Soil hydraulic and salinity restrictions to water availability in very sandy soils

Thesis submitted by

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Summary of thesis

This study tried to evaluate the veracity of Grant and Groenevelt (2015) assertion that the inflection point on the water retention curve (WRC), plotted on semi-log scale, marks the onset of hydraulic stress in plants grown in sandy soils. That is, as the soil dries during drainage and evapotranspiration, there comes a point (argued to be the inflection point) when the unsaturated hydraulic conductivity cannot keep up with plant demand for water; thus, plants begin to suffer. Interest in the inflection point stemmed from the need to find unbiased criteria to weight the water capacity downward in the integral water capacity (IWC) model of Groenevelt et al. (2001) to account for soil hydraulic restrictions. If the inflection point was truly a good indicator of the onset of plant stress, then the matric suction at this point can easily be found from the fitting parameter, k_o (m), in Grant and Groenevelt (2015) water retention model; by coincidence it can also be found from the fitting parameter, $1/\alpha$ (m) in the water retention model of (Van Genuchten 1980).

The experimental components of this study consisted of two main parts: In the first part, water retention curves for a range of different sands and sandy soils were prepared, their inflection points identified, and two points on either side of the inflection point (wetter and drier) identified (**Chapters 3 and 4**). In the second part, wheat plants were grown in a glasshouse to Zadoks et al. (1974) growth stage 21 in pots of the different sands held, constant, at three different soil water suctions: at, above and below the inflection point (**Chapter 5**).

Detailed water retention curves were prepared using multiple replicates (up to 20) of four sands and two sandy soils (Very coarse sand, Coarse sand, Medium sand, Fine sand, Very fine sand, and Sandy loam) placed in small rings on ceramic pressure plates at different matric suctions ranging from saturation to 25 kPa or greater. Each of the individual sets of water retention data (up to 20) were fitted to the water retention models of Groenevelt and Grant (GG), and Van Genuchten (VG), and the inflection points identified from the appropriate fitting parameters. As might be expected, the different models produced slightly different inflection points, but these indeed corresponded pretty well (but not precisely) with k_o and $1/\alpha$ respectively. There was a strong inverse correlation between the mean particle size of the sands and sandy soils, and the values of k_o and $1/\alpha$; that is, the inflections points shifted to greater matric suctions as mean particle size decreased, such that the Very coarse sand had the smallest values of ko and $1/\alpha$ while the Sandy loam had the largest values of k_o and $1/\alpha$.

Because the VG model fitted the measured water retention data slightly better than did the GG model, the parameters from the VG model were chosen to identify the soil water conditions for

the plant experiments. The matric suction at the inflection point, h_i (m), was identified from $1/\alpha$, and this corresponded with the maximum differential water capacity, $C(h_i)$. The wetter, h_w, and drier, h_d, matric suctions were chosen to correspond with the matric suctions at 90 % of the maximum differential water capacity (on either side of the inflection point). The value 90 % was chosen as being close to the inflection point yet falling outside its 95 % confidence interval. The (up to) 20 estimates of hw, hi and hd were used to identify the corresponding volumetric water contents directly from the water retention curves, and these were averaged and converted to gravimetric water contents that could be used to set up the soil water conditions in the pot study.

Following a 6 x 2 x 3 completely randomised factorial design, litre-sized pots of each sand or sandy soil (5 replicates) were set up at the three different water contents corresponding to hw, hi and hd, (covered in plastic beads to minimise evaporation) and wheat seeds (2 different genotypes) planted and grown in them to growth stage 21. To keep soil water contents constant, daily pot weights were recorded and then water added (calibrated for increasing plant mass over time) to replace water evapo-transpired. The measure of plant response to the soil water conditions was the mass (fresh and dry) of shoots and roots.

Although one of the wheat genotypes performed significantly better than the other (consistent with the literature), the F-test or analysis of variance (ANOVA) indicated that the wheat genotypes never responded to the soil moisture conditions or matric suction effects at or surrounding the inflection point. Possible reasons for the lack of response to the soil moisture conditions may be related to the choice of the wet and dry-side matric heads, particularly on the dry side; that is, the matric suction on the dry side of the inflection point, which corresponded to 90 % of the maximum water capacity, may not be sufficiently dry to induce a hydraulic stress. Contrast to this, was the source of variation that arose from the three and two factor interaction effects on the dry weights of shoot and root respectively, which showed significant differences. However, this was not convincing enough for one to accept the null hypothesis of the study due to the inconsistent nature of trends observed in the dry weights obtained at or surrounding the inflection point matric suction. On this basis, the importance of the inflection point as a marker of hydraulic stress in plants is not rejected at this stage – further research is needed.

Declaration statement

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968. I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for some time.

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Date	**Justice Okona Frimpong**

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Dedication

I dedicate this thesis to my immediate extended family: siblings, mother (*Gladys Ekua Otomo, a widow*), little nephews and nieces, who supported me with prayers and guidance.

This is also dedicated to my distance relatives, Dr. Joseph Kwasi Ayim Boakye and Mr. William Atta Yeboah, formerly of the University of Cape Coast and Ghana Atomic Energy Commission respectively, church group members (Church of Pentecost, Hebron Assembly, Accra, Ghana) and everyone who wished me well from the time I begun this two years' academic journey.

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CHAPTER 1

General introduction

Globally, water sources in the earth's biosphere total approximately 14 billion cubic kilometers (Alley et al. 2002; Edwards et al. 1983; Home and Goldman 1994; Van der Leeden 1990; Veen and Boone 1990). Among all natural resources on earth, water is the most abundant and it covers 70 % of the earth surface. The oceans and seas constitute 97 % of the earth's water which is followed by ice and groundwater with other water sources (lakes, rivers, atmospheric and soil water) constituting less than 0.05 % (Lal and Shukla 2004). The lakes, rivers, and atmospheric water are the most used sources to replenish the ever-depleting soil water for crop production. Out of the 0.05 %, which constitutes other water sources, soil water forms 33 %, which sustains plant growth and development via metabolic and physiological processes such as photosynthesis and transpiration.

Transpiration and photosynthesis in plants require adequate supplies of water to replenish the soil water storage as plants increase in size and shape through cell division and tissue development. Restrictions to soil water uptake by roots due to soil physical properties must therefore, be minimised to sustain plant growth. However, variations in soil physical properties often occur such that limitations to water availability restrict free flow of water at all times (Da Silva et al. 1994; Groenevelt et al. 2004; Groenevelt et al. 2001).

Naturally, restrictions to plant available water (PAW) in soil may occur but restriction could also be induced when saline water is used for crop irrigation. The restrictions become more severe when the concentration of soluble salt, especially sodium chloride (NaCl), exceeds critical values. Excess NaCl in the soil solution increases the electrolyte concentration and causes saline condition (Stevens et al. 2003), and regular exposure of the soil to salt (e.g. by irrigating with recycled water) makes the soil vulnerable to sodification (Stevens 2009). The resulting high bulk density reduces water and air transport within the soil to plant roots (Laboski et al. 1998), all of which reduces soil water availability.

Many models have been developed over the past century to predict the amount of water in soil that is available to plants (Plant Available Water, PAW), including the Least limiting water range, Integral water capacity, Non-limiting water range and Classical plant available water concept (Da Silva et al. 1994; Groenevelt et al. 2001; Letey 1985; Veihmeyer and Hendrickson 1927). The integral water capacity (IWC) model of Groenevelt et al. (2001) has been evaluated in various contexts for example the work of Chahal (2010) and Nang (2012) but has not been widely evaluated in terms of its relevance to real plant soil water extraction. The IWC has been used primarily to predict PAW in soils in the absence of plants by developing hypothetical weighting functions to account for various restrictions, including: hydraulic (Grant and Groenevelt 2015; Groenevelt et al. 2001) and salinity restrictions (Groenevelt et al. 2004), and it has also been correlated with measures of soil quality (Asgarzadeh et al. 2011; Asgarzadeh et al. 2014; Asgarzadeh et al. 2010; Grant et al. 2003).

Of particular interest in this study are the restrictions to PAW caused by hydraulic and salinity restrictions because of the increasing use of saline recycled water for irrigation of sandy textured soils, which possess inherently limiting hydraulic properties. Related issues of water quality for crop irrigation will also be reviewed here, as will some of the important models available for predicting PAW, their weaknesses and strengths. Of particular focus, will be an evaluation of the IWC as a measure of PAW through the application of hypothetical weighting functions in very coarse sands.

CHAPTER 2

Literature review

2.1 Plant available water

The concept of PAW has been defined historically (Gardner 1960; Richards and Wadleigh 1952; Veihmeyer and Hendrickson 1927) as the amount of soil water held between matric heads of h = 0.5 or 1 or 3.3 m (known as 'field capacity' or the 'drained upper limit') and h = 150 m (known as the 'permanent wilting point' (Veihmeyer and Hendrickson 1927). This definition assumes equal and total water availability to plants within the boundaries of field capacity and permanent wilting point and total non-availability of water outside these boundaries. The real amount of water available to plants, however, is restricted by various limiting soil physical and chemical factors (Da Silva et al. 1994; Groenevelt et al. 2001; Hillel 1998), hence the classical definition of PAW is the maximum amount of water that a plant can extract from the soil; all other estimates are smaller than PAW.

A broader definition of PAW is the amount of water that can be stored in a soil and released with time for plant uptake during the growing season (Richards and Wadleigh 1952). This definition acknowledges the water release properties of the soil matrix, which depend on the soil texture as well as the environmental demand or potential evapotranspiration (Richards and Wadleigh 1952). Typical water release (or retention) curves are shown for two soils of different texture in **Figure 2.1.**

According to Gardner (1960) plant roots extract water using small differences in soil matric suction within the available water range until the water content approaches the wilting point, whereupon the gradient in matric suction increases dramatically. The PAW concept was re-defined as an integral by Gardner (1960) in the relation:

$$PAW \equiv \int_{h=3.3m}^{h=150m} \frac{d\theta}{dh} dh = \int_{h=3.3m}^{h=150m} C(h) dh \qquad , \qquad [1]$$

where dθ/dh is the modulus of the slope of the water retention curve or classical differential water capacity, C(h). The matric head at the lower boundary, h = 3.3 m (or 1m or 0.5 m), represents the energy status of soil water after drainage from saturation under the influence of gravity, while the matric head at the upper boundary, h = 150 m represents the energy status of soil water at which most economically important crops do not recover from diurnal wilting (Gardner 1960; Veihmeyer and Hendrickson 1928).

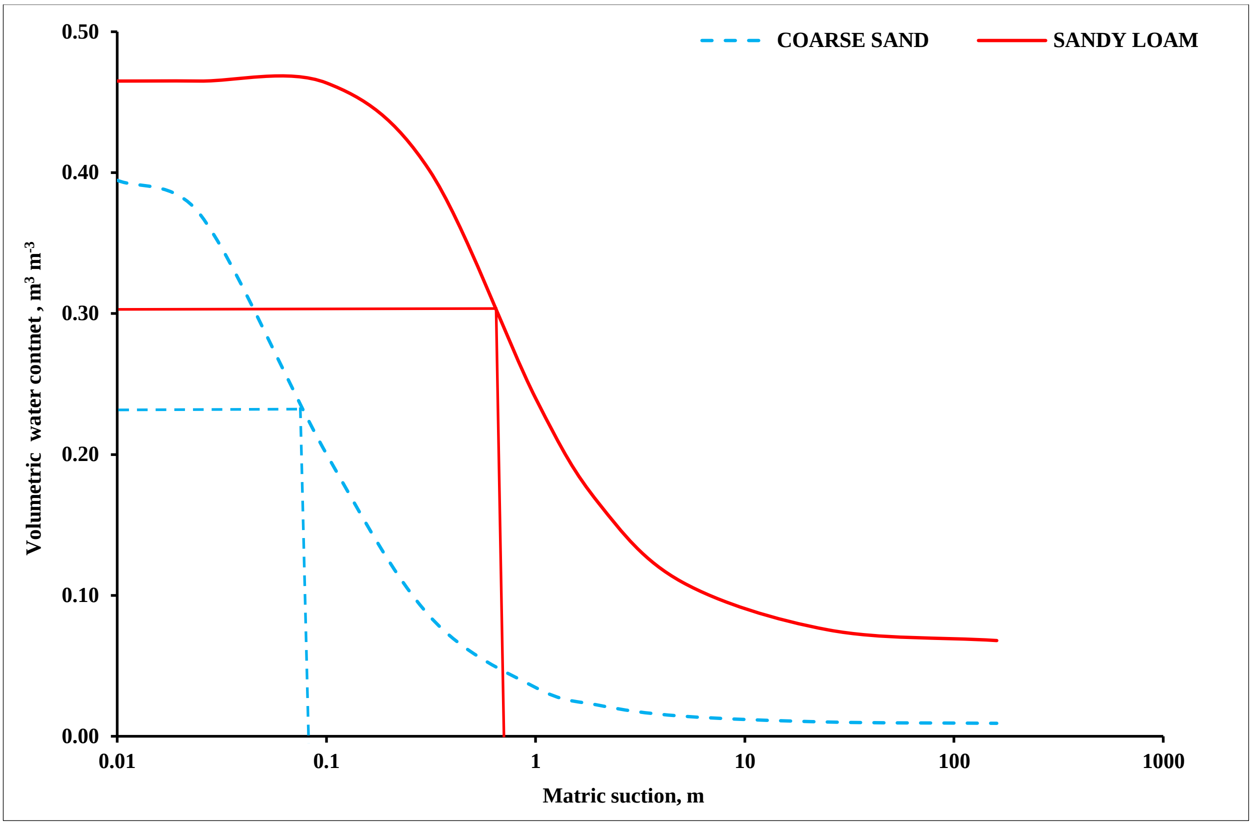


Figure 2.1. Water retention curves for a coarse sand (dashed line) and a sandy loam (unbroken line), adapted from Rijtema (1969).

Plants face restrictions in water availability even though water may be present in the pores defined by Veihmeyer and Hendrickson (1927) and Gardner (1960). Plant water uptake from the soil can be restricted by soil physical and chemical properties (Kramer 1969; Li et al. 2002). Plant characteristics such as root-system architecture also dictate how water flows into roots, through the stem xylem to the leaves and finally to the atmosphere (Lobet et al. 2014). The main physical and chemical restrictions to plant available water uptake are explored in the following sections.

2.2 Pore size distribution

The pore size distribution of a soil controls many processes such as water movement and storage (Droogers et al. 1998; Mallants et al. 1997), root growth (Glinski and Lipiec 1990) and soil development (Richard et al. 2001; Velde et al. 1996). Soil pores are changed by external factors such as compaction and natural rainfall impact. Excessive cultivation destroys the network of large soil pores that harbor plant roots and which allow soil water infiltration, drainage and air entry (Lipiec et al. 2006).

Soil pores form during primary particle aggregation, which depends mostly on soil texture but also on soil biota and organic matter. Soil particle arrangements form ‘textural’ and ‘structural’ pores in soil (Childs 1969; Derdour et al. 1993). The pore size and its distribution in soil are important for supplying roots with adequate air and water. Soil pores range in size from 0.003 µm (between the plates in clay aggregations) up to 30 to 50 µm diameter (Hamblin 1985); the soil as a system constitutes even larger pores, which are classed as macropores with diameters > 1000µm (Kim et al. 2010). These macropores are often linked to the activities of soil macro arthropods such as earthworms, and termites (Friend and Chan 1995).

Soil pores are characterized based on size (Kay et al. 1997) and function (Greenland and Pereira 1977). For example, pores of equivalent cylindrical diameter > 30 µm are called 'macropores', while pores in the range 0.2 to 30 µm are called 'mespores' and those < 0.2 µm are known as 'micropores'. Functionally, pores > 50 µm are responsible for transmission of air and drainage of excess water; pores in the range 0.5 to 50 µm are responsible for storage of water for use by plants and other biota, and pores < 0.5 µm are responsible for the residual store of water involved in mineral weathering. The very large pores that are caused by macro fauna (e.g. pores > 500 µm) are considered 'fissures', which function as habitat for earthworms, ants and larger biota, and the very small pores (e.g. < 0.005 µm) are responsible for inter-particle bonding and aggregation.

The dominant pore size in soils depends largely on soil texture. For example, sandy soils contain macropores and fissures, which allow water to drain quickly (under the influence of gravity) and thus make it effectively inaccessible to plant roots. In contrast, clay-textured soils contain mainly micro-pores in the range < 0.005 µm (Kay et al. 1997), which have large surface areas and significant adsorptive potential. The particle surfaces are often 'reactive' in nature and retain a large amount of water, but because the water is held in such small pores it is often inaccessible to plant roots due to the large suctions required to extract it.

In accordance with the principles of capillarity, for example, pores of equivalent cylindrical diameters of 15 and 9 µm drain at soil matric suctions of 2.0 and 3.3 m respectively (Ahuja et al. 1984; Sillon et al. 2003). The capillary rise equation embodies the primary factors responsible for water retention in large pores, and states that the hydraulic head of water, h (m), held in a cylindrical pore or radius, r (m), is:

$$h \equiv \left| \frac{2 \times \gamma \times cos\alpha}{\rho_w \times g \times r} \right| \quad , \qquad [2]$$

where γ is the fluid surface tension in contact with air (J m^{-1}), α is the contact angle formed between the water and the solid surface (considered to be 0^{o} in wettable soils), ρ_w is the density of water (kg m^{-3}); and g is the acceleration due to gravity (m s^{-2}). Gathering all the constants into one, the capillary rise equation reduces to:

$$h \equiv k \times \frac{1}{r} \quad , \qquad [3]$$

This clearly demonstrates the principle that the hydraulic head of soil water is inversely proportional to the dominant pore radius. Thus, it can be shown that soils containing a predominance of pores having radii in the range 0.15 to 15 μm have greater potential to supply water to plants than other soils.

2.3 Low soil aeration

Soil aeration involves the constant exchange of oxygen (O_2) and carbon dioxide (CO_2) between the soil pores and the atmosphere, and is an important dynamic process that maintains sufficient concentrations of O_2 gas in the plant root zone for root and microbial respiration, and to aid photosynthesis and transpiration in plants (Cook et al. 2004; Cook et al. 1998; Orchard and Cook 1983). Gas exchange between the soil and the atmosphere occurs by convective and diffusive flow. Convective flow occurs due to the difference in total gas pressure between the soil air and atmosphere, and takes place primarily near the soil surface in macropores (Rolston 1986). Air convection rarely meets more than 10 % of the O_2 demand for plant root respiration. Gas diffusion, on the other hand, is more important than convection, and is driven by difference concentration gradients of O_2 and CO_2 between the rhizosphere and the atmosphere (Russell 1952).

