaboration with state agencies, catchment management organisations, consultants and farmers has characterised more than 1000 sites around Australia for PAWC. The data are publicly available in the APSoil database, including via a Google Earth file and in the 'SoilMapp' application for iPad (Verburg et al. 2016).

Plant Available Water Capacity

PAWC defines the maximum amount of water available for plant use (in mm) that can be stored in a soil profile and is sometimes referred to as the 'bucket size' of a soil. It depends on both soil and plant features and can be calculated if the *upper and lower limit* moisture contents are known, provided a soil or rooting depth is assumed.

Upper limit

The Saturated water content (SAT) defines the "top of the bucket". The Drained Upper Limit (DUL) or Field Capacity (FC) of a soil defines the upper limit of the PAWC and is the amount of water retained in the soil after downwards movement of water from gravity drainage becomes negligible.

To measure DUL in the field, soil cores are collected to determine the gravimetric water content after the soil has been fully wet up then allowed to drain. A commonly used method in heavier textured soils involves gently wetting up a plot to saturation using a dripper array system placed over the soil surface (Photo 1). Lighter textured soils usually need to be ponded. The plots may require several–to–many watering's applied over a period of days–to–weeks to fully saturate the soil. Once fully wet, the soil is left to drain while covered with plastic to prevent evaporative losses (Soil Matters, Dalgliesh & Foale 1988). The time it takes for a soil to reach DUL after being saturated is commonly given to be ~ 3 days, however it can be anywhere from hours (sandy soils) to weeks (poorly draining heavy clay soils), depending on soil type and other factors.

Photo 1 A dripper array system placed over the soil surface to wet up a covered plot

The only way to definitively know when a soil has reached DUL is to monitor the soil water content or water potential. On several Vertosol and Dermosol soils types we have installed tensiometers at various depths in the wet–up plots and logged potential as the soils drained. In every instance we found that while one depth may have reached an approximate DUL (–10 to –20 kPa) the surrounding depths were either still draining (wetter than DUL) or near

the surface they were occasionally drier than DUL due to drier surrounding soil taking the moisture. In reality, achieving a uniformly drained profile that is consistently 'at DUL' is rarely possible.

Other methods for estimating DUL include:

- opportunistic gravimetric sampling (after irrigation or significant rainfall),
- using a theoretical value derived from a WRC,
- calculating an estimate from other soil properties such as the total porosity.

These methods will be described in more detail in subsequent sections.

Lower limit

The lower limit (LL) or permanent wilting point (WP) is the minimum amount of moisture left in the soil after a plant crop has extracted all the water it is capable of using. It defines the 'bottom of the bucket'. If the moisture level drops below this amount, the crop will wilt and not recover. It is a function of both soil and plant properties, including the maximum extent of root development, water uptake with depth and the ability of the plant to extract water as the soil dries out (under negative hydrostatic pressure). The lower limit varies for different soils and crops. Crop specific lower limits indicate the specific crop they were measured in, e.g. LLwheat, LLcotton etc.

Photo 2 Rainout cover placed over a sorghum crop to stress the crop to wilting point

The LL can be measured in the field or derived from laboratory tests. Field procedures involve covering a crop with some form of rain excluding shelter to moisture stress a crop to wilting point (Photo 2) (Dalgliesh & Foale 1988). Soil cores are then taken to determine the gravimetric moisture content. A crop specific LL can also be opportunistically sampled once a crop has dried off at the end of the growing season or after the crop has been harvested, provided there has been no recent rainfall. While this is quite an efficient method of obtaining LLcrop, it can potentially underestimate a true LLcrop and needs to be interpreted together

with recent rainfall/irrigation history. If several years of post-harvest data are available, the driest values can be used as a LLcrop estimate with more confidence than a single seasons data. This method takes into account root distribution and declining water extraction patterns with depth as well as potential subsoil constraints. The extractable soil moisture approach introduced by Ritchie (1981) utilises this method.

Laboratory methods involve placing soil samples on 15 bar pressure plate apparatus to extract soil moisture (Klute 1986). Once in equilibrium with this pressure, moisture content is measured. This provides a theoretical 15 bar lower limit (LL15) that can be used to define the bottom of the bucket when no specific LLcrop is available. It loosely relates to the driest water content achievable by plant extraction. However it is not crop specific. Many crops extract moisture below (or above) this theoretical limit, e.g. wheat can extract moisture to ~ 30 bars (3000 kPa). We have measured soil at 40 bar (4000 kPa) in a lucerne crop and 70-100 bar (7000-10000 kPa) under treed native vegetation.

Laboratory LL15 values have been found to underestimate field measured LL's for sands, silt loams and sandy clay loams, while overestimating LL's for loams, silty clays and clays (Ratliff et al. 1983, Ladson et al. 2004).

The DNRME science team have developed a rapid method for deriving LL using psychrometry (rather than pressure plates) to obtain a range of semi *in situ* measures within the drier moisture range. Laboratory measurements are made directly on intact soil core samples (rather than ground samples) to preserve structure and porosity. Methods and sampling techniques for this procedure (rapid–WRC–method) are detailed in subsequent sections.

When using laboratory methods to derive a LL (rather than infield crop measurement), decreasing water use with depth must be accounted for, i.e. the amount of extractable water declines with depth and decreasing root density. Pedotranfer functions such as PAWCER (a modified approach reported by Shaw & Yule, 1978) can be used to predict the depth specific shape of the LL curve, provided physical characteristics of the soil, such as the percentage of sand, silt and clay particle sizes and LL15 data are available (Littleboy 2002).

An example PAWC (for a sorghum crop) is provided in Figure 1a. The total PAWC to 1.9 m for this sorghum crop is 160 mm. Note in this case the total active depth of crop extraction has been sampled, evidenced by DUL and LL curves converging (closing the bucket). The total porosity (TP) was calculated from measured bulk density, while the DUL curve was obtained from cored samples taken in covered wet-up plots fitted with tensiometers to monitor the soil suction during the draining phase. The LLcrop is specific for a sorghum crop and comes from soil moistures collected after harvest.

Soil water potentials corresponding to LLsorghum moistures are plotted in Figure 1b. These values were obtained from multiple depth specific WRC's derived for this site. Post-harvest moistures were close to the LL15 (or drier) in the top meter of soil, becoming wetter at depths approaching the effective rooting depth (~ 1.5 m).

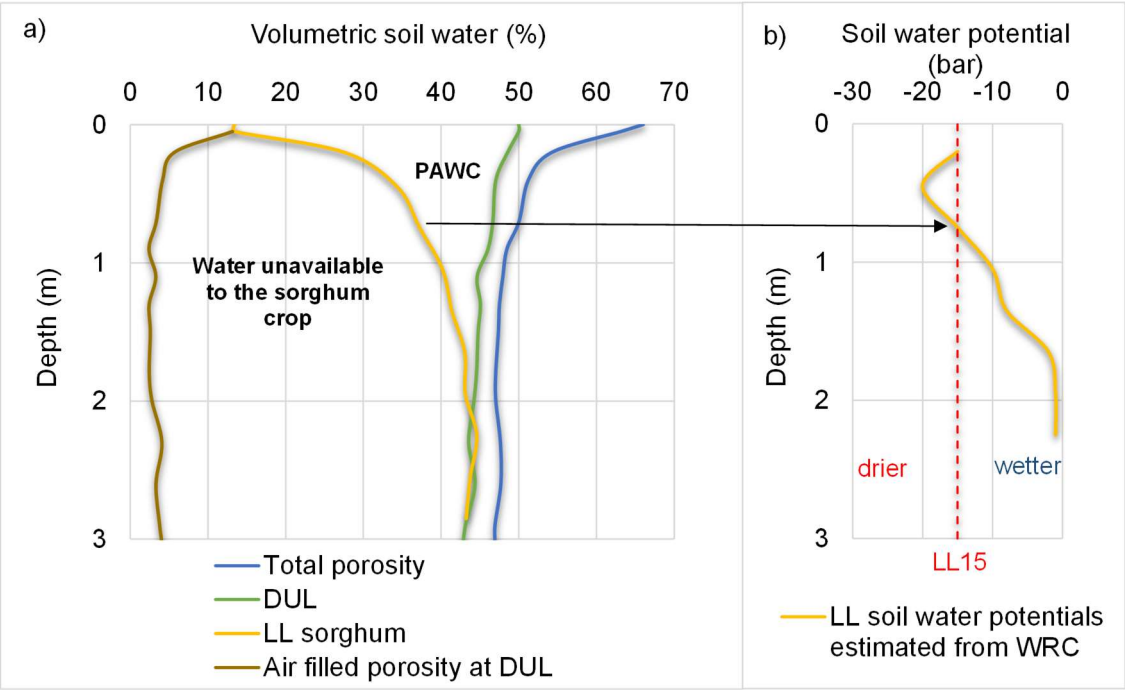

Figure 1 a) PAWC for a sorghum crop grown on a Black Vertosol soil (Darling Downs, Qld); b) water potential values estimated from LLsorghum moistures

Water Retention Curve

A WRC describes the relationship between soil water potential (ψ) (also referred to as suction or tension) and volumetric water content (θ) for a soil. Water potential defines the force with which water is held in the soil matrix. As the soil becomes drier, the water is held more tightly and more energy is needed by a plant to extract it. It is sensitive to changes in soil structure and texture, with more than one curve usually required to account for bulk density and texture changes down a profile.

Water potential is expressed in kilopascals (kPa) or bars.

Some common pressure unit conversions include:

1 kPa = 10 cm

100 kPa = 1 bar (approximate), 1022 cm = 1 bar (exact)

1 MPa = 10 bar or 1000 kPa

1 hPa = 1 cm

An example WRC is provided in Figure 2. This function was derived for a Grey Vertosol soil using the rapid–WRC–method. From this curve, both the DUL and LL15 can be estimated.

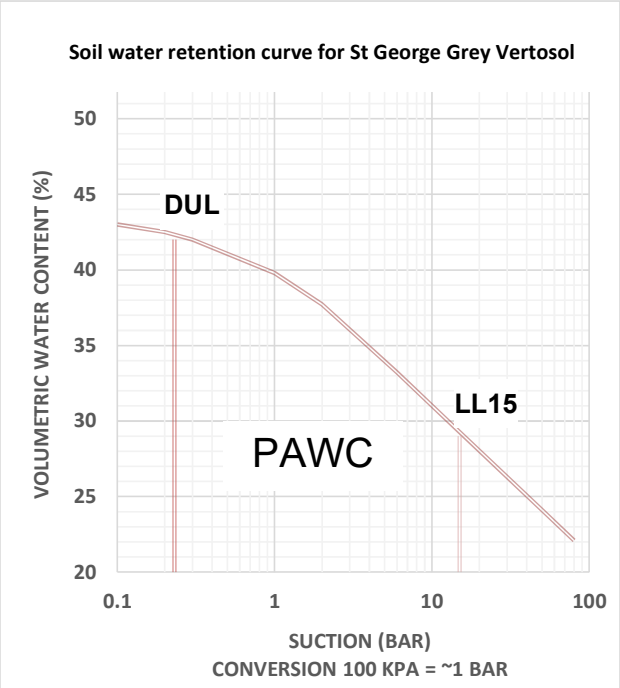

Figure 2 WRC showing the upper (DUL) and lower (LL) limits of the PAWC for a Grey Vertosol

Using this WRC function, the degree of wetness/dryness (and potential plant stress) for any soil moistures collected at the site can be inferred. For example, soil moistures as low as 25% volumetric were measured in a lucerne crop at the site where this WRC was derived. From the WRC we can estimate that the soil suction at 25% volumetric is approximately 4000 kPa (40 bar). This was confirmed through psychrometric analysis of soil samples taken in the lucerne crop, with measured suctions ranging from 4000 to 4300 kPa.

Note: The terms water potential and matric potential can be used interchangeably with the terms soil suction or matric suction. Negativity is implied when using the term suction, i.e. –10 kPa water potential is equivalent to 10 kPa suction.

Simple "cascading" water balance models such as APSIM-Soilwat and HowLeaky utilise PAW, SAT, DUL and LLcrop parameters derived from *in situ* field measurements. More complex soil water balance models such as APSIM-SWIM & HYDRUS use a one-dimensional simulation of water fluxes through a numerical solution of the Richards equation for the simulation of water movement and uptake by plants. These models require a WRC function to define the relationship between the soil water potential and volumetric water content. The values of SAT, DUL, and LL are used to describe three points on the soil water retention curve, $\theta(\psi)$, along with the oven dry water content (Huth et al. 2012). These three water contents are assumed to correspond to potentials of -0.1, -10 & -1500 kPa respectively.

Soil phases

There are a number of ways to describe the volume and mass relationships of the three phases (solid, water, air) of a soil. Figure 3 shows a diagram of a hypothetical soil with the phases separated and stacked (Cresswell & Hamilton 2002). The masses of each phase are shown on the right side and the volume equivalents on the left side. These are used to provide a guide to the quantitative expressions that are of most interest in this section because they are used to calculate a PAWC or WRC.