Reduction in soil air occurs when the soil water content is high or when the total porosity is low (Hundal et al. 1976; Stepniewski et al. 1994) because diffusion of O_2 in soils is much slower through water than through air. Soil aeration influences many physiological processes in plants, as well as many soil biological processes and nutrient transformations (Boon et al. 1987; Glinski and Stepniewski 1985; Letey and Stolzy 1967). Wet soil conditions can reduce the exchange of air between the atmosphere and soil, which makes it difficult for some plant roots to respire and thus create a pressure gradient to allow water flow into plant stem and other parts. Plant growth is retarded due to low nutrient uptake and changes in root metabolism toward fermentation (Boone et al. 1987; Glinski and Stepniewski 1985; Letey and Stolzy 1967). That is, O_2 deficiency for normal root metabolism leads to increased production of toxic ethanol (C_2H_5OH), which can significantly delay the emergence of seedlings, as well as leaf stomata closure, and total cessation of transpiration and photosynthesis (Glinski and Stepniewski 1985; Letey and Stolzy 1967; Sojka and Stolzy 1980).

Anaerobic conditions in soil begin to develop when the O_2 content of the soil drops below critical levels (Glinski and Stepniewski 1985). Early in the process of anaerobic conditions are denitrification, the process by which nitrate (the main form of available nitrogen) is biologically converted to nitrogen gas. The toxic gases produced from denitrification retard plant root growth, which reduces soil water extraction (Ponnamperuma 1972). As nitrate concentrations decline, the redox potential of the soil continues to drop from 300 mV, which directly reduces plant root respiration and hence water extraction by roots (Ponnamperuma 1972; Scott 2000).

Soil aeration status can be measured in numerous ways including the volumetric air content, air permeability, gas diffusion coefficient and respiration rate (Glinski and Stepniewski 1985), although not all of them correlate strongly with plant growth (McIntyre 1970). The best methods account for the movement of oxygen from the atmosphere to the actively growing roots, which involves diffusion through the gas–liquid phase boundary and water films surrounding roots, as well as diffusion through soil pores (Lemon and Erickson 1952). The diffusion coefficient of oxygen is 7500 times greater in air than in water, so the limiting factor in oxygen transport to roots is the diffusion rate through water films.

Lemon and Erickson (1952), developed a platinum microelectrode method to measure *in situ* rate of oxygen diffusion (ODR) through soil solution to a simulated root (a thin platinum wire), with an electrochemical reduction in O_2, and this method has been used extensively in agronomic studies. The ODR methods, however, are considered limited because oxygen diffusion in the soil toward the platinum electrode is affected by factors that also affect oxygen diffusion to the respiration site in the root. Nevertheless, Letey and Stolzy (1967) reported a strong correlation between ODR (as measured by the platinum electrode technique) and plant response. In particular, they found that growth of most plant species (corn, barley, grasses, sunflower, cotton, sugar beet and tomato) was not impaired when the value of ODR > 0.4 μg cm^{-2} min^{-1}, but growth was greatly reduced if ODR < 0.2 μg cm^{-2} min^{-1}. The soil ODR is much more important during emergence than after plant establishment (Letey and Stolzy 1967); various studies have shown that for best plant emergence the ODR should be at least 0.5 to 0.7 μg cm^{-2} min^{-1}. The precise value is difficult to measure, however, and some workers have reported critical ODRs of 0.06 μg cm^{-3} min^{-1} (Hasegawa 1994), while others have reported values of 0.2 μg cm^{-2} min^{-1} (McIntyre 1970); the critical ODR value of 0.2 μg cm^{-2} min^{-1} has been most widely used in research.

2.4 Low soil hydraulic conductivity

Water flow in soil is driven by gradients in the total hydraulic head, h_t, throughout the soil, such that water flows from regions of large hydraulic head to regions of lower hydraulic head according to Darcy's law:

$$q \equiv -K_s \frac{\Delta h_t}{L} \quad , \qquad [4]$$

where q is the flux density ($m^3\ m^{-2}\ s^{-1}$); K_s is the saturated hydraulic conductivity ($m\ s^{-1}$); Δh_t is the difference in the total hydraulic head (m) and L is the length of the soil water flow path (m). The negative sign is the conventional notation to indicate that upward is positive. In three-dimensional flow, Darcy's equation is written:

$$q \equiv K_s \nabla h_t \quad , \qquad [5]$$

where ∇h_t is the three-dimensional gradient in the total hydraulic head, with the positive sign indicating water flow occurs in the direction of decreasing total hydraulic head.

Under non-isothermal conditions where liquid-gas interface exist in the soil system, saturated hydraulic conductivity changes to unsaturated hydraulic conductivity. Coupling the laminar flow equation to the continuity equation describes transient flow as:

$$\frac{\partial \theta}{\partial t} = \nabla K(\theta)\ \nabla h_t \quad , \qquad [6]$$

From **Eqns [5]** and **[6]** the two physical terms that control the soil water flux are the saturated and unsaturated hydraulic conductivity respectively. During saturated flow of water in soil all voids including pores are filled with water, which is made available to plant roots for extraction at small matric suction gradient (Gardner 1960). However, for unsaturated flow (i.e. most field situations), the larger pores are empty and only the smaller pores participate in water flow, the rate of which is greatly reduced, as illustrated in **Figure 2.2.**

The flow of water in soil is limited by the unsaturated hydraulic conductivity, which depends on soil texture (Chahal 2010; Gardner and Ehlig 1962; Sperry and Hacke 2002). Sandy soils have low unsaturated hydraulic conductivity because the large storage pores drain rapidly, which leaves relatively isolated pockets of water either at points of inter-particle contact or in thin films along particle surfaces. Furthermore, very large gradients in total hydraulic head reduce flow of water and make it increasingly unavailable to plant roots as the soil dries out (Gardner 1960). The unsaturated hydraulic conductivity in finer textured soils, by contrast, remains relatively steady across the plant available range because much of the soil remains saturated; thus although the rate of water transport is considerably slower than in saturated sandy soils, the supply of water (and thus its accessibility to plant roots) is maintained (Sperry and Hacke 2002).

Soil water flow into plant roots depend on the water retention and flow properties of the soil (Gardner 1960). For example, plant water uptake from soil can be restricted by soil hydraulic conductivity at soil matric suctions of only 10 m, which is far from the classical permanent wilting point of h = 150 m (Hulugalle and Willatt 1983). As water content decreases through soil drying and increasing soil matric suction, **Figure 2.2** shows that further drying results in lower and lower hydraulic conductivity (Nobel and Cui 1992).

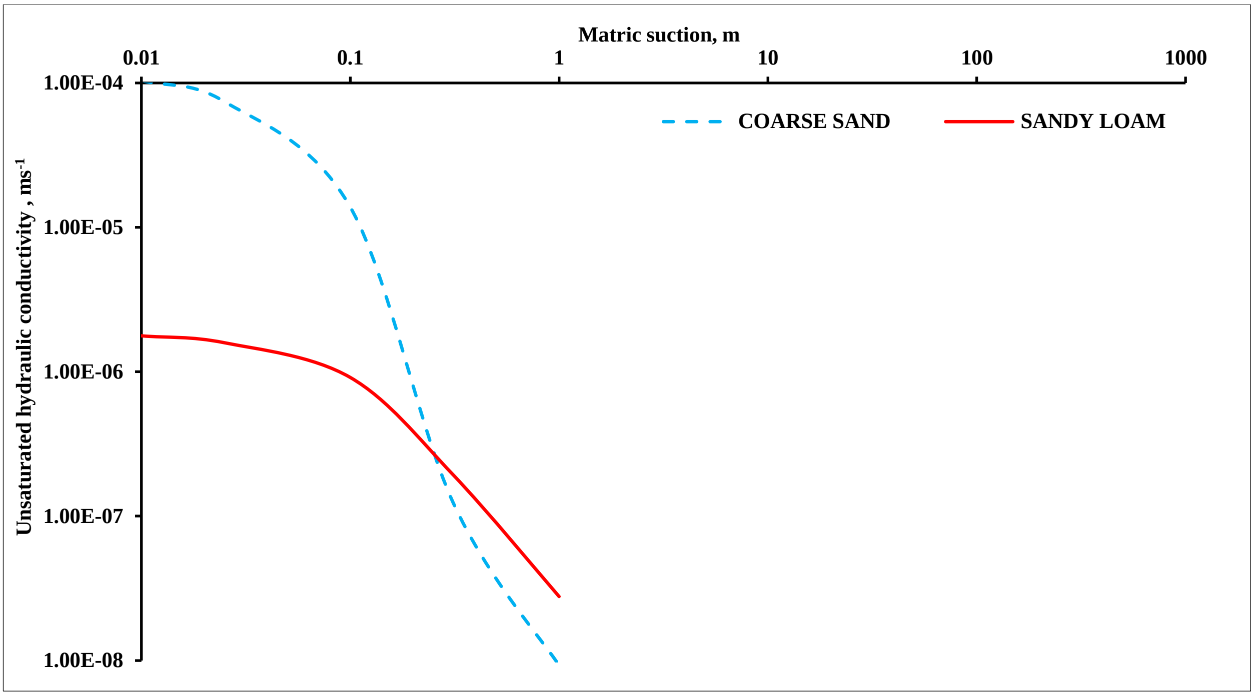


Figure 2.2. Unsaturated hydraulic conductivity functions for a coarse sand (dashed line) and a sandy loam (unbroken line), adapted from Rijtema (1969).

Other research suggests that major restrictions to water uptake relate to the combined effects of restrictions within both the soil and the plant. Significant restriction due to plant roots have been reported for water uptake at matric suctions between 0.3 m and 6 m (Denmead and Shaw 1962; Gardner 1960; Gardner and Ehlig 1962; Gingrich and Russell 1957; Hulugalle and Willatt 1983; Nobel and Cui 1992; Tinklin and Weatherley 1968). Similarly, reductions in root length density can increase plant restriction to water uptake beyond those expected due to declining soil hydraulic conductivity (Reicosky and Ritchie 1976). As a critical soil hydraulic conductivity is reached at about 10^{-8} to 10^{-9} m day^{-1} (corresponding to matric suctions of 10 m and 80 m for sandy and clay soils respectively) the relative importance of plant limitations diminishes and that of soil hydraulic properties increases. Similarly, Newman (1969a) and Newman (1969b) argued that the most sparsely rooted plant in nature would not develop an appreciable root restriction until well below matric suction of 5 m compared to what they claimed for maize; which has an extensive root system. At 1 m soil matric suction the hydraulic conductivity would be greater than at 5 m by a factor of 100 hence no root restriction to water uptake. This line of thinking, however, is not universally agreed upon.

For example, Blizzard and Boyer (1980) found that plant restrictions remained more important than soil restrictions across the entire range of the classically defined plant available water. Under steady state conditions they observed that the gradient in matric suction between the soil and the root was smaller than between the root and the leaf in the range of soil matric heads between h = 2 to 110 m; as soil water content declined, water flow through the soil and the plant decreased to only 10 % of the maximum rate yet both soil and plant restrictions increased (Blizzard and Boyer 1980). Similarly, Sykes and Loomis (1967) found that restrictions to water uptake were due to plant root restrictions in the range of soil matric heads from h = 70 m to beyond the permanent wilting point of h = 150 m for maize, sunflower, *Nicotiana attenuate* and *Agropyron intermedium*.

A critical soil matric suction of h = 25 m was found to cause a drop in leaf hydraulic suction in pepper plants grown in large pots (ca. 11.5 liters) of clay loam soil (Gardner and Nieman 1964). A similar critical soil matric suction was reported by Gardner (1960) in support of the idea that restrictions to water flow into plant roots are caused by declining unsaturated soil hydraulic conductivity. Gardner and Nieman (1964), further found that at leaf water suction of 11 m most economic plants exhibit symptoms of wilting which leads to stomata closure and consequently reduces transpiration rate. Actual transpiration rate has also been found to decline below the potential transpiration rate when soil matric suctions are significantly less challenging than h = 150 m (Gardner and Ehlig 1963).

Gardner and Nieman (1964), concluded that the drop in soil water content at the permanent wilting point does not represent the matric suction at which many plant processes cease. The critical leaf water suction determined in their experiments was not related to any particular soil matric suction. Reicosky and Ritchie (1976); Kramer (1969); and Li et al. (2002) also pointed out that plant water uptake was restricted by unsaturated hydraulic conductivity when soil water content decreases. Further, they said it would be convenient to use the unsaturated hydraulic conductivity factor rather than the permanent wilting point alone to predict PAW for a particular soil, crop or evapo-transpirative demand.

Chahal (2010) tested the results of Gardner and Nieman (1964) under different evapo-transpirative demand, planting density, and crop species grown in two light textured soils. He used the IWC model of Groenevelt et al. (2001) to predict PAW under restricted hydraulic conditions and found that different crop species grown at variable plant populations in different soils textures had different soil matric suctions at which the unsaturated hydraulic conductivity became limiting to water uptake. He found there was no single critical soil matric suction (of say 25 m as suggested by Gardner and Nieman (1964)) on the basis that water uptake ceased for sorghum grown at different densities at average soil matric suctions of h = 101 m or h = 57 m in a loamy sand, and of h = 13 m and 15 m in a very fine sand respectively for low (LET) and high evapo-transpirative (HET) demand. For maize, he reported corresponding values of h = 40 m and h = 56 m in a loamy sand and h = 15 m and h = 8 m in a very fine sand (Chahal 2010). It was concluded that stomatal conductance was a good measure to link plant stress to soil matric head (Chahal 2010).

Restriction to water flow in soil into plant roots has also been found to increase due to high evapo-transpirative demand (Kramer 1969; Li et al. 2002). During soil drying plant water uptake from the soil is restricted as a result of low hydraulic conductivity and root activity. The reduction in water flow and root activity affects the transport of water into the stem through the xylem to the rest of the plant. Plant root growth becomes more sensitive than leaf growth under the same decrease in plant water status (Hsiao and Xu 2000) because greater osmotic adjustment occurs in the lateral roots and root hairs than in leaves (Ober and Sharp 2007). The apical section of maize where seedling primary root emerges, and also proline concentration increases dramatically under water deficit; is known to contribute 50% of osmotic adjustment (Sharp et al. 2004; Sharp et al. 1988). Leaf growth is restricted because of the closure of the stomates, which regulate water vapour exchange between the leaf and the atmosphere. Photosynthesis is thus reduced by shoot water deficit, which increases carbohydrate channeling to the root to facilitate osmotic pressure for root elongation (Chimenti et al. 2006).

2.5 High soil strength

2.5.1 Definition and measurement of soil strength

Soil strength refers to the capacity of a soil body to withstand forces applied to it without experiencing deformation whether by cell rupture, fragmentation or flow (Hillel 1998). The magnitude of soil strength derives from inter- and intra-aggregate bonds (Aluko and Koolen 2000) produced by cohesive forces between particles or aggregates and internal friction generated by particles/aggregates (Marshall et al. 1996).

Soil strength is measured as soil resistance in the unit of MegaPascal (MPa). A common field method for measuring soil strength is the use of a field penetrometer, which measures the resistance experienced by a metal cone being pushed into soil over a range of depths (Fritton 2008; Sinnett et al. 2008). Shear vanes are also used to quantify mechanical resistance experienced by roots in the field (McKenzie and McBratney 2001) but it is sometimes difficult to use for shallow measurements. Field measurements are normally influenced by soil water content, because of changes in soil matric suction and degree of saturation (McKenzie and McBratney 2001; Whalley et al. 2007), so it is sometimes better to use a laboratory measurement in which soil hydraulic properties can be controlled. The miniature penetrometer has been widely used on soil cores extracted from the field and brought to the laboratory (Bengough and Mullins 1990), where it is possible to measure strength at multiple matric suctions. Refinements to the method, which can be complicated by frictional resistance in the metal cone, include using a rotating-tip (Bengough et al. 2011), which reduces penetrometer resistance by more than 50 % (Bengough et al. 1997).

The magnitude of penetrometer resistance is quite different from the pressures real roots encounter (Bengough and Mullins 1990) but the resistance to root growth, σ, can be related to penetrometer resistance using the relation (Bengough et al. 1991):

$$\sigma = \frac{q_p}{(1+\mu \cot\beta)} \quad , \qquad [7]$$

where q_p is the penetrometer resistance, μ is the coefficient of soil-metal friction and β is the penetrometer cone semi-angle. Clark et al. (2003), reported that **Eqn [7]** gave estimates of σ that were similar to their direct measurement obtained by growing roots into soil cores on a balance.

Strength is controlled by multiple soil physical factors: water content, matric suction, bulk density, texture and aggregate coalescence. Soil strength may increase as matric suction increases during drying, which has been found to restrict water availability to *Pisum sativum* L. at matric suctions h > 35 m (Eavis 1972). Strength also increases with bulk density, which reduces root exploration of the soil (Cockroft and Olsson 2000; Eavis 1972; Groenevelt et al. 2001; Taylor et al. 1966). Soil strength increases with increasing clay content, and at a constant soil matric suction of 150 m it reaches a maximum when clay content is approximately 45 % (Smith et al. 1997). Higher clay content in the B horizon can increase soil strength to 2.2 MPa, while those in the A horizon are only 1 MPa at similar bulk densities, in the order of 1500 kg m^{-3} (Smith et al. 1997). The cohesive nature of clay particles due to high surface charge density, in contact with water molecules increase bulk density as the soil dries with increasing soil matric suction. High strength impedes root growth and its exploration for water at deeper soil depths although water may be present. For example, the strength of silt loam at a water content of approximately 20 % was found to increase from 5 to 8 MPa when bulk density increased from 1150 to 1230 kg m^{-3} (Wells and Treesuwan 1978). In a related study, (Ley et al. 1995) found that soil strength increased from 0.73 to 7.52 MPa as bulk density increased from 1170 to 1630 kg m^{-3}.