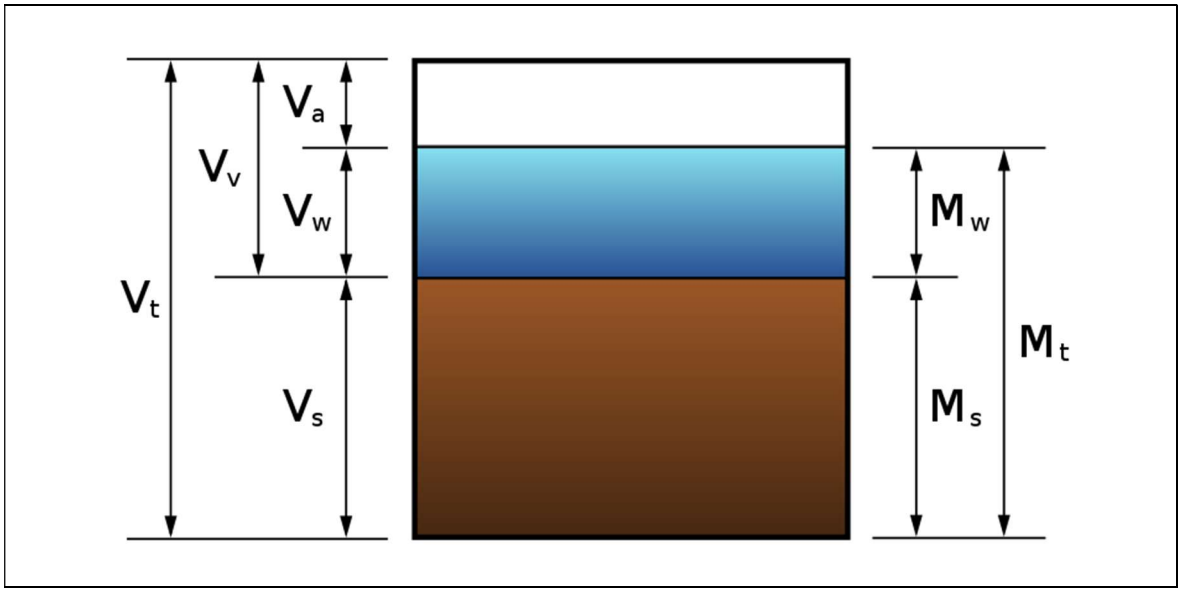

Figure 3 Soil composition by Volume and Mass, by phase: air, water, void (pores filled with water or air), solid, and total (V_s–solid, V_w–water, V_a–air, V_v–voids, V_t–total). (Image provided by Derivative Work)

Expressions of soil water include:

- Gravimetric soil water content (θg) – this is the ratio of soil water to oven dry soil (grams of water per grams of dry soil – g/g). This is depicted in Figure 3 as mass, M_w/M_s,
- Soil bulk density (BD or ρ, g/cm^3) – this is the weight of dry soil (mineral solids–V_s) divided by the total soil volume – V_t (the combined volume of solids (V_s), water-filled soil pores (V_w) and air-filled pore spaces (V_a)). BD can be used to determine how much water a soil can hold, i.e. from the total porosity amount, and it is a useful indication of a soil's physical condition, suitability for root growth and soil permeability. It is affected by the structure of the soil (looseness or degree of compaction) as well as by its swelling and shrinkage characteristics (in turn dependent on clay and water content) (Hillel 2003),
- Volumetric water content (θv) – this value is calculated by multiplying the gravimetric water content and the soil bulk density. It is the ratio of the volume of soil water Vw

(cubic cm or mm) to the volume of dry soil Vs (with units of cubic cm or mm). These measures are used to compare water contents of different soils, experimental treatments, or to look at spatial and temporal variations. This information is used when calculating a PAWC or a soil water deficit.

Calculations

The following calculations are required for determining soil water content, PAWC and related measurements:

$$\textbf{Gravimetric soil water content } (\theta g) = \frac{\textbf{wet weight soil (g) – oven dry weight soil (g)}}{\textbf{oven dry weight soil (g)}}$$

Note: if a sample is being weighed inside a sample bag/container the bag weight must be subtracted from the overall weights

$$\textbf{Soil bulk density (BD) } (\rho d) \textbf{ (g/cm}^3\textbf{) = oven dry soil weight (g) / core volume (cm}^3\textbf{)}$$

Core volume (V) = $\pi r^2 h$, where V is the Volume, r is the radius of the core, h is the core length, and π is the constant pi.

The core volume can be calculated using the following formula in an excel spreadsheet

= (3.1416*(((core diameter/10)/2)^2)*(core length/10)

Note: this equation converts core diameter and length units from mm to cm.

$$\textbf{Volumetric soil water content } (\theta v) \textbf{ = gravimetric soil water content (g/g) x BD}$$

BD measurements can be used to provide additional useful information, including an estimate of the wet-end components of the PAWC (i.e. DUL) and information about the soil porosity.

$$\textbf{Total porosity (TP) = 1 – (BD/2.65)}$$

Where 2.65 is the particle density of the mineral component of the soil. For most soils, this value is ~ 2.65 g/cm^3 because quartz has a specific gravity of 2.65 to 2.67 g/cm^3 and quartz is usually the dominant mineral. Inorganic clays generally range from 2.70 to 2.80. Soils with large amounts of organic matter or porous particles may have specific gravities below 2.60.

The total porosity (V_v) or volume of void spaces in a soil provides a good indication of suitability for root growth, soil condition and permeability. It is a valuable reference point when interpreting the degree of 'wetness' of the measured volumetric moistures, e.g. is the void space mostly water filled (wet) or air filled (dry)? As an example of this, an excel spreadsheet is provided in Table 1. This core was taken in an irrigated crop. The last two columns show the calculated TP and fraction of the total void space that is air filled. The air filled void space (column R) suggest there has been considerable crop water uptake in the top 0.5 m of the soil (voids are mostly air filled). However, below 1.1 m the fraction of air

filled void space is small (pores are mostly water filled) suggesting little soil water is being extracted at this depth. The very small amount of air filled void space in the 1.3–1.5 m layer (1.3%) suggests the soil is likely to be saturated. This was later confirmed using tensiometric methods.

Soil at saturation (SAT) = TP – entrapped air (~ 3%)

SAT is calculated using the above equation. It can be difficult to measure in the field. Saturated soils with a high clay content may be too wet and sticky to sample using hand coring techniques, while vehicle access may not be possible when using a soil coring rig. Free draining sandier soils may also be difficult to sample at saturation because they drain so rapidly there may be insufficient time to collect a sample while macropores are still water filled.

A value of 3% for heavy clays and 6-8% for sandy soils (Dalgliesh & Foale 1988) is commonly subtracted from the TP value to allow for air entrapment within the soil pore structure. However, we commonly observe long–term water logged or frequently irrigated soils having 1% air or less (due to de–airing). We have also measured air contents at saturation as high as 8% in some Black Vertosols (heavy clays) with low BD's (~ 1).

Drained upper limit (DUL) = SAT – Drainable porosity (DP)

DUL is calculated by subtracting the drainable porosity (DP) from SAT. The DP is the volume of soil water held between SAT and DUL. It is a function of the physical characteristics of a soil, i.e. texture, porosity attributes and BD. DP may be as low as 2–5% for fine textured soils (i.e. heavy clay Vertosols) and as high as 20-30% for free draining sandier soils or cultivated layers. The only way to know the exact DP is to measure the soil at SAT and DUL. Relationships have been developed that estimate DP using information about a soil's TP and soil moisture (g/g) to calculate a saturation fraction.

Plant available water capacity (PAWC) = DUL – LL x depth interval (mm)

(cumulative over rooting depth)

A PAWC soil characterisation is often determined only once for a soil type, while the LL component is measured for each crop type on each soil type (Dalgliesh & Foale 1988). However there is the potential for significant errors if generic soil type PAWC's are used to parameterise a soil water balance model that also utilises field specific data (e.g. runoff data) pertinent to the hydraulic behaviour of individual fields.

PAWC is sensitive to changes in soil BD/porosity. These attributes determine the overall volume of pores and pore characteristics (size, shape, connectivity) that hold water in a soil. As BD increases, the overall volume of pore spaces available to hold water decreases. Likewise the ability to store water decreases, resulting in a smaller PAWC bucket size. For every 0.1 increase in BD, there is a 3.8% decrease in the total porosity, the soil phase that stores and transmits water.

BD/porosity varies both as a result of naturally occurring spatial variability in a soil and as a consequence of land management practices that alter the pore structure of a soil, e.g. tillage, controlled traffic, compaction from heavy machinery. BD increases with compaction and tends to increase with depth.

Table 1

Column	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
	Area:		**Owner:**			**Date:**				**Sampled by**					**Data entered by**			
	Treatment	Rep	Depth (cm)	Av Depth (m)	Adjusted depth	Bag wt (g)	Wet wt (g)	Oven Dry wt (g)	θg (g/g)	θg (%)	Average Core Length (mm)	Core Diameter (cm)	V_T (cm3)	Bulk Density	θv (v/v)	θv (%)	Total Soil Porosity *f* (cm3/cm3)	Air filled void space *e* (cm3/cm3)
Row																		
5	1	1	0-10	0.05		9.74	183.58	156.88	**0.181**	**18.15**	100.0	4.415	153.1	0.961	**0.174**	**17.4**	0.637	0.463
6			10-30	0.20		9.74	403.11	341.83	**0.185**	**18.45**	199.0	4.415	304.7	1.090	**0.201**	**20.1**	0.589	0.388
7			30-50	0.40		9.74	529.00	446.40	**0.189**	**18.92**	198.5	4.415	303.9	1.437	**0.272**	**27.2**	0.458	0.186
8			50-70	0.60		9.74	585.0	485.1	**0.210**	**21.02**	201.5	4.415	308.5	1.541	**0.324**	**32.4**	0.419	0.095
9			70-90	0.80		9.74	492.3	409.3	**0.208**	**20.77**	166.5	4.415	254.9	1.568	**0.326**	**32.6**	0.408	0.083
10			90-110	1.00		9.74	649.5	532.1	**0.225**	**22.47**	220.0	4.415	336.8	1.551	**0.349**	**34.9**	0.415	0.066
11			110-130	1.20		9.74	615.4	504.1	**0.225**	**22.51**	200.0	4.415	306.2	1.615	**0.364**	**36.4**	0.391	0.027
12			130-150	1.40		9.74	618.9	508.8	**0.221**	**22.06**	197.5	4.415	302.4	1.651	**0.364**	**36.4**	0.377	0.013
											=(3.1416*((L5/2)^2))*(K5/10)					=1-(N5/2.65)		
													=(H5-F5)/M5				=Q5-O5	

Sample excel spreadsheet showing columns of soil core data and calculations to obtain core volume, BD, TP and void spaces using the volumetric soil moisture data.

Field sampling for PAWC and WRC

In this section we provide details of how to collect soil samples for PAWC and WRC determination using procedures developed by the DNRME Science team.

When planning a sampling strategy, it is important to factor in the degree of variability/uniformity in soil type across the area to be sampled. This will determine coring locations, the number of cores needed, and also whether separate management units for fields with distinct variability are required.

When taking the soil cores in the field aim to:

1. take sufficient cores to sample the soil variability in the field/area of interest,
2. collect a sufficient number of cores for the laboratory procedure,
3. aim for some replication,
4. treat each layer in texture contrast soils discretely, i.e. use a flexible approach when core cutting to preserve discrete layers. Don't pool different layers,
5. record a GPS location where a soil core has been taken,
6. collect an additional soil core for a soil morphology description at each new site.

For PAWC/WRC sampling 'cluster coring' is preferred, i.e. 3 cores taken close together, followed by another 3 cores taken some distance away. Coring should occur during suitable field conditions. Ideally the soil should be moist, at DUL or wetter, but sufficiently dry for vehicle access. Don't sample soils (particularly swelling clays) when surface layers are extensively dry and cracked as this will produce errors in the BD estimates.

If the soil cores are to be used for both PAWC and WRC determination, two different types of samples are required:

1. *Gravimetric water content and soil bulk density for PAWC.* These samples are ~ 0.2 m core lengths (see top cutting configuration shown in Figure 4). The length and width of each core must be *accurately measured* and recorded. **Taking shortcuts in this step is the single biggest contributor to errors. These errors affect all other calculations and the PAWC/WRC derivations** (Verburg et al. 2001). Measure core lengths initially to get an approximate 0.2 m cut, then cut the core sections vertically while holding/supporting the core near the cut line to prevent crumbling. After each core has been cut, use a metal ruler to accurately measure the cut core length. Take at least two length measurements (in different locations around the core circumference) and record the average value (see Photo 3). Work quickly to avoid the soil drying out in the field. Don't expose a core to the atmosphere (by removing it from the coring tube) until you are ready to cut and bag the samples.

If the soil is wet, compression of soil in the coring tubes may occur while the coring tube is being pushed into the soil. To minimise this, take smaller core lengths each time the coring tube is driven into the soil. We commonly sample down to ~ 0.6 m depth in a wet profile, then core the remaining depth by inserting the tube in the same hole a second time. This means the coring tube will need to be inserted multiple times to obtain 1.5 m of core sample, however it prevents wet soils compressing in the tube.

Measure the total depth cored (using a measuring tape placed down the hole) and compare this to the length of core obtained, to ensure no/minimal core compression or expansion has occurred.

A blank field sheet with suggested columns for entering the data is provided at the end of the document.