High soil strength is also caused by aggregate coalescence, which can occur regardless of soil bulk density (Cockroft and Olsson 2000; Grant et al. 2001). Soils in which aggregate coalescence occur have high soil strength, which restricts root growth, water uptake and crop yield (Cockroft and Olsson 2000). The effects of aggregate coalescence become more severe when age-hardening and densification also occur (Grant et al. 2001).

The particle size distribution of soils (texture) can have a large influence on the magnitude of soil strength. Mullins and Panayiotopoulos (1984) for example, found that simply by blending coarse and fine sand with kaolin, the suction at the same water content increased from h = 10 m to h = 100 m, which greatly increased soil strength. Soil texture also influences frictional and cohesive forces that bind soils particles (Aluko and Koolen 2000; Marshall et al. 1996), such that the strength of sandy soils is largely associated with frictional resistance rather than cohesive forces, whereas strength in fine textured soils arises primarily from cohesive forces. Smith et al. (1997), found that at similar packing density (of 1390 and 1370 kg m^{-3} for sandy and clayey soils respectively) sandy soils had significantly greater penetrometer resistances of 0.64 MPa. Similarly, Spivey et al. (1986) found that at similar bulk density (ca. 1600 kg m^{-3}) and similar conditions, a soil comprising > 70 % sand had a penetrometer resistance of 4.5 MPa while that for a soil comprising > 30 % clay was only 1 MPa.

Plant roots must exert a growth pressure exceeding the strength of the soil to displace soil particles, overcome friction, and elongate through deeper layers in search of water and nutrients. Plant roots can detect physical impedance in the soil and send signals to the shoot system to induce stomatal closure (Masle 1999). Stomatal closure decreases water use efficiency, which reduces the rate of photosynthesis and consequently plant yield.

Plant root sensitivity to high soil strength cause changes to root morphology (Bennie 1991). Root thickening is common in strong soils (Bengough et al. 1991; Materechera et al. 1991) and this allows greater forces to be applied at the root tip, to overcome root restrictions to allow further elongation to greater depths in the soil (Abdalla et al. 1969). The rate of root elongation decreases with increasing soil strength irrespective of plant type (Bengough and Mullins 1990; Goss 1977; Goss and Russell 1980; Taylor and Gardner 1963).

Increased lateral root formation is another indicator of high soil strength and restriction to primary root elongation (Goss 1977; Goss and Russell 1980). In a fine sandy loam, Materechera et al. (1992) found elongation rate of roots for six different species to decreased by 40 to 60 % when they encountered a compacted layer with a strength of 3.0 MPa. The rate of root elongation, dl/dt, may be described as (Greacen 1987):

$$\frac{dl}{dt} = l, m(\sigma, h) \times [P - Y(\sigma, h) - \sigma(h)] \quad , \qquad [8]$$

where *l* is the length of elongating root tissue, *m* is the cell wall extensibility, *P* is the turgor pressure, *Y* is the cell wall yield threshold, σ is the root penetration resistance of the soil and *h* is the soil matric suction. P, Y, σ, and h all have the dimensions of pressure, while m is strain rate per unit pressure.

In the field where numerous stresses exist, soil strength increases rapidly as the soil dries; with root exposed to both water stress and high soil strength (Bengough et al. 2011; Whitmore and Whalley 2009). A study conducted on a range of nineteen selected physical soil properties indicated that high soil strength often poses a greater restriction to root elongation in drying soil than does water stress alone (Bengough et al. 2011). Low water contents in the surface layers of soil can especially increase soil strength and induce water stress by limiting root exploration of deeper soil layers (Whalley et al. 2006). High soil strength combined with water stress in drying soils may be involved in regulating plant growth, but it is difficult to separate the effects of soil strength and soil matric suction (Passioura 2002).

In some cases, soil strength may only be a serious limitation to water uptake if the soil hydraulic properties cannot overcome a restricted water supply, i.e. if the only access to water is by root penetration. In support, Bengough et al. (2006) reported that in fine textured soils, however, the unsaturated hydraulic conductivity is sufficiently large that water may be able to move toward the plant roots even if the soil is compacted to the point where roots cannot grow into the soil.

2.6 Osmotic stress caused by salt

Salt sources in soil originate from mineral weathering, inorganic fertilizers, soil amendments (gypsum, composts, and manures) and irrigation water (Kotuby-Amacher et al. 2000). Irrigation water can also be a major source of salt in the soil (Rengasamy 2006), and elevated electrolyte concentrations can significantly alter the environment of plant roots. Most sensitive plants are affected when soil electrolyte concentration increases, while non-sensitive plants can thrive well in salty conditions.

At low salt concentration yields of crops are slightly affected (Maggio et al. 2001). As salt concentrations increase, yield declines toward zero, since most glycophytes, do not tolerate salt concentrations exceeding 10 – 20 dS m^{-1} (Munns and Termaat 1986). By contrast, halophytes can survive salt concentration in excess of 30 – 40 dS m^{-1}, because they have specific adaptation mechanisms (Parida and Das 2005). For instance, halophytes tend to accumulate salts whereas glycophytes attempt to exclude the salts (Zhu 2001).

Water uptake restriction by roots as a result of high soluble salt concentration depends on the total water potential of the soil solution (Ayers and Westcot 1985). Excess soluble salts in the root zone of affected crops restrict plant root from taking water in soils within the root volume, which effectively reduce PAW (Bauder and Brock 2001). The osmotic head of any soil solution, h_{os} (m) can be related to the soluble salt concentration as (Groenevelt et al. 2004):

$$h_{os} = 3.6 \times EC_e \quad , \quad [9]$$

where EC_e is the electrical conductivity of a saturated paste extract (dS m^{-1}).

High soluble salt concentrations in the soil solution affect plant growth through the inhibition of many physiological and biochemical processes such as nutrient uptake and assimilation (Hasegawa et al. 2000; Munns 2002; Munns et al. 1995; Munns and Tester 2008). A two-phase model to describe the osmotic and ionic effects of salt stress on plant-adaptation is depicted in **Figure 2.3**. Plant sensitivity to high salt concentration may differ in the rate at which salt reaches toxic levels in leaves. During the first phase of the effect, growth in both halophytes and glycophytes are reduced and for the second phase, older leaves in most sensitive plants senesce to reduce photosynthesis, which retards growth.

The first phase starts immediately after salt concentrations around the roots zone increase to critical levels, which affect root water extraction, causing a significant decline in shoot growth (Benyon et al. 1999; Mahmood et al. 2001). An immediate response to this effect is to mitigate ion flux into shoot, which could result in stomatal closure. But because of the water suction difference between the atmosphere and leaf cells and the need for carbon fixation, it is an indefensible long-term strategy of tolerance (Hasegawa et al. 2000).

Shoot growth has been found to be more sensitive than root growth to salt-induced osmotic stress. This is because a reduction in leaf area relative to root growth causes a decrease in water use by plants, which allows conservation of soil water to dilute the salt concentration in the soil near the roots (Munns and Tester 2008). Reduction in shoot growth due to salt stress is expressed by a reduced leaf area and stunted shoots (Lauchli and Epstein 1990). Inhibition of leaf growth due to salt stress appears to be a consquence of restriction by salt of symplastic xylem loading of Ca^{2+} in the root (Läuchli and Grattan 2007). Leaf expansion also depends on cell division and elongation. Salt stress has been reported not to affect leaf initiation in sugar beets, but leaf extension was found to be sensitvie depending on the Ca^{2+} status (Papp et al. 1983). Moreover, the salt–induced inhibition of water uptake also inhibits uptake of important mineral nutrients, such as K^+ and Ca^{2+}.

The second phase, which is the ion specific effect, corresponds to the accumulation of ions, in particular Na^+, in the leaf blade, where Na^+ accumulates after being deposited in the transpiration stream, rather than in the roots (Munns 2002). Na^+ accumulation turns out to be toxic especially in older leaves of sensitive plants, which are no longer expanding to dilute incoming salts as younger leaves do. According to Munns and Tester (2008), if the rate at which older leaves senescence become greater than the rate at which new leaves forms, the photosynthetic capacity of the plant to supply carbohydrate to younger leaves is reduced. In plant photosynthetic tissues Na^+ accumulation affects photosynthetic components such as enzymes, chlorophylls and carotenoids (Davenport et al. 2005).

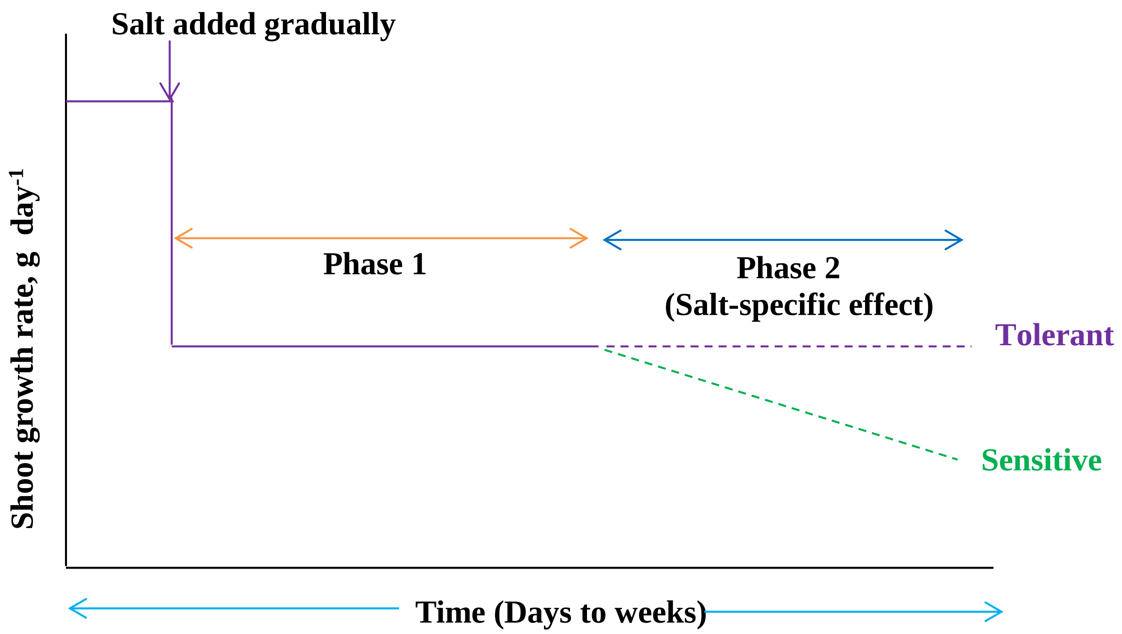


Figure 2.3: Schematic representation of two-phase growth response to salinity for genotypes that differ in the rate of at which salt reaches toxic levels in leaves. Adapted from Munns et al. (1995).

The reduction in photosynthesis in salt sensitive plants also increases the production of reactive oxygen species, which although normally removed rapidly by anti-oxidative mechanisms, is impaired when plants are exposed to salt stress (Allan and Fluhr 1997; Foyer and Noctor 2003).

2.7 Recycled water: benefits and quality issues

The agricultural industry is the largest user of water and this will continue while the human race's existence depends on agricultural products for food. Water to meet future demands for agricultural production has become a challenge. Though water may be abundant for use, not all is suitable for crop production. Water source for example: rivers, streams, lakes and lagoons in many parts of the world have been polluted through the discharge of municipal sewage and industrial waste (Parsons and Wheaton 1996).

Surface water pollution provided the drive to find a substitute for fresh water sources. The aspiration yielded a positive result which led to the treatment of municipal waste water for reuse, pioneered in Israel (Angelakis et al. 1999). Waste water treatment was seen to be necessary because many researchers realised the need, especially in preventing water resource pollution (Hamilton et al. 2006). However, others argued that waste water treatment was rather a disadvantage to the environmental resources (Müller et al. 2007).

Despite these problems, recycled water has contributed to irrigated agriculture in locations where other sources of fresh water are limited; where recycled water is available, it has invariably increased nutrient inputs and yield. For example, a 20,000 m^{-3} ha^{-1} yr^{-1} irrigation rate for recycled water with typical total nitrogen (N) and phosphorus (P) concentrations of 15 mg L^{-1} and 3 mg L^{-1}, respectively, corresponded to annual nutrient inputs of 300 kg ha^{-1} N and 60 kg ha^{-1} P (Mara and Cairncross 1989).

The potential of waste water to improve the structural properties of soils and at the same time, increase agricultural productivity has been discovered by many researchers (Leader et al. 2008; Lehrsch and Robbins 1996; Lehrsch and Robbins 1994). The preference for (and acceptance of) treated wastewater for irrigation has increased crop production. Importantly, the cost of conveying recycled water to famer's field is low compared to transporting conventional potable water (Haruvy and Sadan 1994). Also, the supply of treated wastewater for agricultural purposes is generally reliable and uniform during the year (Haruvy and Sadan 1994).

Nutrients in recycled water can lead to eutrophication of surface waters if it escapes from its agricultural purpose. Recycled water quality has been an issue for the past three decades. The main quality issue of agronomic concern arise from large concentrations of dissolved inorganic compounds such as NaCl, plus organic compounds such as carbon, nitrogen and phosphorus (Kretschmer et al. 2002). Sodium chloride, which has been a major problem with recycled water use for crop irrigation is reviewed in the subsequent sections.

2.8 Salinisation and sodification

Soil salinisation and sodification are the two main effects associated with the use of recycled water on soils (Jalali et al. 2008; Lado and Ben-Hur 2009; Lado et al. 2004; Muyen et al. 2011). Salinisation and sodification arise because of the high concentrations of charged inorganic cations (e.g. Na^+, Ca^{2+}, Mg^{2+}, K^+, NH_4^+ and H^+) and anions (e.g. Cl^-, HCO_3^{2-}, SO_4^{2-} and NO_3^-). Among these, Na^+ and Cl^- are the main ions involved in salinisation and sodification in Australia and many parts of the world.

Soil salinisation is defined for soils having electrical conductivity, $EC_e \geq 4$ dS m^{-1}, as measured on a saturated soil-paste extract (Richards 1954). Such values of ECe generally occur when soils are exposed to recycled water over long periods of time depending on the salt concentration, the type of irrigation system used, and the climatic conditions in the form of temperature, wind speed and relative humidity (Chinnusamy et al. 2005). Saline water application for crop irrigation above critical concentrations enhances salinization, particularly where there is poor drainage. The combination of poor water quality and poor drainage results in upward movement of the water table and waterlogging in the root zone. With elevated temperatures, evapo-transpirative demand causes salt to concentrate near the soil surface.

Salt accumulation in soils irrigated with recycled water depends on the irrigation system used and the amount of water applied in excess of crop requirement (Ayers and Westcot 1985). When water is uniformly applied across irrigated land, as in sprinkler and border irrigation, the surface soil depths become the zone of salt leaching and the subsoil becomes the zone of salt accumulation (Ayers and Westcot 1985). The extent of salt accumulation in the bottom of the root zone depends on the leaching fraction applied. The higher the leaching fraction, the less salt is accumulated (Grattan 2002). When water is applied by furrow irrigation between raised beds, salt builds up beneath the base of the furrow as well as in the root zone of the raised bed. By contrast, drip irrigation causes salt to accumulate concentrically around the wetted perimeter of irrigated zone.

Improper management of salt accumulation leads to soil sodification (Rengasamy and Olsson 1993), which occurs when the *exchangeable sodium percentage* (*ESP*) of a soil exposed to saline irrigation water exceeds 6 (Isbell 1996). The *ESP* is a measure of the proportion of the exchange surfaces occupied by exchangeable sodium, ${Na^+}_X$, and is calculated as follows:

$$ESP \equiv \frac{{Na^+}_X}{\sum({Ca^{2+}}_X, {Mg^{2+}}_X, {Na^+}_X, {K^+}_X)} \times 100 \qquad , \qquad [10]$$

in which the concentration of exchangeable cations is expressed in mmol (+) kg^{-1}. The procedures involved to measure *ESP* are time consuming and expensive, so they are often estimated indirectly by considering the equilibrium that exists between exchangeable cations, ${M^+}_X$, and solution cations, $[M^+]$. The main four cations of interest in soils are Na^+, Ca^{2+}, Mg^{2+} and K^+, and these are relatively easy to measure in solution. When the concentration of solution cations is measured, they are used to calculate a quantity known as the *sodium adsorption ratio*, *SAR*:

$$SAR \equiv \frac{[Na^+]}{\sqrt{[Ca^{2+}]+[Mg^{2+}]}} \qquad , \qquad [11]$$

in which the concentration of cations in solution is measured in units of mmol L^{-1}.

With knowledge of the *SAR* of the soil solution, plus the selectivity coefficient (*Gapon constant*, k_G) for a given soil, the *ESP* of a soil can be calculated. This is done using the *Gapon equation*, which describes the preferential adsorption of divalent cations at the expense of the monovalent cations:

$$ESR \equiv k_G \times SAR \qquad , \qquad [12]$$

The value of k_G usually falls in the range between 0.01 to 0.02, and the *ESR* is the *exchangeable sodium ratio*:

$$ESR = \frac{Na^+{}_X}{CEC - Na^+{}_X} = \frac{Na^+{}_X}{\Sigma(Ca^{2+}{}_X, Mg^{2+}{}_X, K^+{}_X)} \quad , \qquad [13]$$

which is directly related to the *ESP* as follows:

$$ESP = \frac{100 \times ESR}{1 + ESR} \quad , \qquad [14]$$

Thus, when the concentration of monovalent and divalent cations is equal, the cation exchange complex is preferentially occupied by divalent cations. The equilibrium condition is influenced by the electrolyte concentration of soil solution, which regulates ion sorption and desorption on the exchange complex. In some cases, particularly in high pH soils where calcite precipitation may occur, the calculated value of *SAR* should more realistically be divided by two (Ayers and Westcot 1985).

During evaporation of irrigation water, particularly in alkaline soils, some of the cations such as Ca^{2+} and Mg^{2+} may precipitate as carbonates, while other cations such as Na^+ remain soluble and thus dominates in the soil solution. When Na^+ is the main cation in solution, it dominates the soil exchange complex (Serrano et al. 1998), and this generates highly sodic soils plus extremely high ratios of Na^+/Ca^{2+}, Na^+/Mg^{2+} or Na^+/K^+ (Grattan and Grieve 1998). The extreme ratios cause nutritional imbalances and deficiencies in crops irrigated with recycled water, especially in relation to Ca^{2+}.