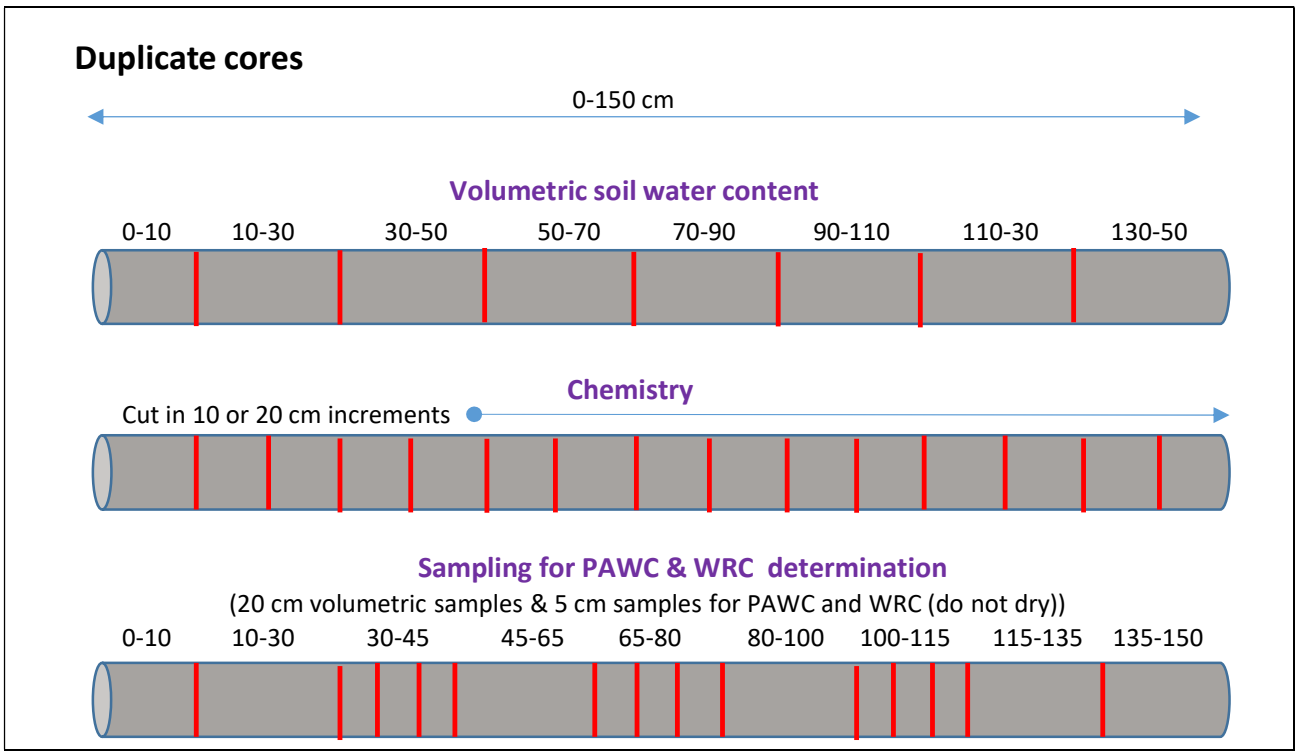

Figure 4 Examples of core cutting and sampling layouts – length units are in cm

Use callipers to measure the *internal cutting tip diameter* of the soil coring tube (see Photo 3). BD is very sensitive to the core diameter measurement. If using different coring tubes to take the samples, record which tube is used for each core sampled and measure the cutting tip of each tube.

The 0.2 m core samples are weighed and dried at 105°C for 7–10 days, then reweighed to determine gravimetric water content. The core volume measurements are used to calculate BD and volumetric water content.

Photo 3 Measuring the internal cutting diameter of the soil coring tube using callipers

2. *Laboratory psychrometer (WP4-C) samples for WRC determination*. A number of small sub-samples are collected from soil cores, at specific depths of interest, and then used to develop a WRC (Photo 4 & Photo 5). These depths are usually either discrete soil layers down the profile or they may be key layers needed to inform a modelling process. Examples of soil cutting layouts are provided in the bottom core cutting configuration shown in Figure 4.

Accurate BD measurements of the soil depths directly above and below these 5 cm sub-samples is vital.

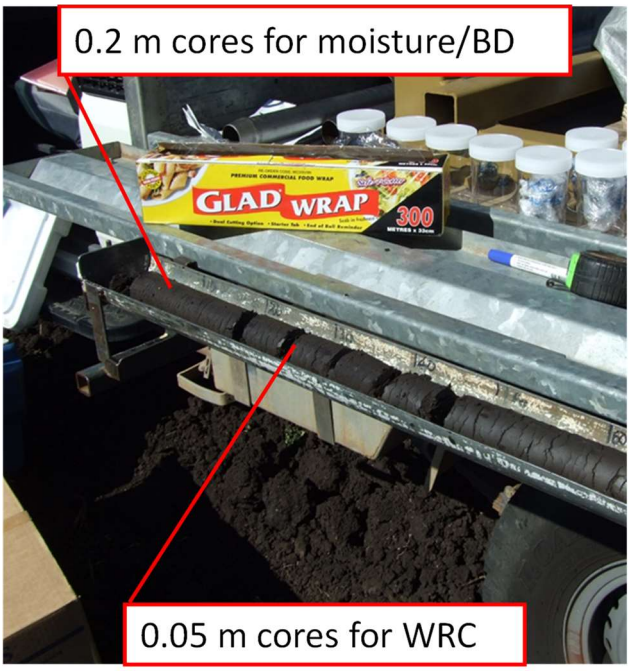

Photo 4

0.2 m soil core cut for bulk density and gravimetric soil moisture. Core length is accurately measured using a metal ruler.

Photo 5

0.05 m samples taken to obtain a series of psychrometer readings in the laboratory using a WP4-C dewpoint potentiometer. No core dimension measurements are required for the 0.05 m samples.

Make sure each 0.05 m sample is wrapped in several layers of plastic wrap then placed into a sealed bottle to prevent cores drying out (Photo 4 & Photo 6). Ensure there is sufficient space between soil core samples and the sides of the plastic bottles so that they can be easily removed. The samples need to remain intact. Complete the cutting, wrapping and bottling of these samples as rapidly as possible in the field to prevent them drying out (within 2 minutes of exposing the core to the air). Consider covering the whole core with a 'just-damp'

towel if it is hot and/or windy, and only peel back the cloth to expose sections of the core as needed.

Store the bottled samples in an eski away from direct sunlight if coring during summer months. The samples should not 'sweat' as this results in moisture loss. Placing ice in the eski or near the cores is not recommended as this can cause moisture to condense on the samples.

Photo 6

Samples for psychrometer analysis wrapped in plastic wrap and sealed in a labelled specimen bottle

Bulk density measurement

As there are many misconceptions about the application (and appropriateness) of various methods of measuring BD, the most commonly used methods are briefly discussed here.

A common (traditional) method of measuring soil BD involves collecting a known volume of moist soil within a metal ring (Dalgiesh & Foale 1988; McKenzie et al. 2002). An undisturbed surface is prepared at various depths in the soil using an excavator or shovel. The rings are then pushed or hammered into the soil to obtain the samples, which are weighed after drying (Photo 7).