Excess Na^+ in saline water used for irrigation reduces water- and air-permeability of soils because Na^+ adsorption on the negatively charged sites of soil colloids and organic matter causes excessive swelling and dispersion, which closes transmission pores (Gupta and Abrol 1990; Sharma and Manchanda 1996; Suarez et al. 1984), which leads to hypoxic and anoxic soil conditions (Singh and Chatrath 2001). Intensive irrigation with treated waste water in loam and clay soils can also result in a significant dispersion and eluviation of colloids from the upper soil layers (Warrington et al. 2007).

Many studies have demonstrated the effect of applied treated waste water (recycled water) on soil physical properties as linked to the dominance of Na^+ on the soil exchange surface. Of particular importance is the salt concentration of the sodic water – if it is relatively high, the magnitude of the *SAR* is less important for soil structural stability than it would be if there was no electrolyte present. At high *SAR* with high EC of soil solution, soil structure remains stable. However, the soil is still sodic so when saline recycled water is replaced by high quality (non-saline) water, the soil swells and disperses and thus reduces permeability (ANZECC and ARMCANZ 2000).

Balks et al. (1998), evaluated the change in *ESP* for soils at the Wagga Wagga effluent plantation following five seasons of irrigation with either (i) treated sewage effluent or (ii) bore water with similar salinity and *SAR*. The *ESP* increased from < 2 % to > 25 % at some sites within the top 0.6 m of the profile. They assessed the impact of increased soil sodicity on soil physical properties by measuring a dispersion index and saturated hydraulic conductivity at three depths within the top 0.6 m. The *ESP* and dispersion in distilled water were positively correlated (but not in the saltier bore water or recycled water), and saturated hydraulic conductivity (using distilled water after five cycles of irrigation with bore water) decreased significantly (Balks et al. 1998). Soils with finer texture at the same *ESPs* had greater dispersion indexes (Balks et al. 1998). High levels of soil sodicity tended not to induce soil structural problems unless recycled water use ceases or the water is replaced with zero EC water such as rain water (Bethune and Batey 2002).

An increase in mean *ESP* in soils with recycled water application has also been reported by Jalali et al. (2008), although the effects of high Na^+ concentration were less in soils with initially high *ESP* compared to soils with initially low *ESP*. Leaching soil columns resulted in increased salinity and loss of Mg^{2+} and K^+, particularly for soils that had low *CEC*, which could induce nutrient deficiencies and affect plant growth (Jalali et al. 2008). Upon leaching with distilled water, the flow rate through soil columns decreased to zero after only 2.2 pore volumes, indicating damage to soil structure, which is consistent with the findings of Nang (2012) and Ayers and Westcot (1985).

Recycled water application increased exchangeable Na^+ at all soil depths after $CaSO_4$ treatment on an irrigated Vertisol (Hulugalle et al. 2006). They found that exchangeable Ca^{2+} and K^+ increased in clay-textured surface soils at 0.6 m soil profile depth, with a decreased exchangeable Ca^{2+}, K^+, and soil organic matter in coarser textured soil at depths > 0.6 m. Hulugalle et al. (2006) concluded that application of commercial $CaSO_4$ at sub-optimal rates with sodium-rich irrigation water is unlikely to improve soil physical properties in sodic soils.

The effects on soil physical properties during reclamation of a saline-sodic soil to the non-saline state and on PAW were evaluated by Nang (2012). He collected soil samples from nine horizons at their initial saline-sodic states, plus at a less saline / sodic state and measured changes in soil physical properties and their effects on PAW. A preliminary electrolyte treatment was applied to all samples followed by leaching with distilled water to reduce salt concentration. Reclamation of affected soils from the saline-sodic state to the non-saline state by leaching with highly concentrated Ca-solution was found to improve the soil's physical structure (Nang 2012). In Ca-treated soils the water retention curves were steeper than the other treatments and the network of larger pores was enhanced, which increased soil aeration and saturated hydraulic conductivity. Furthermore, when calcium salt was leached from the soil, the lower EC increased soil water availability, whereas when the sodic soils were leached with a dilute Ca-solution, swelling and dispersion occurred, which reduced pore size, flattened the water retention curves and reduced soil aeration, which consequently reduced soil water availability (Nang 2012).

2.9 Models to describe PAW

Plant available water (PAW) is an important yield determining factor (Timlin et al. 2001) in crop production. There are several models available to predict soil water availability, including the classical PAW, the *non-limiting water range* (NLWR), the *least limiting water range* (LLWR), and the *integral water capacity* (IWC), each of which will be explored below.

2.9.1 PAW and Least Limiting Water Range

The classical concept of PAW was introduced by Veihmeyer and Hendrickson (1927) and defined as the amount of water held between the *field capacity* (or the *drained upper limit*) and the *permanent wilting point* of a soil (Veihmeyer and Hendrickson 1927). The *permanent wilting point* is the soil matric head at which plants wilt and can no longer recover when stress is removed (Veihmeyer and Hendrickson 1928), usually taken to be the water content at a matric suction of h = 150 m (Richards and Weaver 1943). Others have reported some plants to be able to take up water beyond a matric suction of 150 m (Cassel et al. 2000; Chahal 2010; Jordan and Ritchie 1971). The *field capacity* or *drained upper limit* is the soil matric head that occurs after a saturated soil has been left to drain under the influence of gravity (Veihmeyer and Hendrickson 1931), variously taken to be 0.5 m, 1 m or even 3.3 m (Groenevelt et al. 2001). An inherent assumption in this model is that all water held between the *drained upper limit* and *permanent wilting point* is completely and equally available to plants, and that all water outside these boundaries is completely unavailable to plants. However, even 60 years ago, Richards and Wadleigh (1952) recognized that this is not strictly true: as the soil matric head increases, the availability of water to plants changes in accordance with the prevailing soil physical properties and environmental conditions.

Following a similar line of reasoning Letey (1985) introduced the concept of the *non-limiting water range* (NLWR) to encompass the relationship between water content, aeration, and mechanical impedance in soil (**Figure 2.4**). It is defined qualitatively as the range of water contents across which aeration and soil strength are non-limiting to plant growth. The availability of water for plant growth is restricted by poor oxygen diffusion at the wet end and by great resistance to root penetration at the dry end.

The NLWR has been used as a soil quality indicator for farming systems. Applications of organic amendments had no effect on oxygen diffusion, mechanical impedance, NLWR, and saturated hydraulic conductivity (Wu et al. 2003). Average values of mechanical resistance and oxygen diffusion rate were not significantly different in the four agricultural systems evaluated. Soil in the organic farming system treatment had a relatively narrow NLWR because less water was retained at field capacity, indicating that the soil surface of the organic farming system had larger pores (Wu et al. 2003). The saturated hydraulic conductivity was found to be significantly higher in a 4-year conventional treatment and a 2-year rotation treatment than in an organic, low-input treatment.

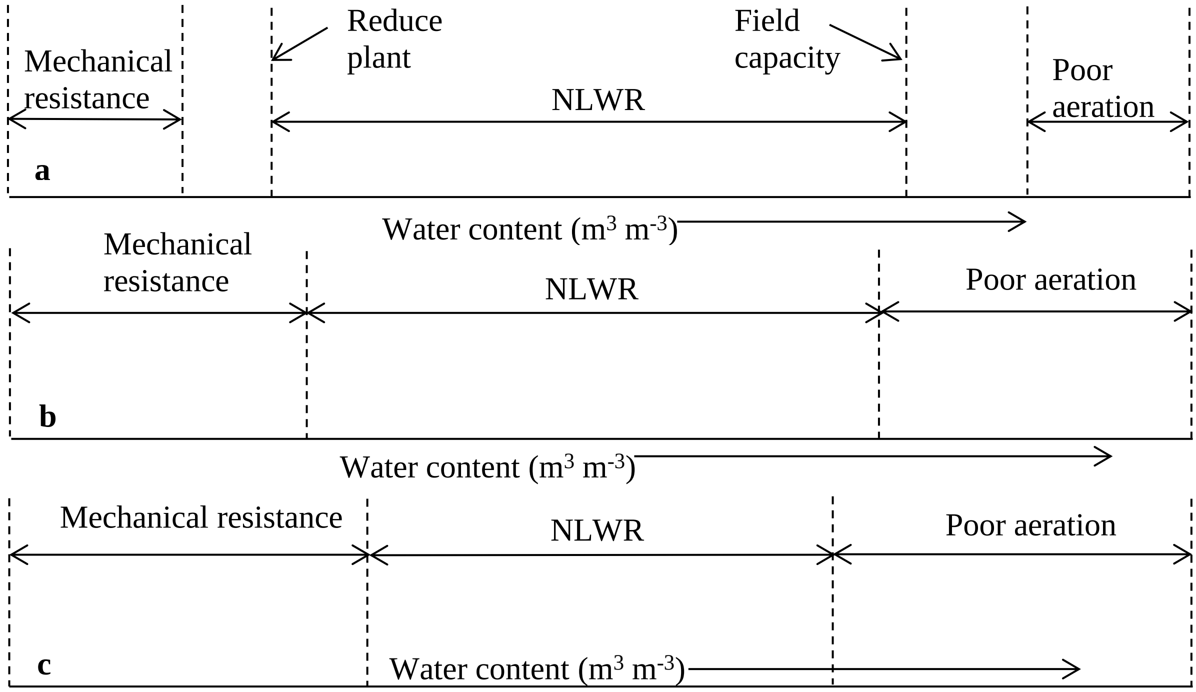


Figure 2.4. Schematic representation of the Non Limiting Water Range (NLWR), illustrating the influence of soil aeration, mechanical resistance in soils with increasing bulk density and structural degradation from **a** downward to **c** (Letey 1985).

By exposing soil to increasing irrigation water salinity above 4 dS m^{-1} the saturated hydraulic conductivity progressively decreased as water quality improved but had relatively little effect on other physical properties. In contrast, Verma and Sharma (2008) found that application of organic material increased the NLWR in both maize-wheat and rice-wheat cropping systems. Furthermore, the NLWR was linearly, significantly and positively correlated with wheat grain yield (Verma and Sharma 2008).

The NLWR concept was later modified as the *least limiting water range* (LLWR) by Da Silva et al. (1994) and defined as the range in soil water content after rapid drainage has ceased within which restrictions to plant growth associated with water potential, aeration, and mechanical impedance to root penetration are minimal as shown in **Figure 2.5** (Da Silva and Kay 1997b; Lapen et al. 2004).

They assumed rapid drainage and aeration to be the two physical restrictions that affect PAW at the wet end of the available water range. The water content corresponding to a volumetric air content of 0.10 $m^3 m^{-3}$ was taken as the point where aeration could restrict plant water uptake in soil that is wetter than the drained upper limit. As the soil dries out toward the permanent wilting point at h = 150 m, they identified the water content at which mechanical impedance ≥ 2.0 MPa as the lower limit of the range of available water because plant roots would be unable to explore the soil to extract water.

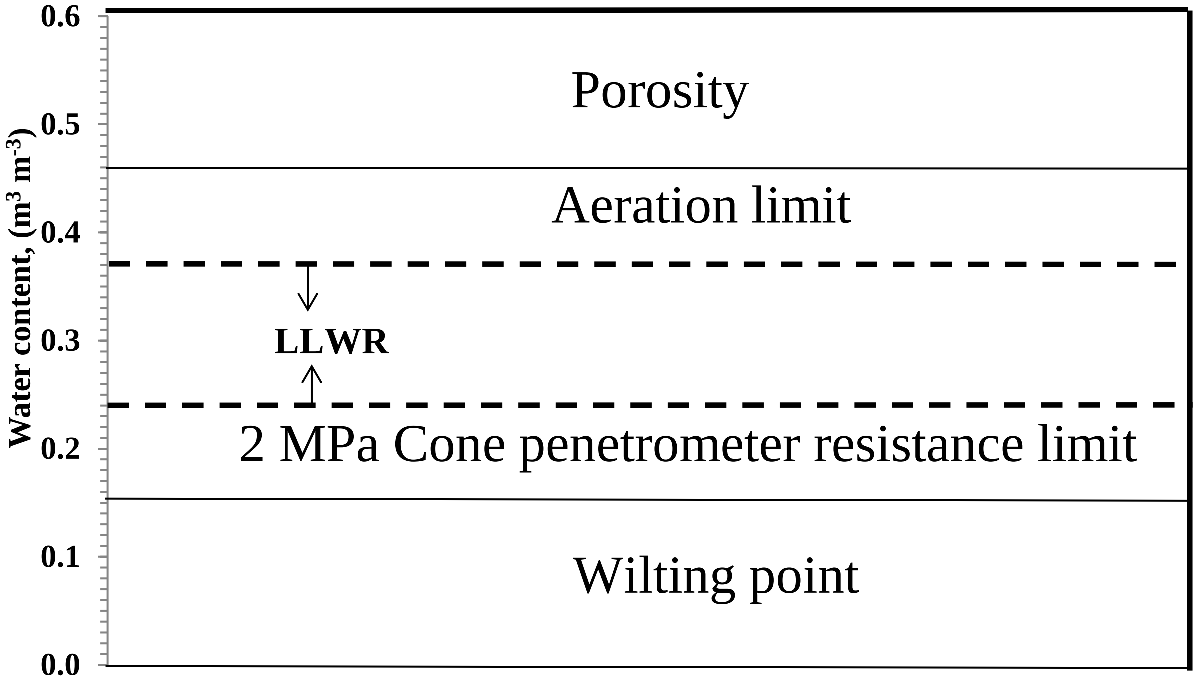


Figure 2.5. Schematic diagram of the LLWR concept, with cut-off points, adapted from Lapen et al. (2004).

The combination of the LLWR for a soil plus its water content over time allows the effects of physical stresses during the growing season to be quantified (Bengough et al. 2006; Da Silva and Kay 2004). Also, it has been proven to be a good indicator of soil physical conditions for plant growth in reduced tillage soil seedbed (Filho et al. 2013) sensitive to near surface soil physical properties (Lea˜o et al. 2006) and biological chiseling by forage radish cover crop (Filho et al. 2014).

The LLWR has been used to evaluate the physical quality of soils exposed to different management. Tormena et al. (1999), estimated greater values of LLWR in conventional tillage systems than in no-tillage systems, with a negative correlation for bulk density > 1020 kg m^{-3}. The LLWR varied between 0 - 0.1184 $cm^3 cm^{-3}$ in both systems, with mean values of 0.0785 $cm^3 cm^{-3}$ for no-tillage and 0.0964 $cm^3 cm^{-3}$ for conventional tillage (Tormena et al. 1999). High soil resistance to root penetration determined the lower limit of LLWR in 89 % and 46 % of soil samples in conventional and no-till plots, respectively, suggesting the soil physical quality of the conventionally tilled soil was better for crop production on that soil.

Filho et al. (2014), found soil penetration resistance to be the main limiting factor in plots exposed to no tillage, mechanical, and biological chiseling. The LLWR was greater in no tillage, and mechanical chiseling in the top 10 cm than in the biological chiseling plots (Filho et al. 2014). Lapen et al. (2004), concluded that conventionally tilled soils that were not preferentially trafficked were better aerated and had greater corn populations and yields, whereas the no-tillage soils were less well aerated, especially those in continuous corn and preferentially trafficked (Lapen et al. 2004). Mishra et al. (2015), quantified the LLWR for two conservation agricultural practices and confirmed that residue retention on field plots improved LLWR. They found in the top 30 cm, that the LLWR for permanent broad-beds in rotation (0.0756 cm^3 cm^{-3}) was greater than that for conventionally tilled soil (0.0636 cm^3 cm^{-3}). At greater depths, however, this was reversed (Mishra et al. 2015).

Lea˜o et al. (2006), evaluated the LLWR as an index of near-surface soil quality after conversion from savanna vegetation to continuous and short–duration grazing systems. They found near-surface soil physical qualities to be most restrictive for potential root growth in short–duration than in continuous and native cerrado grazing. Da Silva and Kay (2004), employed the LLWR as a soil physical quality indicator to evaluate the physical properties of a Luvisol at a site with different forest management systems. They found a decrease in LLWR with increasing bulk density for all treatments. At critical bulk densities of 1690, 1620, 1560, and 1560 kg m^{-3} respectively for agro-silvipasture, silvipasture, natural vegetation, and conventional crop management, the LLWR was found to be zero (Silva et al. 2011). The agroforestry system had high values of LLWR, which were similar to the values for natural vegetation, with associated superior aeration, matric suction and reduced resistance to penetration by roots (Silva et al. 2011).

Zou et al. (2000), reported an initial increase in LLWR with compaction of some coarse sandy soils under forestry but further compaction decreased LLWR. In contrast, Chen et al. (2014) found that compaction of loamy and sandy surface soils reduced LLWR through either greater soil strength or lower soil aeration or both. They concluded that tap-rooted cover crops could increase LLWR and air permeability because they formed root channels that allowed greater soil aeration and alternative pathways for roots to explore the otherwise hard soil. De Lima et al. (2012) also found that the cover crops, *Hermarthria altissima* and *Brachiaria brizantha*, grown on coal mining soils increased LLWR relative to other treatments attempted during reclamation.

Safadousta et al. (2014), observed higher values of LLWR for clay loams grown to wheat at water contents exceeding ‘field capacity’ (LLWR = 0.034 to 0.167 m^3 m^{-3}) and precisely at ‘field capacity’ (LLWR = 0.034 to 0.119 m^3 m^{-3}). In sandy loams grown to wheat at the same water contents, the LLWRs were greater (0.137 to 0.151 and 0.087 to 0.111 m^3 m^{-3} respectively at water contents exceeding ‘field capacity’ and precisely at ‘field capacity’. LLWR decreased sharply with increases in bulk density.

Wilson et al. (2011), used the LLWR concept to obtain critical bulk density values and assess their effects on early wheat growth. They found that wheat growth in the Mollisol was limited when bulk density exceeded 1400 kg m^{-3} and this was primarily due to poor soil aeration rather than to high penetration resistance. In a Vertisol, however, growth was not affected by increases in bulk density because shrinkage introduce sufficient air without extreme increases in penetration resistance (Wilson et al. 2011). Similarly, for soil conditions they were highly restrictive to plant growth. Guimara˜es et al. (2013), reported zero LLWR when the visual evaluation of soil structure was found to be ≥ 3.5.

Da Silva and Kay (1996), tested the idea that plant response, specifically shoot growth rate of corn, was functionally related to the proportion of the total growing season in which the water content falls outside the LLWR ($P_{\theta out}$) plus the magnitude of LLWR. Although there was a high correlation between shoot growth rate and LLWR for water contents measured within the available water range, they found that variations in $P_{\theta out}$ accounted for a greater % change in shoot growth rate than did the magnitude of LLWR alone. Others for example, Mishra et al. (2015), however, found non-significant relationships between mean grain yields and LLWR for crops of rice, wheat and cotton, which suggests LLWR may not account for all factors that reduce water uptake or reduce crop productivity.

Da Silva and Kay (1997b), postulated that the frequency of soil water content falling outside the LLWR ($P_{\theta out}$) increases with decreasing LLWR and that the relation is controlled by tillage, position (row versus inter-row), and climatic conditions. A logistic regression analysis showed that $P_{\theta out}$ was negatively related to LLWR, regardless of climate, tillage, or position. $P_{\theta out}$ was also lower in the no-tillage plots than in the conventional tillage plots, and the inter-row plots had lower $P_{\theta out}$ than the mid-row plots. Da Silva and Kay (1997a), concluded that the sensitive nature of pedotransfer functions used in predicting soil physical properties for LLWR estimation could be used for any selected limiting values associated with soil aeration, soil resistance, and soil matric suction.

Mohammadi et al. (2010), criticised the LLWR concept by pointing out that plant functional and soil physical considerations were not considered directly in defining the upper limit of the

LLWR. They argued the upper soil matric suction of the LLWR could be predicted from knowledge of the soil moisture characteristic curve, plant root depth and oxygen diffusion rates. Their results suggested that the often-assumed upper soil water content at which the volumetric air content = 10 % may not be appropriate in calculating LLWR because it does not appropriately reflect the crop water requirement. As the upper soil matric suction set for the LLWR approaches volumetric soil water content at saturation, the oxygen diffusion rate of soil drops to < 2 μmol m^{-3} s^{-1}. Mohammadi et al. (2010), concluded that the upper soil matric suction for LLWR could exceed the soil water content at field capacity depending on the drainage flux rate, especially in sandy soils.

2.9.2 Integral Water Capacity

Critics of the classical and modified approaches to calculating plant available water (e.g. Mohammadi et al. (2010); Kutílek and Nielsen (1994); Hillel (1998) argued against using abrupt upper and lower limits. They argued, for example, that the measured soil water content and matric head of soil at 'field capacity' in the field depends upon the initial water content and the depth of wetting before the start of redistribution. Furthermore, the rate of change in water content over time varies between soils and even for the same soil. Hillel (1998) argued that the point at which the transpiration rate in plants starts to drop below the potential rate is probably a better indicator, because it depends on the integrated effects of soil, plant, and weather (Hillel 1998). He also argued that attempts to calculate plant available water using only soil factors (or only plant factors) was futile. Groenevelt et al. (2001), on the other hand argued that one has to start somewhere, and it is not always possible to involve plants directly, so a soil-based model was as good a place to start as any. They proposed the *integral water capacity* (IWC) model as their starting point.

The IWC theory of Groenevelt et al. (2001), encompassed multiple soil physical restrictions (aeration, hydraulic conductivity, resistance) and chemical restrictions (soluble salt concentration) to predict soil water availability using weighting functions linked to the soil matric head. Weighting functions were applied to the differential water capacity followed by integration. It allowed the distinctiveness in soil properties and crop behaviour near the matric suction points of water availability to be compared to those from previous models. The integral water capacity was defined as follows:

$$IWC \equiv \int_0^\infty \prod_{j=1}^n \omega_j(h)\, C(h) dh \quad , \qquad [15]$$

where ω_j (h) are weighting functions accounting for various limiting physical properties, j=1 to n; the operator, $\prod$, indicates the applicable weighting functions must be multiplied, C (h) is the differential water capacity, dθ/dh, and h is the matric head expressed in m.

The measured data points for soil water content and matric suction are fitted to a differentiable function such as that of Groenevelt and Grant (2004):

$$\theta(h) = \theta_a + k_1 \cdot \left\{exp\left[-\left(\frac{k_0}{h_a}\right)^n\right] - exp\left[-\left(\frac{k_0}{h}\right)^n\right]\right\} \quad , \qquad [16]$$

in which θ_a and h_a are the coordinates of the point at which the model is anchored, in this case, at the classical 'wilting point' (h_a = 150 m; $\theta_a = \theta_{150}$), and where k_1 and n are dimensionless adjustable fitting parameters and k_0 is an adjustable fitting parameter with units of length (m). Substituting the values of the anchor point into **Eqn [16]** gives the water retention curve to be used here:

$$\theta(h) = \theta_{150} + k_1 \cdot \left\{exp\left[-\left(\frac{k_0}{150}\right)^n\right] - exp\left[-\left(\frac{k_0}{h}\right)^n\right]\right\} \quad , \qquad [17]$$

The differential water capacity, C(h), is obtained from **Eqn [17]** and reversing the sign:

$$C(h) = \left|\frac{d\theta}{dh}\right| = \frac{k_0 n\, exp\left(\frac{k_0}{150}\right)^n \left(\frac{k_0}{h}\right)^{n-1} (\theta_s - \theta_{150})}{h^2} \quad , \qquad [18]$$

where θ_s is the volumetric water content at saturation. The water capacity shown in **Eqn [18]** is attenuated according to **Eqn [15]** using appropriate weighting functions to produce an effective water capacity, E(h) (e.g. **Figure 2.6**):

$$E(h) = \omega(h) \times C(h) \quad , \qquad [19]$$

The weighting function in **Eqns [15]** and **[19]** may be linear or non-linear and it is generally constructed to have a range between zero and unity at appropriate matric suctions. The IWC is then calculated by integrating **Eqn [19]** between h = 0 and ∞, using appropriate initial and final matric heads, h_i and h_f for the weighting, as follows:

$$\begin{array}{lll} & 1 \quad , & h < h_i \\ IWC = \int_{h_i}^{h_f} E_i\,(h)dh & , & h_i < h < h_f \qquad [20] \\ & 0 \quad , & h > h_f. \end{array}$$

Grant et al. (2003), tested the model to predict PAW in a Sodic Hypercalcic Chromosol. Weighting functions developed to account for aeration, hydraulic conductivity, and soil strength restrictions used by Groenevelt et al. (2001) were employed such that $\omega_j(h) = 1$ for non-limiting conditions, and $\omega_j(h) = 0$ for completely limiting conditions of water availability. Grant et al. (2003), calculated IWC for soils sampled from the different horizons and compared values of IWC with values of the classical PAW for same soil samples. Because of the low overall storage capacity of the soil (only 55 to 65 mm m^{-1}) the values of IWC were less than the values of PAW by only 12.5 mm m^{-1}.

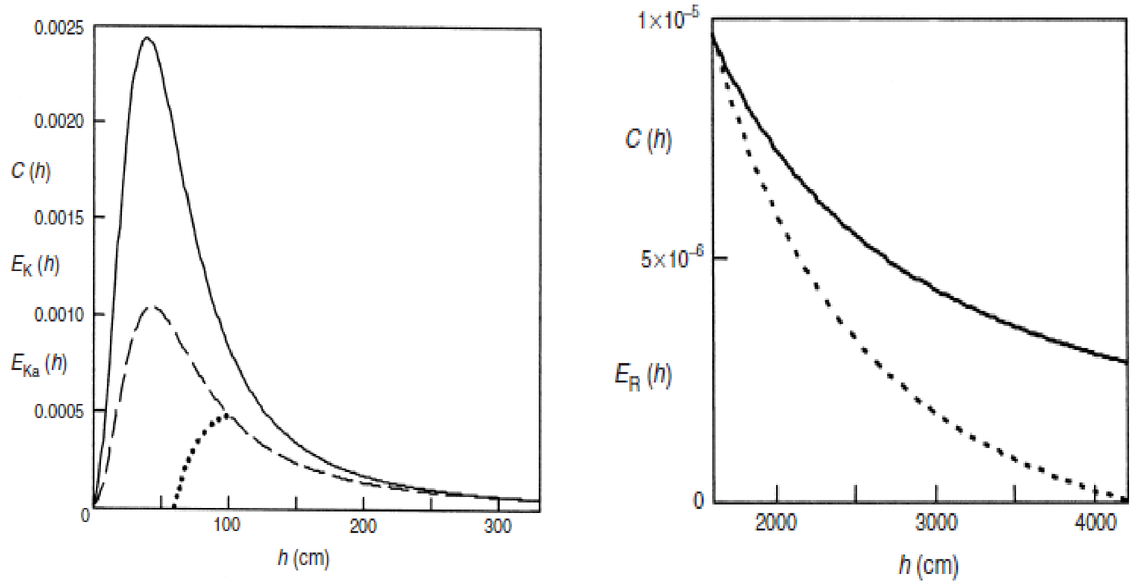


Figure 2.6. Differential water capacity, $C(h)$, (—); Effective water capacity, $E_K(h)$, when $\omega_K(h)$ is applied (– –), Effective water capacity, $E_{Ka}(h)$, when both $\omega_K(h)$ and $\omega_a(h)$ are applied (…) and Effective water capacity, $E_R(h)$, when $\omega_R(h)$ is applied (- - - -). Adapted from Groenevelt et al. (2001).

Groenevelt et al. (2004), developed weighting function, which considered the effect of soluble salt concentration on IWC. They developed the weighting function for different soil textures with varying electrical conductivities in the saturated paste. Without real plants, the putative weighting function produced the greatest possible reduction in soil water availability by assuming that plants behave as perfect semi-permeable membranes. This, of course, does not reflect what real plants experience because they are able to regulate the intake of salts according to plant requirement for nutrients, so their weighting function may or may not be very useful. Nang (2012), found that by also including the limiting effects of high soil resistance, low soil aeration and low hydraulic conductivity, the IWC was greatly reduced in the presence of salt. The assumption of a unit reflection coefficient in developing the weighting function might have accounted for its severe restriction of IWC. Therefore, to use it for plants with different salt tolerance the reflection coefficient of the plant must be varied accordingly.

Another putative weighting function was developed by Grant and Groenevelt (2015) to account for low unsaturated hydraulic conductivity in the IWC model. The modification took into consideration the soil water diffusivity function (ratio of hydraulic conductivity and differential water capacity as functions of the soil matric head) and the weighting was applied from the inflection point in the water retention curve (plotted on a semi-log scale) in the relation:

$$IWC \equiv \frac{D(h)}{D_{ip}} \times \int_{h=h_{ip}}^{\infty} C(h)dh \qquad , \qquad [21]$$

in which D(h) is the diffusivity function, or K(h)/C(h), D_{ip} is the point value of the diffusivity at the inflection point, h_{ip}, identified on the water retention curve. The diffusivity function and the hydraulic conductivity function for a soil are shown in **Figure 2.7 (a)** and the weighting function arising from **Eqn [21]** is shown in **Figure 2.7 (b)**.

A feature of the water retention model used by Grant and Groenevelt (2015) is that the matric head at the inflection point is easily identified as the point-value of the parameter, k_o, in their equation. The value of k_o for a number of sandy textured soils lies relatively close to the nominal matric head at "field capacity", h = 1 m.

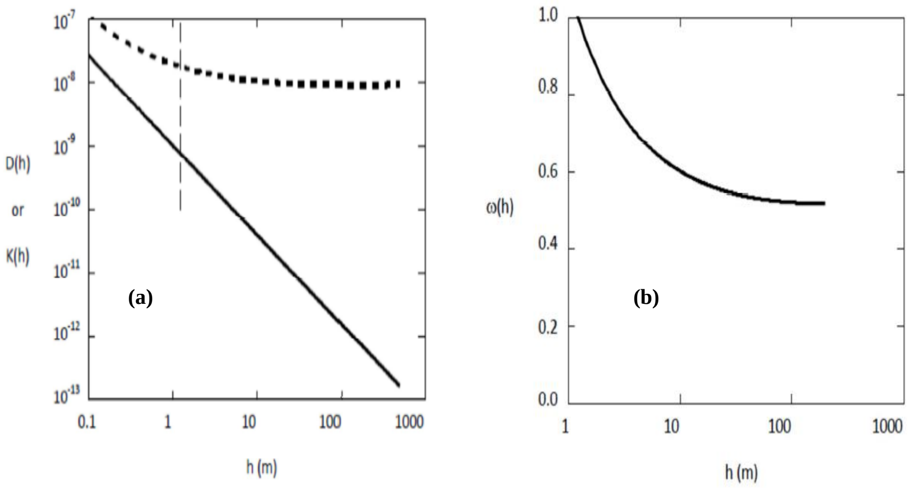


Figure 2.7. (a) Functions for the diffusivity (dotted line) and hydraulic conductivity (solid line). The vertical (dashed) line identifies the matric head, h (m), at the inflection point of the water retention curve (b) hydraulic conductivity weighting function (thick continuous curve) derived from relative diffusivity. Adapted from Grant and Groenevelt (2015).

2.10 Limitations to IWC model

The primary weakness of the IWC model for predicting plant available water is that only limited work has been done to evaluate the weighting functions against plant response. Most of the weighting functions are based solely on theoretical considerations, which may or may not be accurate in reality. There is considerable scope for testing the accuracy of the weighting functions (and their upper and lower limits) on a wider range of different soil textures and for economically important plants (Asgarzadeh et al. 2010).

2.11 Links to soil quality and plants

The IWC model has been evaluated against other soil physical quality indicators such as the classical PAW, LLWR plus an index of soil physical quality, S (defined as the slope of soil water retention curve at the inflection point when the curve is plotted as gravimetric water versus the natural logarithm of *h* (Dexter 2004), in both the laboratory and the field (Asgarzadeh et al. 2011; Asgarzadeh et al. 2014; Asgarzadeh et al. 2010). The IWC has also been used to predict plant available water in soils to evaluate the physical quality of the soil (Asgarzadeh et al. 2011; Asgarzadeh et al. 2014; Asgarzadeh et al. 2010). Asgarzadeh et al. (2010), reported highly significant soil water availability values calculated by the IWC approach compared to the LLWR procedure with low PAW for twelve selected soil cores. They found broad general agreement between IWC and LLWR, with some soils having smaller, larger or equal magnitudes depending on whether the volumetric air content was calculated at h = 1 m or h = 3.3 m. Again significant relationships were obtained between the available water values predicted and the soil physical quality (S) index values, which indicates how suitable the S-index could also be used to predict soil water availability for plants, when a comprehensive procedure like the IWC is considered (Asgarzadeh et al. 2010).

Asgarzadeh et al. (2014), compared and contrasted laboratory and field methods used in measuring soil hydraulic properties required for the calculation of S, PAW, LLWR and IWC. The reliability among four laboratory and two field methods was evaluated to determine basic soil variables required to predict soil water availability (Asgarzadeh et al. 2014). A highly positive correlation was found between available water values and S-values calculated by laboratory, laboratory data "Total" and field methods suggesting that all the methods are reliable and quick (Asgarzadeh et al. 2014). There was also a highly significant positive relationship between LLWR and IWC using soil matric suctions measured by tensiometer and pressure plate apparatus, which showed how LLWR and IWC could be calculated in the field in about ten days (Asgarzadeh et al. 2014).

However, from the plant perspective only the works of Chahal (2010) and Nang (2012) have been done to test the model's efficiency in predicting the exact amount of water required for crop uptake in soil. Water availability in light textured soils under the limitation of only unsaturated hydraulic conductivity was evaluated for maize and sorghum by Chahal (2010). The variable evapo-transpirative demand used as an experimental factor appeared to have no significant impact on the soil matric suction at which unsaturated hydraulic conductivity became limiting to plants grown in very fine sand and loamy sand (Chahal 2010). The only effect was on the overall time required to extract the water. For high evaporative demand, it took less time to reach the same matric head at wilting. Chahal (2010), found that stomatal conductance of plants grown in very fine sand was highly responsive to water stress brought on by low unsaturated hydraulic conductivity. Plants stopped transpiring at soil matric suctions much smaller than the classical wilting point (h = 150 m) whereas those grown in a loamy sand persisted to much greater soil matric heads, sometimes significantly beyond h = 150 m. Different soil textures and structures have varying pore size distributions and so the restriction on water availability due to hydraulic conductivity varies in different soils. The work conducted on the two soil textures examined by Chahal (2010) needs to be extended to both coarser and finer soil textures.

Nang (2012), used plants to evaluate the utility of the IWC for predicting soil water availability in soils being reclaimed from the saline-sodic to non-saline state. Weighting functions were developed to account for poor soil aeration at the wet end, plus rising penetration resistance and declining hydraulic conductivity at the dry end (Groenevelt et al. 2004; Groenevelt et al. 2001). He included plant- and soil-specific variables for Rhodes grass (and Faba bean in solution) and soil water under salinity restriction (Nang 2012). His weighting function produced a more gentle attenuation of the water capacity than did the one proposed by Groenevelt et al. (2004).

The findings of Nang (2012) need to be authenticated on economically important crops, particularly those varying in their salt tolerance. The assumed soil matric suctions chosen at the wet and dry ends as the basis for IWC calculation currently does not consider the plant sensitivity factor, which may influence water uptake under saline conditions. Therefore, the matric suctions at which salt sensitive plants cease to grow can be determined to develop a more realistic weighting function for the effect of salt on IWC.

The relative diffusivity has been applied as a weighting function to account for hydrodynamic restrictions in a drying coarse sand (Grant and Groenevelt 2015). They argued that water movement to plant roots in soil is limited by two components: a release component and a transport component. The release component is embodied in the differential water capacity, and the transport component comes from the unsaturated hydraulic conductivity. Weighting the measured water capacity based solely on the hydraulic conductivity component would generate a very harsh reduction, as seen in **Figure 2.7a** (thick solid line), which may account for the unrealistically weighted result developed to mimic the measured plant response in the work of Chahal (2010). To develop a gentler weighting, both the transport and release components of water supply need to be considered at the dry end, along the gentler lines suggested by the diffusivity function shown in **Figure 2.7a** (thick dotted line), and plotted as a weighting function in **Figure 2.7b.** The new model has not yet been tested on real plants to confirm its hypothetical weighting effect on the water capacity. More especially, the choice of the matric head at the inflection point as the initial point where hydrodynamic restrictions start to limit water uptake in drying coarse textured soils needs to be evaluated.