Photo 7 BD ring used to collect a known volume of soil

This method is used to collect samples for pressure plate WRC derivation methods, however we do not use it in the rapid–WRC–method.

Another method that has been used for many years to accurately determine BD involves taking soil cores using a large 100 mm diameter coring tube (Photo 8) (Cresswell & Hamilton 2002). While this method avoids the need to dig pits and provides easier access to soil at depth, it is never–the–less a time consuming procedure and is usually only undertaken once to characterise a site.

While both sampling methods yield highly accurate data, the values obtained from these localised and intensive sampling endeavours often become the 'standard BD values' used to calculate volumetric moistures across an entire field. They may even be used for a number of years. However, BD is so locally and temporally variable that this inevitably leads to errors in calculated volumetric moistures. Ironically the accuracy of the method is lost in the application of the results.

Photo 8 Large diameter soil coring apparatus used to take BD measurements

A study was conducted by the DNRME science group several years ago where traditional 100 mm diameter soil cores and thinner cores (45-38 mm diameter cores) were collected together in a paired study on a range of Vertosol and Dermosol soils in cultivated and pasture/treed land uses. There was little to no discernible difference in BD values, or loss of accuracy, when replacing larger diameter coring with smaller diameter coring.

The DNRME science team utilise the methods described in the 'Field sampling for PAWC and WRC' section to measure soil BD. Measurements are taken every time a soil core is taken and therefore spatial, temporal and depth variations are fully accounted for. There are also considerable time saving advantages associated with taking smaller cores and this method can be adopted during all soil soiling procedures. When taking cores for EMI soil–water calibrations, this method must be used to obtain accurate results.

Rapid–WRC–method

The rapid–WRC–method is a laboratory-based procedure that uses the dewpoint method (psychrometer) to measure water potential (ψ) after the moisture content (θ) of a number of core samples have been manipulated to create a range of $\theta(\psi)$ data points. Because measurements are made directly on undisturbed soil cores, the inherent soil structure/pore configuration is retained and measurement is possible that reproduces semi *in situ* hydraulic behaviour.

The dewpoint method is one of the most accurate and rapid methods for determining the WRC ($\theta(\psi)$) relationship in the drier –200 to –10 000 kPa range (Leong et al. 2003; Agus & Schanz 2007). In this method, a chilled mirror dewpoint technique is used to determine the relative humidity of the air above a soil sample in a closed chamber. At temperature equilibrium, relative humidity is a direct measure of water potential (Gee et al. 1992; Campbell et al. 2007).

To obtain $\theta(\psi)$ data in the wetter range, mini tensiometers are installed in moist intact cores to measure water potential. These values are added to the drier range WRC and may be used to estimate a theoretical DUL. DUL can be reasonably approximated when the soil has a water potential of around –20 kPa for most clay soils (Rajkai et al. 2004) and –10 kPa for sandy soils.

The WRC $\theta(\psi)$ relationship differs between wetting or draining soil pore states due to hysteresis. Soil tends to hold onto more water at specific potentials when it is draining than when it is wetting up, i.e. water is given up less freely than taken in. For this reason, we make all rapid–WRC–method measurements on soils that are in a draining phase.

Laboratory procedure

When samples first come in from the field, they are stored in a constant temperature room for a few days and 'allowed to settle' at this temperature. Antecedent moisture and water potential is then measured on a small subset of the 0.05 m core samples. This information is used to determine the moisture status of the cores and likely drying times needed to induce a range of moistures, or even if they need a rewetting/drying cycle. Individual core samples are then dried in an oven at 40°C for varying amounts of time, e.g. 0.5, 1, 1.5, 2, and 3 hours. After drying, they are re–wrapped, sealed and stored in a constant temperature room for 7+ days to allow moisture levels to equilibrate throughout the entire core sample.

A dewpoint potentiometer (WP4-C, Decagon Devices Inc., Washington, USA), also known as a psychrometer, is used to measure water potential in drier samples (see Photo 9). A small amount of the core is placed in the WP4-C chamber and a reading is available after 4 minutes. Logged output can be monitored for 20-30 minutes to confirm the reading has stabilised. The remaining core sample is oven dried at 105°C for a week to obtain a corresponding gravimetric water content. These are converted to volumetric water contents using BD measurements from the larger core samples cut on either side of the 0.05 m increments.

Wet-end measurements are obtained from the wetter soil core samples (> –160 kPa) using T5x mini-tensiometers (UMS, Germany) (see inset photo in Photo 9). A micro auger is used

to cut a pilot hole in the core, then the tensiometer is installed and left to equilibrate. A reading is taken once no change has been detected for over an hour.

Because all measurements are made on intact cores, there is no need to correct the data for lack of overburden pressure, as is required (but rarely done) for swelling soils if they have been wet up to SAT then drained on pressure (or ceramic) plates.

We also have the capacity to rewet drier soils to SAT then allow them to drain on ceramic plates using the hanging water column method (Klute 1986) to obtain WRC data in the moisture range from SAT to -10 kPa. However, this method becomes considerably more complex for swelling clays, because unconfined swelling occurs on the plates due to a lack of overburden pressure.

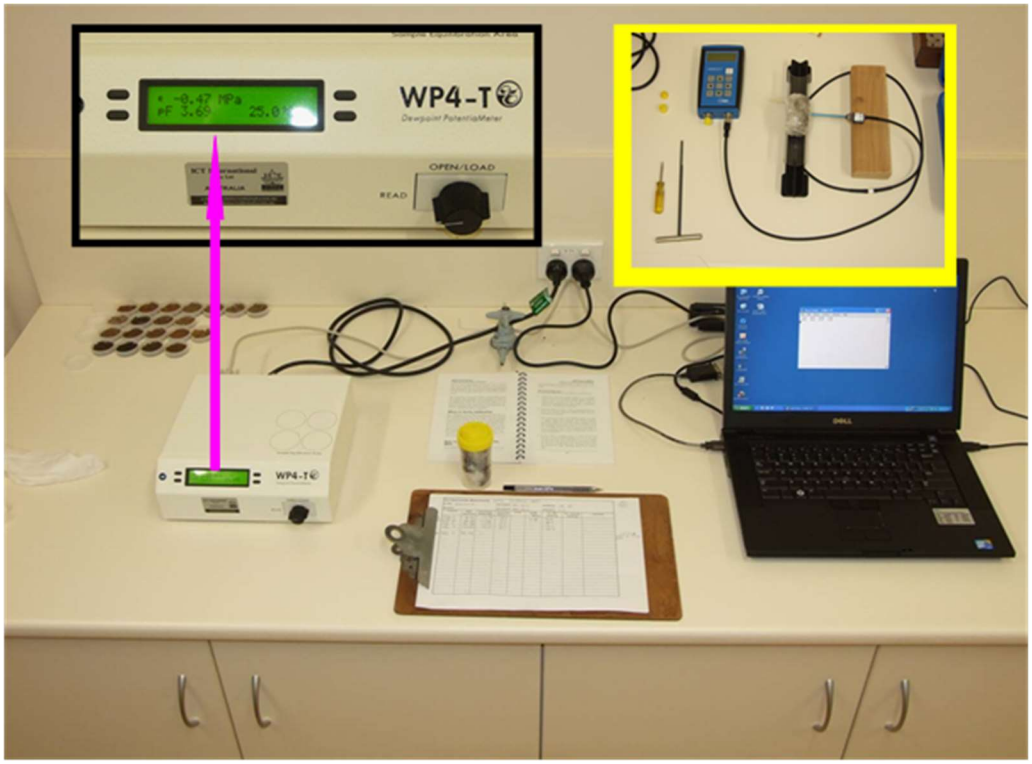

Photo 9 WP4 psychrometer used to measure water potential in drier soil and mini tensiometers used to measure water potential in moist soil cores

An example WRC dataset

Once we have a WRC function, water potential can be estimated for any measurement of water content taken in the field. The WRC functions derived using the rapid–WRC–method provide a LL15 estimate, as well as considerable information beyond this potential. This is useful in treed and grazing studies where soil moistures are often well below 1500 kPa (LL15).

An example of the (drier end) data obtained from manipulating core moistures is shown in Figure 5. Water content is linearly related to the logarithm of water potential (negative suction). The slope can be used to predict LL. For this particular Black Vertosol the predicted

LL15 is 38.7 %. Any desired θ(ψ) in the drier range can be accurately determined using the regression function.

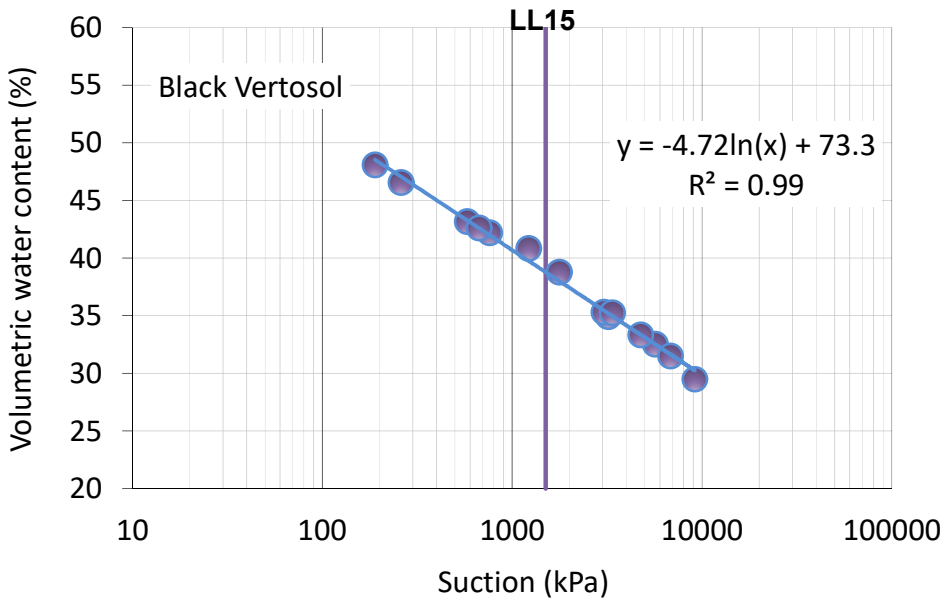

Figure 5 Drier range WRC for a Black Vertosol – soil suction measured (using a WP4-C) across a range of moistures in core samples dried for between 1-4 hours

A full WRC measured for this site is also provided in Figure 6. In this figure, three methods for deriving WRC data sets have been depicted and are compared at two depths in the soil profile:

1. Lab WRC – small intact cores were taken at depths of 0.4 and 0.7 m and θ(ψ) measured using the standard hanging water column and pressure plate apparatus methods (Klute 1986). These curves have been adjusted for lack of overburden pressure on the plates,
2. Insitu field – these rare and opportunistic measurements come from water potentials directly measured in the field using tensiometers (UMS T8) permanently installed at 0.4 and 0.7 m depths in the sampling area. Logged readings are matched to the times when soil cores were collected for volumetric moisture determination,
3. Rapid–WRC–method – small core moistures were manipulated using the rapid–WRC–method, to derive drier range data (the same data that is depicted in Figure 5).

The *in situ* field values align well to the lab WRC's once the curves have been adjusted for overburden pressure. This confluence validates the appropriateness of the overburden corrections (Neil Huth, personal communication).

The data match between the rapid–WRC values and those measured using the other methods is good in the drier range. Water content is overestimated in the wetter range (200–250 kPa), however this is beyond the effective working range of the WP4-C (too wet) so some discrepancy is to be expected.

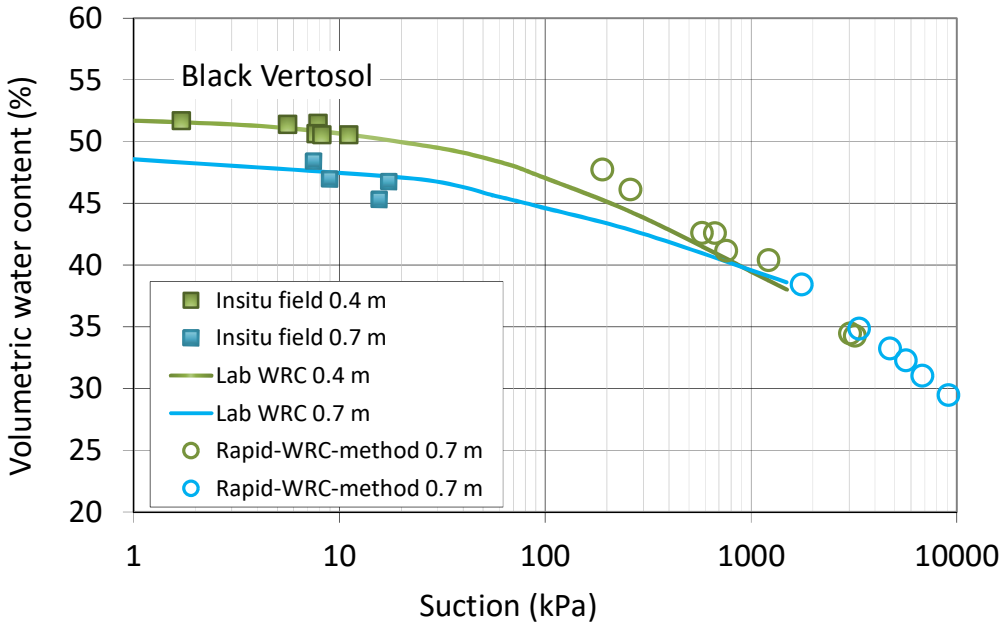

Figure 6 WRC's at 0.4 & 0.7 m depths obtained from using standard methods, measured in the field and using the rapid–WRC–method

Overburden

Adjustments for overburden pressure (or lack of) are required when using traditional pressure plate methods to derive a WRC for swelling soils. Overburden pressure is a naturally occurring phenomenon in the field. It is equivalent to the weight of soil above any depth within a soil profile. The deeper the soil, the heavier this weight, and the greater the restriction it places on a soils' ability to take in water and increase in volume (swell) upon wetting. When this overburden is removed (as occurs when samples are processed in a laboratory) the soil can swell and take in significantly more water than would be possible with an *in situ* overburden restriction. At depths beyond 0.3 m this can affect the $\theta(\psi)$ relationship, resulting in significantly inflated θ at a given ψ. Shallow depths are less affected because the weight of overlying soil in the field is small or negligible.