2.12 Indicators of plant stress

Soil water stress (or drought) is a condition that occurs in soil when plant available water becomes a limiting factor to crop growth. This usually becomes evident when plant cells and tissues are seen to be less than truly turgid (Kumar et al. 2014). Explicitly, it occurs whenever the amount of water required for transpiration exceeds the rate of root water uptake from the soil system. Plant inability to uptake enough water from the soil through the root system to replace the loss water by transpiration exposes the plant system to water stress. The resultant effect is wilting, reduction in photosynthesis, disturbance in physiological processes, cessation of growth or even death of crop plant (Kumar et al. 2014).

Practically, water stress affects all aspect of plant growth, through the modification of plant anatomy, morphology, physiology and biochemistry, which reduce turgor, water and osmotic potential (Chundawat 1990). Wilting is the main visible effect of plant water stress. Soil drying through the effect of evapotranspiration induced plant stress, which may be physiological or biochemical depending on the stress intensity. High evapotranspiration demand increases the intensity of water stress by reducing the rate of water movement toward plant roots for absorption (Kramer 1969; Li et al. 2002). As an example, sorghum and maize plants grown in loamy and very fine sand under high evapo-transpirative demand showed signs of water stress earlier than when grown under low evapo-transpirative demand (Chahal 2010).

Plant water uptake from the soil is restricted because of low hydraulic conductivity and root activity. The reduction in water flow and root activity affects the transport of water into the stem through the xylem to the rest of the plant. This becomes evident when the pressure in plant leaf drops (low turgor pressure) which reduces plant growth (Kumar et al. 2014).

Photosynthesis is reduced when moisture in plant tissues and soil become limiting to crop growth. Cell enlargement slows down, stomates close and leaves wilt, which reduces leaf area and thus reduces photosynthetic rate per unit leaf area (McCree 1986) thus increasing leaf senescence, interfering with basic metabolic processes (Kramer and Boyer 1995), which in turn reduces photosynthesis in the remaining leaves (Boyer 1976). Carbon dioxide (CO_2) fixation declines when water stress closes stomates and this reduces photosynthesis (Chaves 1991; Cornic and Massacci 1996) depending on the amount of water lost by transpiration and the sensitivity of the plant (Akıncı and Lösel 2006; Chaves et al. 2003; Ghannoum 2009).

Plants use osmotic adjustment to maintain turgor in leaf as soil moisture limits transpiration. Osmotic adjustment arises when solutes accumulate in growing cells at low water potential to maintain turgor in tissues (Morgan 1984; Turner and Jones 1980). This normally depends on the supply of photosynthates to plant sink points. As moisture content in plant tissue declines, osmotic adjustment delays but cannot completely prevent dehydration (Kramer and Boyer 1995). Plant root growth is more sensitive than leaf growth (Hsiao and Xu 2000) because greater osmotic adjustment occurs in lateral roots and root hairs than in leaves (Ober and Sharp 2007). The apical sections of maize, where primary roots emerge and where proline concentration increases under water deficit, contribute significantly to osmotic adjustment (Sharp et al. 2004; Sharp et al. 1988). Vendruscolo et al. (2007) found that stressed transgenic wheat plants responded with a drought-induced proline accumulation in which leaf growth was restricted by stomates closure and reduced water vapour loss. Photosynthesis is thus reduced by shoot water deficit, which increases carbohydrate channeling to the root to facilitate osmotic pressure for root elongation (Chimenti et al. 2006).

Many plant species use the same mechanism to mitigate the effect of water stress either by maintaining stomatal conductance, photosynthesis, leaf water volume and growth (Morgan 1984; Turner and Jones 1980). For example osmotic adjustment in wheat and other cereals happens quickly (Richter and Wagner 1983). Water stress increases the osmotic pressure of the cell sap, which increases sugar percentage (in sugarcane and sugar beet) even though this may reduce crop yield (Russel 1976). Some solutes that accumulate in the cells and tissues of non-halophytic plants comprise inorganic cations, organic acids, carbohydrates and free amino acids. In some plants, potassium is the primary inorganic cation accumulating in cells during water stress and is often the most abundant solute in leaf (Ford and Wilson 1981; Jones et al. 1980). Osmotic adjustment is a temporary phenomenon, which allows root tissue to regain its turgor and increase photosynthesis as soil water conditions improve. Morgan and Condon (1986) showed that osmotic adjustment in tissues diminishes as conditions improve and photosynthesis resumes. **Figure 2.8** shows a flow chart of interactions between soil hydraulic restriction and water stress.

2.12.1 Measuring plant and soil water status

Procedures for appraising water stress in soils and plants are grouped into (i) direct and (ii) indirect (Bhattacharjee and Saha 2014). Direct measurements include tissue water content, relative water content (RWC), and water saturation deficit for plants, and soil water content or potential (or even rainfall distribution) in soils. Indirect measurements include plant physiological responses such as leaf water potential, stomatal conductance, transpiration rate, leaf temperature, canopy temperature, water use efficiency for plants (Farooq et al. 2009; Jones 2004), and a quantitative water balance for soils. The choice of methods depends on the aims of the experiment (Jones 2007). For example, studies concerned with mechanisms of water movement in the plant-soil system will use different methods than studies focusing on mechanisms of water stress and adaptive plant responses. Studies concerned with identifying differences in drought tolerance among crop genotypes will use even more different methods (Jones 2007).

The procedures used are broadly divided into methods that measure the amount of water or its energy status (Jones 2007). Measuring the amount of water can be done directly by weight (gravimetric) or indirectly by volume (volumetric) using neutron moisture probes (in the field)

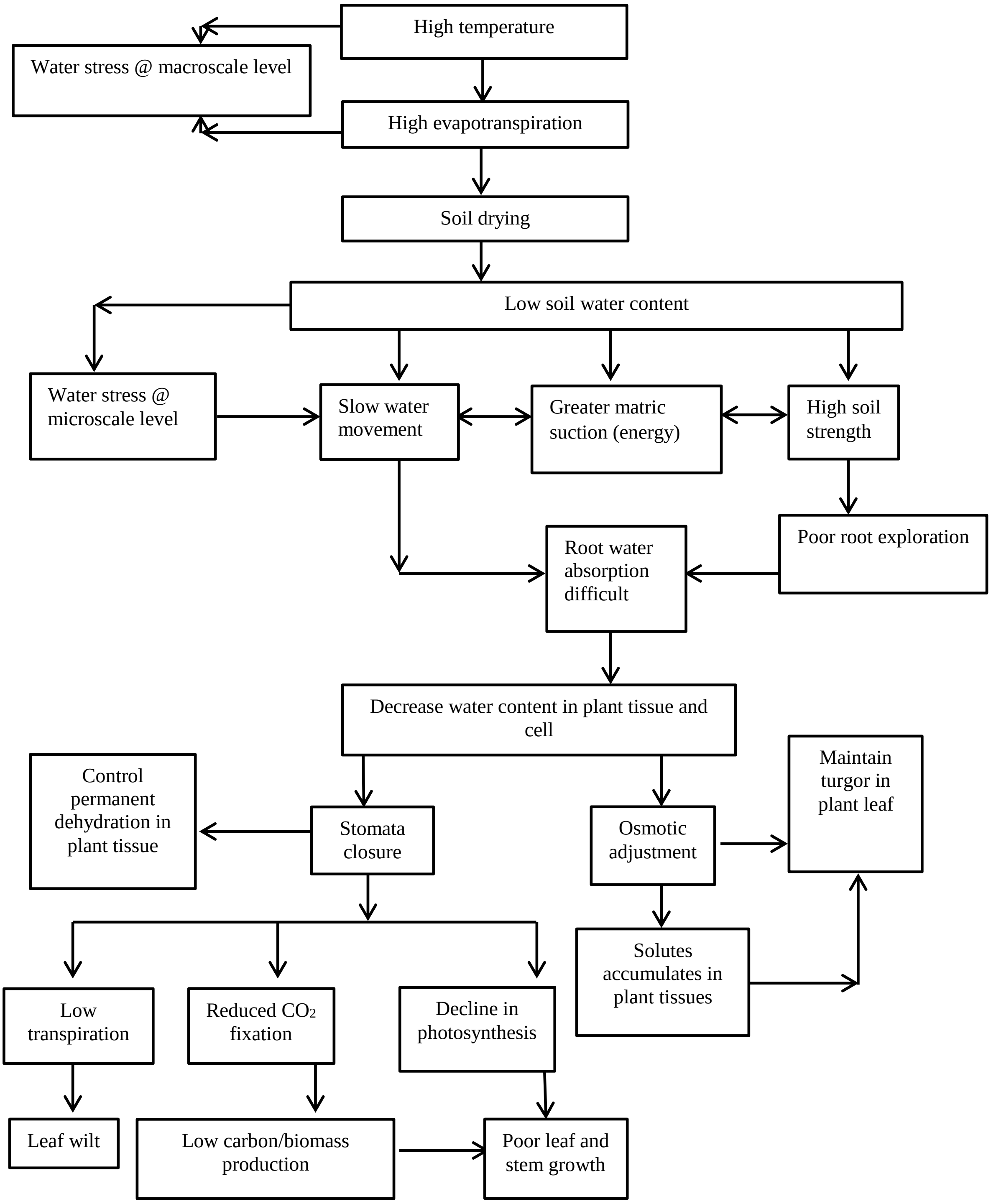


Figure 2.8 Links between soil hydraulic restrictions and water stress at both macro and micro scale in relation to crop response and growth under limiting water conditions.

or dielectric instruments in both field and laboratory (Gardner et al. 2000; Kirkham 2004). Another indirect approach is the water balance method, which can be indirectly based on changes in soil moisture, $\Delta\theta$, as used by Frimpong et al. (2012):

$$\Delta\theta = \mathrm{P} + \mathrm{I} - \mathrm{ET} \pm \mathrm{RO} \pm \mathrm{D} \quad , \qquad [22]$$

where, P is precipitation, I is irrigation, ET is evapotranspiration, RO is run-off or run-on and D is deep drainage beyond the root zone. The components (all expressed as depths of water, mm) and how they are estimated are described in Allen et al. (1998), and in most cases the RO and D components can be considered negligible (Jones 2007).

The amount of water in plants can be used to assess water stress, and this is usually expressed as a mass ratio on a dry or fresh weight basis (Turner 1986), *viz.*:

$$\mathrm{W_{PDry}} = \frac{\mathrm{M}_F - M_D}{\mathrm{M}_D} \times 100 \qquad [23]$$

or

$$\mathrm{W_{PFresh}} = \frac{\mathrm{M}_F - M_D}{M_F} \times 100 \qquad [24]$$

In practice, measuring $\mathrm{W_{PDry}}$ or $\mathrm{W_{PFresh}}$ involves simply measuring the fresh weight at sampling and after oven drying to constant weight. However, tissue dry mass depends on growth stage (time), and fresh mass varies with species and previous growth conditions (Turner 1986) so it is not a simple matter to relate plant water content to plant water stress. The same data can be used, however, with one additional measurement to generate a normalized plant water content called the *relative water content* (Hsiao 1973). The r*elative water content* (RWC) expresses the water content of a fresh sample of plant relative to the water content of that sample at full turgor (Barrs 1968; Barrs and Weatherley 1962; Weatherley 1950):

$$\mathrm{RWC} = \frac{\mathrm{M}_F - \mathrm{M}_D}{\mathrm{M}_T - \mathrm{M}_D} \times 100 \qquad [25]$$

The *water saturation deficit* (WSD) is the reciprocal of the RWC (Turner 1986):

$$\mathrm{WSD} = \frac{\mathrm{M}_T - \mathrm{M}_D}{\mathrm{M}_F - \mathrm{M}_D} \times 100 \qquad [26]$$

The RWC approach is widely used because it requires no sophisticated equipment and it is closely related to cell turgor, which drives leaf cell expansion (Jones 1990). For example, Nerd and Nobel (1991) found RWC decreased in *Opuntia ficus indica* by 57% during drought stress, and (Egilla et al. 2005) found that the RWC and turgor pressure in leaves of *Hibiscus rosa-sinensis* also declined under drought stress. Stage of maturity also influences RWC. For example, (Siddique et al. 2000) found that RWC in wheat leaves was initially high during leaf development but decreased as dry matter accumulated in matured leaves. Rampino et al. (2006)

found that RWC was a good indicator of water stress when evaluating differences in wheat genotypes. Teulat et al. (2003) also used RWC to distinguish between drought-resistant and drought-sensitive wheat genotypes.

Despite its simplicity, the RWC approach only measures the amount of water in plant tissue, not the energy required for water extraction from the soil or plant system (Jones 2007). To evaluate the energies involved in water extraction, the soil matric potential and the plant tissue pressure deficit can be used. Slatyer and Taylor (1960), for example, expressed the concepts of capillary potential on a thermodynamic basis in terms of total water potential, ψ, which is the Gibbs free energy relative to water at standard temperature and pressure. The total potential can be expressed as (Dainty 1963; Slayter 1967):

$$\psi = \frac{(\mu - \mu_o)}{V_w} = -\left(\frac{RT}{V_w}\right) log_e \left(\frac{e}{e_s}\right), \qquad [27]$$

where V_w is the partial molal volume of water, μ_o is the chemical potential of pure water at a reference level, R is the universal gas constant, T is the temperature, and e/e_s is the vapour pressure in equilibrium with the water-containing matrix divided by the saturation vapour pressure at that temperature. The value of ψ anywhere in the soil–plant system can therefore be described as:

$$\psi = \psi_S + \psi_P + \psi_G + \psi_M \quad , \qquad [28]$$

where ψ_S is the osmotic potential due to dissolved solutes, ψ_P is the pressure potential when the soil is saturated, ψ_G is the gravitational potential reflecting elevation differences between the site of interest and the reference level, and ψ_M is the matric potential due to the soil matrix. **Eqn [28]** holds regardless of which components operate, such that under non-saline conditions it reduces to:

$$\psi = \psi_M \quad \text{, for unsaturated soils, and} \qquad [29]$$

$$\psi = \psi_P \quad \text{, for plants} \qquad [30]$$

Where saline conditions operate, solutes exert an additive influence on the total water potential:

$$\psi = \psi_M + \psi_S \quad , \qquad [31]$$

The water status of tall trees takes into account the fact that water must be lifted against gravity to great heights, thus the total water potential is:

$$\psi = \psi_M + \psi_S + \psi_G \quad , \qquad [32]$$

A more direct method to determine water status in plant tissue uses the thermocouple psychrometer, in which plant tissue is placed into a hermatically sealed chamber until the relative vapour pressure in the chamber equilibrates with that in the plant tissue (Turner 1986).

Leaf water potential is arguably the easiest and most reliable (indirect) measure to detect the onset of water stress in plants (Meyer and Green 1981). A thermocouple psychrometer and pressure chamber are commonly used to measure leaf water potential on excised leaves but non-destructive, portable devices have also been developed for this purpose. Leaf water potential is highly sensitive to environmental conditions to such an extent that short-term fluctuations can be greater than treatment differences (Jones 2004), so the conditions during measurement need to be carefully controlled.

In addition, stomatal conductance, transpiration rate, osmotic adjustment, water or transpiration use efficiency and growth parameters are among plant physiological responses that have been used extensively to assess plant response to water deficit. For example, Craufurd et al. (2000) measured a decrease in stomatal conductance in stressed, non-irrigated plants, despite the fact that transpiration rates were similar in both stressed and unstressed plants. They argued that the lower total water use for the stressed plants resulted entirely from a smaller leaf area index. Clarke and McCaig (1982) used leaf diffusive resistance, leaf temperature and drying rate of excised leaves to screen wheat genotypes for drought resistance. Izanloo et al. (2008) used stomatal conductance to identify stress sensitive Australian bread wheat cultivars and found high stomatal conductance in the leaves of Excalibur compared to that of Kukri and of RAC875. Soleimani et al. (2014) also found that stomatal conductance (and RWC) were useful for evaluating drought tolerance in Iranian wheat genotypes; they found a negative correlation between RWC and stomatal opening, and that the wheat genotype, Kohdasht, had the greatest ability to retain water under stress, which was mainly due to efficient osmotic adjustment and stomatal closure in this genotype. Molnár et al. (2004) also used stomatal conductance and transpiration rate to evaluate the drought tolerance of different genotypes of *Aegilops biuncialis* and wheat. By decreasing the osmotic pressure of nutrient solution (-0.027 to -1.8 MPa) they found significantly greater water loss, less stomatal closure plus a reduction in the intercellular CO_2 concentration (C_i) for the *Aegilops* genotypes (from dry habitats). By contrast, the same treatments increased stomatal closure, reduced water loss and increased C_i for the wheat genotypes. Importantly, *Aegilops* genotypes produced more biomass under water stress than the wheat genotypes.

In general, however, the above measurements of plant water stress tend to depend on delicate and expensive instruments (Jones 2004) and so most studies apply simple plant weight measurements, which imply plant water stress when used to calculate parameters such as *water* *use efficiency*, WUE (Asare et al. 2011). Abbate et al. (2004), for example, found that wheat grown under limited water supply had a greater WUE than wheat grown in well-watered conditions. Similarly DeLucia and Heckathorn (1989) and Lazaridou and Koutroubas (2004) found that WUE increased in water-stressed clover, where the transpiration rate declined, leaf area declined and yet yield reduction was minimal. Studies using *Pinus ponderosa* and *Artemisia tridentate* showed that drought stress increased WUE mainly due to a rapid decrease in stomatal conductance with increasing water deficit. Lazaridou et al. (2003) reported that Lucerne (*Medicago sativa*) grown under drought had greater WUE than under irrigated conditions for the same leaf water potential. By contrast, early season drought stress in potatoes significantly reduced WUE and decreased growth and biomass accumulation (Costa et al. 1997). Rawson and Constable (1980) used WUE and transpiration to assess sunflower response to adequate water supply under glass house and field conditions with supplementary irrigation. They concluded WUE of sunflower in the short term was similar to that of C3 species such as wheat, in spite of the high rate of gas exchange.