Theoretical adjustments for lack of overburden pressure are possible, but complex if the BD deviates from 1 (Ross & Prebble 1989).

There is no need to apply an adjustment to data measured on rigid soils.

Because overburden pressure is rarely applied to samples in conventional pressure plate apparatus, the resulting WRC function inevitably overestimates the $\theta(\psi)$ relationship in the wet range (only for swelling clay soils – smectite dominant). The rapid–WRC–method avoids these potential overburden related errors by using intact cores that have been wet up naturally in the field under normal confining pressures.

References

Agus SS, Schanz T (2007) Errors in total suction measurements; In *Experimental unsaturated soil mechanics,* T. Schanz (Ed.); 112 Springer Proceedings in Physics, 2007, 59-70.

Campbell G, Smith DM Teare BL (2007) Application of a dewpoint method to obtain the soil water characteristic; In *Experimental unsaturated soil mechanics,* T. Schanz (Ed.); 112 Springer Proceedings in Physics, 2007, 71-77.

Cresswell HP, Hamilton GJ (2002) Bulk density and pore space relations. Chapter 3. In 'Soil physical measurement and interpretation for land evaluation', McKenzie N, Coughlan K, Cresswell H. CSIRO Publishing: Collingwood, Victoria.

Dalgliesh NP, Foale MA (1998) Soil matters: Monitoring soil water and nitrogen in dryland farming. Toowoomba, Queensland, Australia: Agricultural Production Systems Research Unit.

Gee GW, Campbell MD, Campbell SG, Campbell JH (1992) Rapid measurement of low soil water potentials using a water activity meter. *Soil Science*, 56, 1068-1070.

Hillel D (2004) Introduction to environmental soil physics. Amsterdam; Boston: Elsevier Academic Press.

Huth NI, Bristow KL, Verburg K (2012) SWIM3: Model use, calibration, and validation. *Transactions of the ASABE*, 55(4), 1303-1313.

Klute A (1986) Water Retention: laboratory methods. In 'Klute A (Ed.), Methods of soil analysis. Part 1', 2nd ed. *Agronomy Monograph*, 9, ASA and SSSA, Madison, WI, 635-662.

Ladson T, Lander J, Western A, Grayson R (2004) Estimating extractable soil moisture content for Australian soils. Technical Report 04/3, June 2004, Cooperative Research Centre for Catchment Hydrology.

Littleboy M (2002) Integrating biophysical modelling and soil properties for quantitative land evaluation. Chapter 24. In 'Soil physical measurement and interpretation for land evaluation', McKenzie N, Coughlan K, Cresswell H. CSIRO Publishing: Collingwood, Victoria.

McKenzie N, Coughlan K, Cresswell H (2002) Soil Physical Measurement and Interpretation for Land Evaluation. CSIRO Publishing: Collingwood, Victoria.

Rajkai K, Kabos S, van Genuchten M.Th (2004) Estimating the water retention curve from soil properties: comparison of linear, nonlinear and concomitant variable methods. Soil & Tillage Research, 79, 145–152.

Ratliff LF, Ritchie JT, Cassel DK (1983) Field-measured limits of soil water availability as related to laboratory-measured properties. Soil Science Society of American Journal, 47, 770-775.

Ritchie JT (1981) Water dynamics in the soil-plant-atmosphere system. Plant and Soil, 58, 81-96.

Ross PJ, Prebble RE (1989) Non-destructive measurement of soil clod volume using hexane displacement. *Australian Journal of Soil Research*, 27, 39-44.

Shaw RJ, Yule DF (1978) The assessment of soils for irrigation, Emerald, Queensland. Queensland Department of Primary Industries, Agricultural Chemistry Branch Technical Report 13, Brisbane.

Verburg K, Bridge BJ, Bristow KL, Keating BA (2001) Properties of selected soils in the Gooburrum–Moore Park area of Bundaberg. Technical Report 09/01, CSIRO Land and Water, Canberra, Australia.

Verburg K, Cocks B, Webster T, Whish J (2016) Methods and tools to characterise soils for plant available water capacity (North Star), GRDC Updates 03 March 2016. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2016/03/methods-and-tools-to-characterise-soils-for-plant-available-water-capacity-north-star

Soil composition image By Derivative work:

https://commons.wikimedia.org/w/index.php?curid=10590627

Suppliers of sampling bags and bottles

Chicken bags for soil samples (large unprinted foil-lined)

Chicken bags are an excellent option when collecting and bagging core samples in the field. Because they are foil-lined, they can be well sealed (roll down and scrunch the top), preventing moisture losses until the samples can be weighed.

These bags can be dried in an oven at 105°C. However if the oven has poor temperature regulation and is likely to exceed 105°C (even by 5-10°C) at any time during the drying process, we recommend that you dry the soil for the first ~ 5 days with the oven set to 100°C then turn up the oven to 105°C for the last 24 hours of drying. Otherwise the bags may scorch, and give off a burnt odour.

We purchase chicken bags at:
Toowoomba Wholesale Distributors
244 Anzac Ave, Toowoomba QLD 4350 Ph: 4630 1434
QTY: 250 Price: $29.30

Hospitality Store (Rewards)
Unit 5/12 Prescott Street, Toowoomba QLD 4350
Toowoomba store: 46381260 or 46381463
Code: PB-CBL, QTY: 250 L310 x W165 Price: $42.60

Jars for psychrometer samples
Labtek
PO Box 5316, 19 Leonard Cres, Brisbane PH: 1300881318

Jar size - depending on core diameter:

- 120ml, 108 x 44 mm, yellow capped specimen jars, pack 264, Product code: S10844UU-2
- 250ml, 100 x 65 mm, pack 147, Product code: S10065UU, Price: $67.00 per box

Soil Moisture and Bulk Density Measurements

Locality: **Date:** **Initials:**
Site Name:

Treatment	Plot	Sample description	Depth interval (cm)	Core Width (mm)	Core Length (mm)		Bag wt.	Wet weight (g)	Dry weight (g)	Comments