Coleoptile length of young seedlings is another simple measure of plant response to water stress and can be used to differentiate among wheat genotypes for differences in osmoregulation, growth and yield (Morgan 1988). Seed vigour index, germination percentage, root length, shoot length, and root-to-shoot length ratio were used as indices of drought tolerance in wheat genotypes at early growth stage (Dhanda et al. 2004).

There are clearly many indicators of plant stress, some more easily measured than others, and some more effective depending on plant sensitivity to water stress. Many plant physiological processes respond directly to changes in tissue water status (in roots, stems or leaves), which do not always reflect changes in the bulk soil water content or potential (Jones 2004). Tissue water potential at any time depends on a complex interaction between soil moisture status, rate of water flow through plant, and hydraulic resistance between bulk soil and roots. Much research is needed to define the many links between soil water status and plant response. In response to the need for a link between soil hydraulic properties and plant response, Grant and Groenevelt (2015) proposed the inflection point on the water retention curve to be the initial point where water stress begins to occur in plants grown on coarse sandy soils. As indicated earlier in the text, this is yet to be evaluated with real plants.

2.13 Summary and conclusions

Restrictions to plant available water include pore size distribution (influenced by texture and structure), poor soil aeration, excessively large or small hydraulic conductivity, high soil strength, and osmotic stress caused by excessively high salt concentrations. Of these, the major restriction to plant available water in coarse textured soils would appear to be the unsaturated hydraulic conductivity, and possibly the osmotic stress caused by salinity.

To account for the rapid decline of the hydraulic conductivity function, Grant and Groenevelt (2015) proposed using the relative diffusivity function to attenuate the measured water capacity, and furthermore that the attenuation should start at the matric head corresponding to the inflection point on the water retention curve (easily identified from the fitting parameter, k_0, in **Eqn [16]**). There are several problems with their proposal:

1) The weighting function proposed was found to only attenuate the water capacity to about 50 % and the only way to bring this down toward zero (as required by a true weighting function) was to introduce an artificial 'plant sensitivity' factor, ξ. The utility of the relative diffusivity and the ξ-factor as weighting functions therefore needs to be evaluated to determine whether a 50 % attenuation is sufficient for many plants and whether plant sensitivity can be matched to specific values of ξ.

2) Using the inflection point of the water retention curve at $h = k_o$ as the starting point for attenuating the water capacity was proposed by Grant and Groenevelt (2015) but this has never been properly evaluated for soil textures finer than very coarse sand. It is possible the approach may only apply to very coarse sands but not to finer textured soils, so the correlation between the magnitude of k_o and the modal pore size distribution needs to be evaluated; one would expect the correlation to degrade as the modal pore size distribution declined in finer textured soils.

3) Salinity has a large impact on soil hydraulic properties but mainly in soils that contain significant amounts of clay and organic matter. In very coarse textured soils, where colloid dispersion would be minimal, there may be little influence of salinity and sodicity. The link between k_o or $1/\alpha$ and the modal pore size in saline and sodic soils is yet to see evaluation, as the link between k_o or $1/\alpha$ and the onset of plant stress.

These three problems reduce to the following three research questions, which form the basis for this research.

2.14 Research questions

1) Is the matric head at the inflection point of the water retention curve $h = h_i = k_o$, really the best matric head to start weighting water capacity in calculating the integral water capacity, IWC, for sandy soils as suggested by Grant and Groenevelt (2015)? Furthermore, if $h = k_o$ is indeed useful for sandy soils, is it also useful for finer textured soils?
2) Does the matric head, $h = h_i = k_o$, correspond to the matric head at which plants begin to suffer water stress in sandy soils?
3) If the matric head, $h = h_i = k_o = 1/\alpha$, does it correspond with the onset of plant stress symptoms? In addition, can the correlation hold under varying degree of salinity in sandy soils?

2.15 Hypotheses

The three questions above lead to the following testable hypotheses:

Hypothesis 1: Under controlled environmental conditions, the matric head, $h = h_i = k_0$, represents an unbiased point on the water retention curve (plotted on a semi-log scale) for all soils of sandy texture, and its location depends on (or can be related to) the single dominant (e.g. modal) pore size of the soil. The value of k_o will therefore shift in close (linear?) relation with some measure of particle size (or pore size) for sandy textured soils. A corollary to this would be that for soils of finer texture, where the pore size distribution may be multi-modal, the correlation between pore size and k_o will become weaker and weaker.

Hypothesis 2: Under controlled environmental conditions, water stress in plants grown on soils (for which there is a strong correlation between k_o and particle size) will only begin when the matric head of the soil water reaches $h = h_i = k_o$. The degree of correspondence will depend on the sensitivity of plant species to water stress; that is, highly sensitive plants will experience stress symptoms from $h = k_o$ while less sensitive plants will display symptoms only for $h >> k_o$.

Hypothesis 3: The degree of correlation between h_i (or k_o or $1/\alpha$) and the matric head (h) at which water stress begins for soils and crops varieties in question, depends on salt concentration; as salt concentration increases at crop stress onset at h_i, the degree of association declines.

2.16 Proposed experiments

Three main experiments were conducted to address the three questions raised, as follows;

Experiment 1: Location of the inflection point in different textured soils.

Aim: To determine whether the inflection point ($h = k_o$) on the water retention curve varies in a predictable manner with some measure of particle and pore size in a range of different soils in the coarse-textured range.

Experiment 2: Degree of correlation between the matric head at $h = k_o$ and the onset of water stress symptoms in plants.

Aim: to determine whether the theoretical inflection point on the water retention curve marks the point at which different plants begin to experience water stress.

Experiment 3: Influence of salinity on the degree of correlation between the matric head at $h = k_o = 1/\alpha$ and the onset of water stress symptoms in plants.

Aim: to determine the extent to which the presence of salt in the soil solution, influences whether the theoretical inflection point on the water retention curve marks the point at which different plants begin to experience water stress.

CHAPTER 3

Materials and methods to select soils

3.1 Introduction

Soil materials with a high fraction of sand-size particles were needed for this study because plant available water is most restricted in sandy textured soils, primarily due to their large pores and very small unsaturated hydraulic conductivities. An essential component of plant available water is the *water retention curve*, θ(h), so water retention curves were therefore prepared for several different soils of sandy texture. Details of the procedures used in sample selection and physical characterization are described in the sections below. The more specific methods applicable to the water retention curves and the plant experiments will be reported in subsequent chapters.

3.2 Selection of soil materials

Pure commercial sands with trade names 1–3 mm, ABC30, WSC70, and 300WSC were obtained from Sloans Sands Pty Ltd, Dry Creek, South Australia and fractionated by manual sieving into eight size ranges passed through a nest of sieves: 2 mm, 1.4 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, 0.105 mm, 0.090 mm and 0.075 mm. A sandy textured soil was also sampled from three depths (0-15, 15-30 and 30-45 cm) in an almond orchard on the northern Adelaide Plains that had been irrigated with Class-A recycled water (**Figure 3.1**).

Figure 3.1: Sampling location within South Australia for the almond orchard soil. The yellow region represents the Northern Adelaide Plains horticultural district and the red dot shows the location of the trial site near Hillier (Gawler), Latitude -34.628, Longitude 138.682.

The soil was taken to the laboratory, air dried and passed through a 2 mm sieve to remove stones and plant debris. Another soil with a fine sand texture was also included because it was used by Chahal (2010) and had a detailed characterization. The materials are listed in **Table 3.1**.

Table 3.1: Pure sands and sandy soil materials evaluated for final screening and selection based on measured soil physical properties. * ≡ geometric particle-size diameter (refer to **Table 3.1a**)

Soil sample #	**Particle size range (sieve aperture, mm)**	**Nominal particle size (arithmetic mean, mm)**	**Texture name & acronym**
1	1.4 – 2.0	1.7	Very Coarse Sand, VCS
2	1.0 - 1.4	1.2 (not used)	VCS
3	0.5 – 1.0	0.75	Coarse Sand, CS
4	0.25 - 0.5	0.375 (not used)	CS
5	0.125 - 0.25	0.19	Medium Sand, MS
6	0.105 - 0.125	0.115 (not used)	MS
7	0.090 - 0.105	0.098 (not used)	MS
8	VFS	0.178*	Fine Sand, FS
9	0.075 - 0.090	0.08	Very Fine Sand, VFS
10	Almond soil 0-15 cm	0.048*	Sandy Loam, SL
11	Almond soil 15-30 cm	(not used)	Sandy Clay Loam
12	Almond soil 30-45 cm	(not used)	Clay Loam

***Table 3.1a** Geometric particle-size diameter (GMD, mm) of the two sandy soils that were dispersed and passed through a nest of sieves.

Particle size name**	Sieve size or minimum particle diameter, mm	Size range, mm	Mean sieve size or particle diameter, M_i (mm)	lnM_i	Almond soil (0-15 cm) Sandy loam		(Chahal 2010) "Very fine sand" (actually Fine sand)	
					%Mass fraction of soil, %f_i	lnM_i x %f_i	%Mass fraction of soil, %f_i	lnM_i x %f_i
Sand	1	1 to 2	1.5	0.41	0.756	0.3	0.184	0.1
	0.7	0.7 to 1	0.85	-0.16	1.600	-0.3	0.335	-0.1
	0.5	0.5 to 0.7	0.6	-0.51	3.025	-1.5	0.898	-0.5
	0.25	0.25 to 0.50	0.375	-0.98	14.586	-14.3	29.368	-28.8
	0.21	0.21 to 0.25	0.23	-1.47	5.869	-8.6	15.119	-22.2
	0.125	0.125 to 0.21	0.1675	-1.79	16.366	-29.2	33.229	-59.4
	0.09	0.09 to 0.125	0.1075	-2.23	13.214	-29.5	9.986	-22.3
	0.075	0.075 to 0.09	0.0825	-2.49	2.483	-6.2	2.812	-7.0
	0.05	0.05 to 0.075	0.0625	-2.77	9.892	-27.8	2.015	-5.6
Silt	0.002	0.002 to 0.05	0.026	-3.65	10.887	-40.8	4.826	-17.6
Clay	0	0 to 0.002	0.001	-6.91	21.321	-147.3	1.228	-8.5
					GMD (mm)	**0.048**	GMD (mm)	**0.179**

3.3 Other physical characterisation of experimental materials

3.3.1 Particle density

The specific gravity , ρ_s (g cm^{-3}) of each sand and sandy soil was measured using small samples of air-dried soil (ca. 7 grams) corrected for water content, plus de-gassed water (20 °C) in pycnometers according to the method outlined in Blake and Hartge (1986).

3.3.2 Bulk density

The sands were assumed to consist of spherical (roughly) particles, which could be brought into closed packing (as opposed to open packing) by agitation. The bulk density, ρ_b (g cm^{-3}) of each sand was determined by pouring a weighed quantity of air dry material (corrected on an oven dried basis) into a small graduated cylinder while tapping the contents until they settled to a maximum density; the volume was then read directly from the graduated cylinder (Nimmo 2004). This was repeated many times to obtain a consistent bulk density, which was then used for all future packing of the sands.

The bulk density of the two natural soils (Very fine sand soil, and Almond orchard soil) was determined after they were air dried and passed through a 2 mm sieve. Soil was poured into stainless steel cylinders (of known diameter) to a height of 2 cm, then gradually wetted by capillary action to saturation, and allowed to dry and consolidate on the laboratory bench for three days and then in an oven at 105 °C for 24 hours. The soil cores were then removed from their rings to measure their heights and diameters with a digital Vernier caliper, **Figure 3.2**.

Figure 3.2: Soil core length and diameter were measured using digital Vernier calipers to determine bulk volume of soil after saturating and drying for three days at 105 °C.

3.3.3 Total porosity

The (dimensionless) total porosity, ε (cm^3 cm^{-3}) of each soil was calculated using the measured particle and bulk densities according to the relation of Vomocil (1965) and Danielson and Sutherland (1986):

$$\varepsilon = 1 - \frac{\rho_b}{\rho_s} \qquad [33]$$

3.3.4 Particle size distribution

Particle size distribution was measured on the < 2 mm fraction of three soil horizons from the almond orchard soil (0 to 15 cm, 15 to 30 cm, and 30 to 45 cm). This was done by sedimentation of replicated 15-gram samples that were dispersed using solutions of sodium hexametaphate and sodium hydroxide. Samples were allowed to settle, for times according to Stoke's law, in tall, 1-litre cylinders according to the method of Smith and Tiller (1977). The clay fraction (< 2 µm) was sampled first by removing a small volumetric sample of suspension and drying it (corrected for dispersants), then collecting all particles > 20 µm (total sand fraction) and using a 200 µm sieve to separate fine and coarse sand fractions. The silt fraction (2 to 20 µm) was calculated by difference. The cumulative particle size distributions are shown in **Figure 3.3** for the soils from the three horizons, and shows that the two soils in the 0 to 30 cm depth are essentially the same texture, while the soil in the deeper horizon (30 to 45 cm) was of heavier texture.

3.3.5 Saturated hydraulic conductivity, K_s

The saturated hydraulic conductivity, K_s, which describes the ability of a soil matrix to transmit water when all the pores are filled, was measured on all sands and soil using modified procedures for constant-head and falling-head methods described by Klute and Dirksen (1986). Stainless steel cylindrical rings (ca. 5 cm high, ca. 5 cm diameter) were fitted with a 38 µm nylon mesh at one end and packed to pre-determined bulk densities according to preliminary packing experiments described above. Triplicate samples were then wetted with distilled water by capillary action until saturated, then tubes 10 cm high were fitted above them to allow a positive hydraulic head to be established. Samples were secured to a retort stand with collection pots underneath to contain and either discard or measure the mass (volume) of water flowing through.

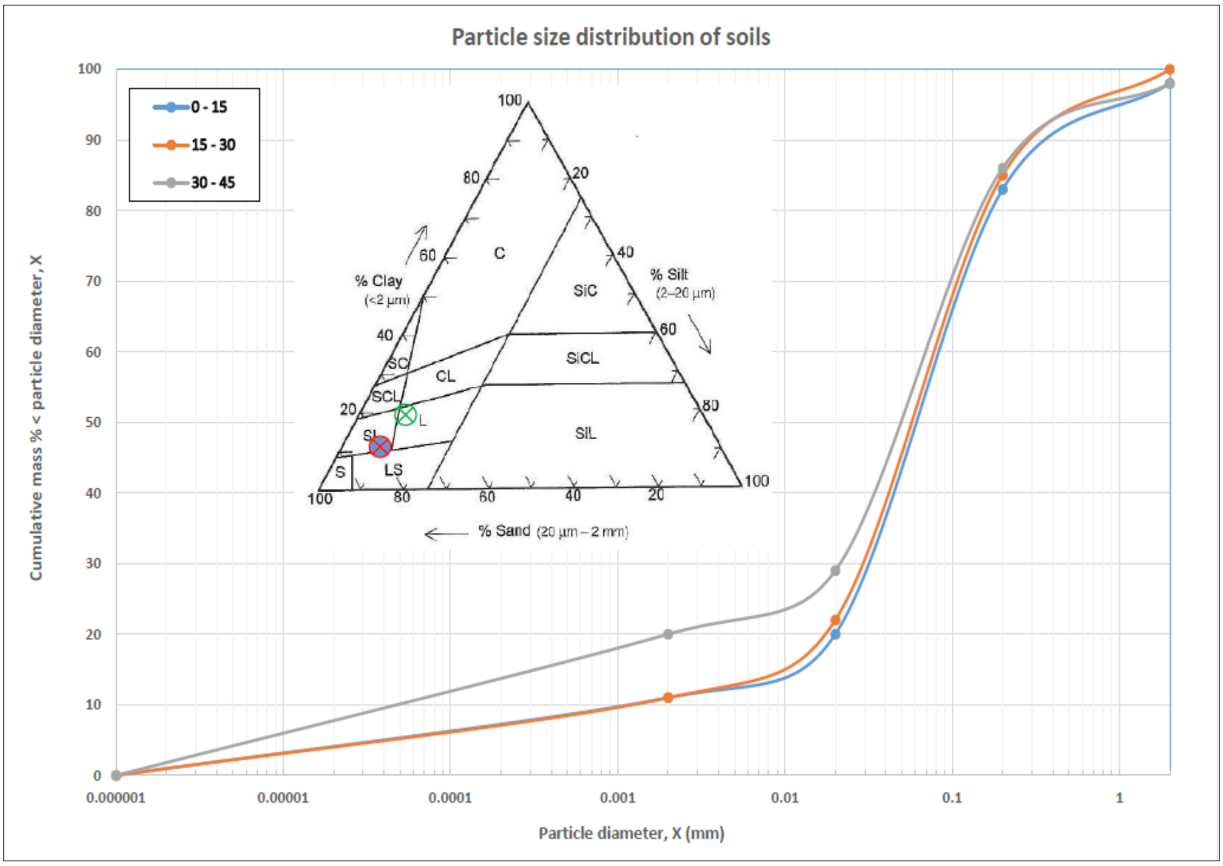


Figure 3.3. Cumulative particle size distribution for 3 soil horizons (0-15 cm, 15-30 cm, 30-45 cm) sampled from the profile of an almond orchard in the northern Adelaide plains horticultural region that was irrigated using Class-A recycled water. Above the lines is shown an Australian texture diagram (Marshall 2003) with the 3 soils plotted from laboratory sedimentation/sieving data. The green circle with internal X on white background marks the soil texture (loam) of the lowest horizon (30-45 cm). The red circle with internal X on blue background marks the texture (sandy loam) of the two upper horizons (0-15 cm and 15-30 cm).

A falling head method was used for the medium and finer texture ranges (< 0.5 mm) where it was physically possible to observe and measure the falling head with time. By contrast, a constant head method had to be used for the coarser textured sands in the range 0.5 to 2 mm because it was physically impossible to monitor a falling head over time (it happened too quickly). The constant head method required one person to maintain the head, while a second person measured the flux and dealt with the large volumes of water involved. The flux of water was measured to calculate K_s (m s^{-1}) using Darcy's law, as follows:

$$K_s = \frac{V \times L}{A \times t \times (H+L)} \quad , \qquad [34]$$

where V is the volume of water passing through the cross-section of soil (m^3), L is the length of the soil sample (m), A is the cross-sectional area of soil sample (m^2), t is the time increment (s), H is the height of water maintained above the soil surface (m), and L is the length of the soil sample (m).

For the falling head method, saturated samples were secured to a retort stand and the total hydraulic head monitored (using a mm-scale secured to the inside of the samples) as it declined over time (outflow water discarded). The natural logarithm of the total hydraulic head (H+L) was then plotted as a function of time, t (s), and K_s determined from the relation:

$$\frac{d(H+L)}{dt} = -K_s \frac{H+L}{L} \qquad [35]$$

which produced:

$$ln(H+L) = -\left(\frac{K_s}{L}\right) t + ln(H_0 + L) \qquad [36]$$

The slope of this relation is $-\frac{K_s}{L}$, so when multiplied by the length of the soil sample, –L, it produced the saturated hydraulic conductivity, K_s.

3.3.6 Water retention curves θ(h)

Detailed water retention curves for each sand or soil in this study were measured according to the methods of Klute (1986). All samples were placed on ceramic plates of capacity 10 m (1 bar) air-entry pressure, and the hanging water column method (Berliner et al. 1980) was used for matric heads < 2 m; for greater matric heads, positive N_2-gas pressures were applied in air-tight chambers.

Twenty replicate-samples of each sand or soil were packed to prescribed bulk densities into plastic rings (1 cm high × 2 cm diameter) with meshes sealed to their bases. They were then placed onto ceramic plates, saturated and connected to hanging columns of water at matric heads ranging from 0 cm to 120 cm relative to the middle of the samples (**Figure 3.4**).

For the coarser sands (with nominal particle diameters of 1.7, 0.75, and 0.19 mm), matric heads were applied in 1 cm increments from 1 to 10 cm (using the central height of the rings as a reference point), then in 10 cm increments from 10 to 120 cm. Hydraulic equilibrium was established when the mass of a soil sample did not change from one day to the next. For this study, the time required for hydraulic equilibrium ranged between 24 and 72 hours, the greater times applying to greater matric heads. At hydraulic equilibrium, samples were taken off the pressure plates, weighed and then replaced on the pressure plates, re-saturated and set to a greater matric head.

For the finer sands and soils, however, the water retention curves did not plateau before matric heads of 120 cm, so additional data were collected after placing the samples into sealed chambers pressurized at (depending on the soil) between 330 to 1000 cm using N_2 gas. For example, the water retention curve for the very fine sand soil plateaued near a pressure of 500 cm, which took approximately 7 days to reach equilibrium. Similarly, the water retention curve for the fine sand fraction with a nominal diameter of 0.08 mm plateaued at a matric head of 700 cm, which took approximately 10 days to reach equilibrium. Finally, the water retention curve for the finer textured almond orchard soil plateaued near a pressure of 1000 cm, which took two full weeks.

At hydraulic equilibrium, samples were weighed and any variation in height of the soil in the containing rings was recorded before drying in an oven for 24 hours at 105 °C. Gravimetric water contents, θ_m g g^{-1}, were converted to volumetric water contents, θ_v cm^{3}cm^{-3}, using the bulk density, ρ_b g cm^{-3}, and the density of water, ρ_w g cm^{-3}, in the relation:

$$\theta_v = \theta_m \times \frac{\rho_b}{\rho_w} \qquad [37]$$

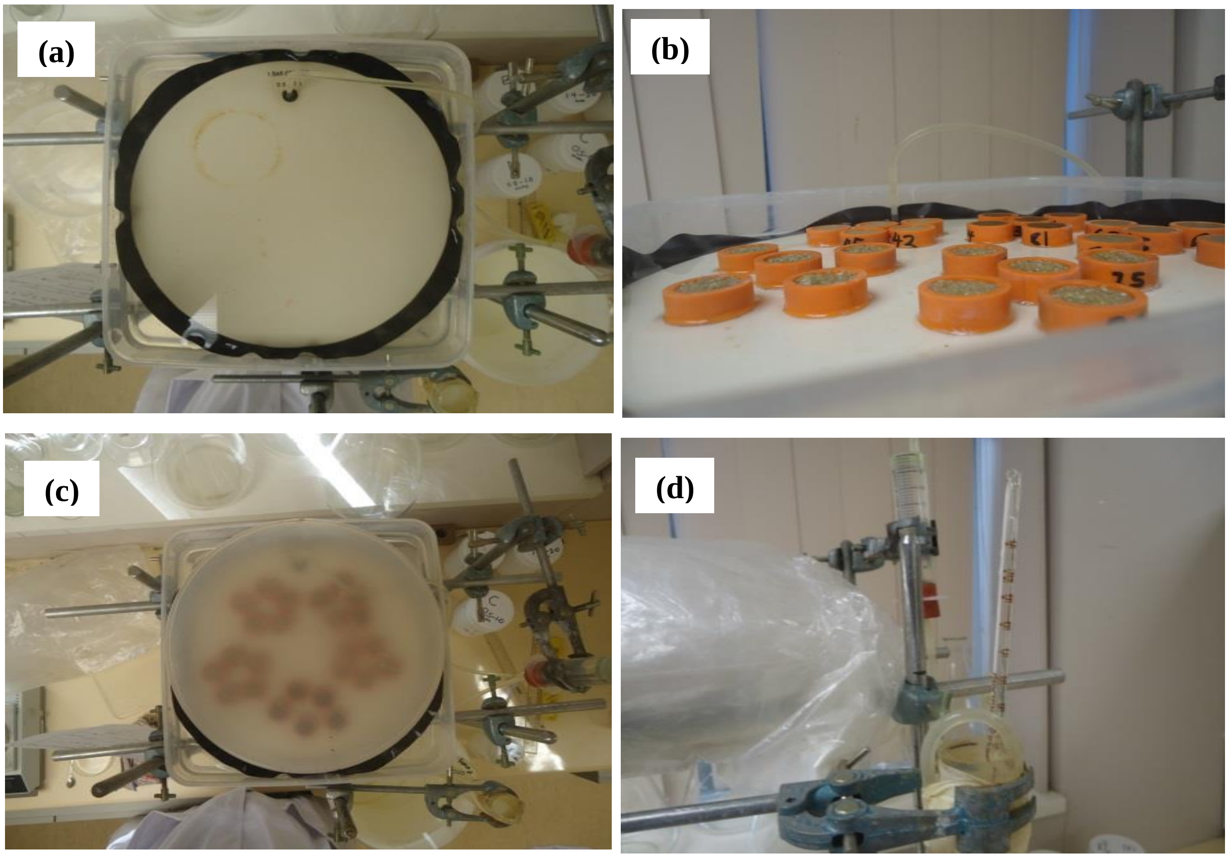


Figure 3.4. Laboratory set up for soil water retention measurement, depicting (a) 1-bar ceramic pressure plate in a water bath to saturate its pores, (b) 20 saturated soil samples in rings placed on ceramic plate, (c) soil samples covered with a plastic lid to reduce evaporation, and (d) polyethylene sheet to further limit evaporation.

3.4 Results and discussion

The physical properties of the 10 sands and sandy soils examined in the preliminary work were compared to select soils for further detailed characterization and use in the plant studies. The objective was to identify materials of similar composition (i.e. particle density) but distinctly different hydraulic properties across the sandy texture range.

All sands and soils had statistically similar particle densities in the range 2.65 ± 0.029 g cm^{-3} but their packing (bulk) densities varied significantly and thus their total porosities also varied significantly. Importantly, among the 10 sands and soils there were materials that exhibited saturated hydraulic conductivities ranging across 4 orders of magnitude from the coarsest sand particles (ca. 10^{-2} m s^{-1}) to the finest sandy clay loam aggregates (ca. 10^{-6} m s^{-1}) (**Table 3.2**).

Table 3.2 Mean ± standard deviation (of 3 replicates) of particle density, ρ_s, bulk density, ρ_b, total porosity, ϵ, and saturated hydraulic conductivity, k_{sat}, for the 10 sands and soils examined. Coefficient of variation and least significant difference are shown below each measurement.

Particle size range (mm)	Nominal particle size (mm)	ρ_s (g cm^{-3})	ρ_b (g cm^{-3})	ϵ ($cm^{-3}cm^{-3}$)	k_{sat} (m s^{-1})
1.4 - 2.0	1.7	2.64± 0.02 a	1.52± 0.02 b	0.43± 0.01 a	$1.1x10^{-2}$ ± $2.4x10^{-4}$ a
1.0 - 1.4	1.2	2.66± 0.01 a	1.50± 0.01 b	0.44± 0.00 a	1.1 $x10^{-2}$ ± 9.5 $x10^{-4}$ a
0.5 - 1.0	0.75	2.64± 0.02 a	1.47± 0.01 b	0.45± 0.01 a	8.4 $x10^{-3}$ ± 1.9 $x10^{-4}$ b
0.25 - 0.50	0.38	2.66± 0.01 a	1.61± 0.01 a	0.39± 0.01 b	8.9 $x10^{-4}$ ± 3.1 $x10^{-4}$ c
0.125 - 0.250	0.19	2.66± 0.01 a	1.58± 0.02 a	0.41± 0.01 a	2.5 $x10^{-4}$ ± 3.5 $x10^{-5}$ d
0.105 - 0.125	0.12	2.68± 0.05 a	1.49± 0.02 b	0.44± 0.02 a	2.3 $x10^{-5}$ ± 1.9 $x10^{-6}$ e
0.090 - 0.105	0.1	2.67± 0.01 a	1.40± 0.01 c	0.47± 0.00 a	1.3 $x10^{-5}$ ± 0.00 e
Fine sand	0.178	2.69± 0.05 a	1.36± 0.01 d	0.49± 0.01 a	6.0 $x10^{-5}$ ± 1.0 $x10^{-5}$ e
Very fine sand (0.075 - 0.090)	0.08	2.67± 0.02 a	1.40± 0.01 c	0.48± 0.00 a	1.0 $x10^{-5}$ ± 3.5 $x10^{-6}$ e
Sandy loam (Almond soil1)	-	2.59± 0.07 a	1.46± 0.06 b	0.43± 0.01 a	2.0 $x10^{-6}$ ± 1.2 $x10^{-7}$ e
Almond soil2	-	2.66± 0.03 a	1.52± 0.00 b	0.43± 0.01 a	2.0 $x10^{-6}$ ± 1.2 $x10^{-7}$ e
Almond soil3	-	2.61± 0.14 a	1.41± 0.00 c	0.46± 0.03 a	2.0 $x10^{-6}$ ± 1.2 $x10^{-7}$ e
	CV	3.9%	1.4%	5.7%	14%
	lsd	0.17	0.02	0.04	5.8 $x10^{-4}$

Means followed by the same letter are not significantly different from each other at $p = 0.05$; means followed by different letters are significantly different from each other at $p < 0.012$, 0.001, 0.002 and 0.001 respectively across the table. Shaded rows identify sands excluded from further study on the basis that their hydraulic properties were not sufficiently distinct from the others.

Table 3.3 Names of the sands and soil materials used in the remainder of this study.

Sand fraction or soil name	Textural name for the material
1.4 to 2 mm (nominally 1.7 mm)	Very coarse sand, VCS
0.5 to 1 mm (nominally 0.75 mm)	Coarse sand, CS
0.125 to 0.25 mm (nominally 0.19 mm)	Medium sand, MS
Very fine sand from Chahal (2010)	Fine sand, FS
0.075 to 0.09 mm (nominally 0.08 mm)	Very fine sand, VFS
Almond orchard soil (0 to 15 cm)	Sandy loam, SL

The very wide range of hydraulic properties shown among the materials allowed 6 of the 12 sands/soils to be selected for further investigation. The shaded rows in **Table 3.2** indicate sands/soils that were eliminated from further study due to their high packing (bulk) density, or to their having similar properties to other fractions. In summary, the materials used for the remainder of this study are named in **Table 3.3**.

3.5 Conclusion

The six materials isolated in **Table 3.3** for further characterization span the full range of textures in the sandy range of soils. In the next chapter, I will describe the methods used to characterize these materials in terms of their water retention characteristics so they could be used in subsequent plant studies.

CHAPTER 4

Inflection points on water retention curves

4.1 Introduction

The prime purpose of the work outlined in this chapter was to identify the location of the inflection point on the water retention curve (plotted on a semi-log scale) for a range of coarse textured soils. The water retention data was needed to evaluate the idea proposed by Grant and Groenevelt (2015) that the inflection point on the water retention curve marks the matric suction at which dynamic hydraulic restrictions begin to limit soil water availability. The work of Grant and Groenevelt (2015) was based upon only one soil; number 6 of a light loamy medium coarse sand (Rijtema 1969), so the present work included a range of coarse textured materials, identified in **Chapter 3**.

Also, in the equation of Grant and Groenevelt (2015) their parameter, k_o, marks the location of the inflection point but the utility of k_o depends on how well the water retention model fits the data relative to other models such as, say the Van Genuchten (1980) model. A second purpose of this work, therefore, was to evaluate which of the two models provided the best fit to the data collected. Finally, the work of this chapter aimed to identify experimentally manageable matric heads as close to the inflection point as possible that could serve as distinctly different 'wetter' and 'drier' matric heads against which the importance of the inflection point could be assessed.

4.2 Preliminary evaluation of water retention data

Water retention data for each sand or sandy soil consisted of 20 replicate water contents at up to 22 different matric heads from saturation to a nominal field capacity (ranging from 0.0001 to 10 m). The great detail was required to produce water retention curves of sufficient detail to allow precise determination of their shape in the region of the inflection point.

Preliminary examination of the data was conducted in Excel by plotting the volumetric water contents for each sample as a function of the corresponding matric head on a semi-log scale. There was inevitable variability in the data for each of the 20 replicates due to experimental error plus differences in sample hydraulic contact with the pores in the ceramic plates. Furthermore, the location of the inflection point on the curves was not known in advance, so in many cases much more data was collected than was actually required to produce good water retention curves. Some of the data points therefore needed filtering in an unbiased way to gain water retention data that was both physically real and also balanced around the inflection point. For example, points that were anomalously wetter as the matric head increased from one value to the next (accounting for ca 10 % of data) were considered physically impossible and were therefore, eliminated. Also, some data points were eliminated where a large concentration of data points occurred between saturation and the approximate location of the inflection point (accounting for ca. 30 % of data); this allowed equal weighting to the less concentrated data on the dry side of the inflection point. The filtered set of water retention data are listed in **Appendix 1** for each of the 6 soils used in this study.

4.3 Curve fitting of the water retention data

Each of the replicated sets of water retention data were fitted to the differentiable Groenevelt-Grant water retention model e.g. Grant et al. (2010) as well as to that of Van Genuchten (1980) to obtain multiple estimates of the relevant parameters. Of particular interest in the Groenevelt-Grant water retention equation was the idea promoted by Grant and Groenevelt (2015) and others e.g. Van Lier (2014) that the matric head at the inflection point can be identified precisely from the fitting parameter, k_o, in the relation:

$$\Theta(h) = 1 - \frac{k_1}{\theta_s} exp\left[-\left(\frac{k_0}{h}\right)^n\right] \ , \qquad [38]$$

where Θ(h) is the *relative water content*, $\theta(h)/\theta_s$, as a function of the matric suction (h, m), θ is the volumetric water content, $m^3\ m^{-3}$, and θ_s is the saturated volumetric water content. The two fitting parameters, k_1 and n, are dimensionless, while the parameter, k_o, has the dimension of length (m).

The widely used Van Genuchten equation can be expressed:

$$\Theta(h) = \frac{\theta_{res}}{\theta_s} + \left(1 - \frac{\theta_{res}}{\theta_s}\right) \times [1 + (1{+}\propto \times h)^N]^{\left(\frac{1-N}{N}\right)} \ , \qquad [39]$$

where Θ(h) and θ_s are defined above, N and θ_{res} are dimensionless fitting parameters, and α is a fitting parameter having the dimension of length^{-1} (m^{-1}). Of interest in this work is the fact that $1/\alpha$ has the dimension, length (unit m) and is comparable to k_o in the Groenevelt-Grant equation in as much as it identifies the matric head at the inflection point on the water retention curve.

Curve fitting for each soil sample (up to 20 samples per soil type) was conducted using Mathcad solve blocks, which applied the Levenberg-Marqhart iteration to minimize the sum of squared errors in producing values for the fitting parameters in **Eqns [38]** and **[39].** For each set of water retention data, the values of the fitting parameters k_o, k_1, n and α, N, θ_{res} were inserted into **Eqns [38]** and **[39]**, respectively, to produce up to 20 replicate water retention curves for each equation and each sand or sandy soil type. Twenty were produced for each of the Very Coarse Sand (1.7 mm), the Coarse Sand (0.75 mm), the Medium Sand (0.19 mm) and the Sandy Loam. However, due to experimental problems, only thirteen curves were produced for the Fine Sand Dust (0.08 mm) and only eighteen curves were produced for the Very Fine Sand (Chahal 2010).

The values for each of the fitting parameters in **Eqns [38]** and **[39]** were averaged to produce a mean value for each sand or sandy soil. The use of these mean parameter values will be described in greater detail below.

4.4 Matric suctions either side of the inflection point in the water retention curves

To evaluate the matric head at inflection as the point where plant hydraulic stress begins, as suggested by Grant and Groenevelt (2015), the coordinates of the inflection point needed to be determined first. Two additional points were then required for comparison on either side of the inflection point (i.e. a wetter point and a drier point were needed for each soil). The following unbiased procedure was therefore developed to identify the relevant matric suctions and volumetric water contents at these three points for each sand or sandy soil.

The average water retention curves described above were differentiated to produce differential water capacity curves, $C(h) = {}^{d\theta}/_{dh}$, which are the slope-functions for each water retention curve, θ(h). The inflection point on each water retention curve, (θ_i, h_i) marks the point where the slope of the curve reaches its maximum value (i.e. the point where the second derivative of C(h) = 0). To obtain 'wetter' and 'drier' points that were as close as possible to the inflection point but statistically independent, the maximum value of C(h) was identified and the 95 % confidence interval around that value determined. The chosen points on either side of the inflection point had to fall outside the 95 % confidence interval to ensure they were statistically distinct. The analysis showed that so long as the water capacity was at least 10 % smaller than the maximum, the points fell outside the 95 % confidence interval surrounding the inflection point. The procedures involved for one of the sands is shown in **Figure 4.1**.

The appropriate matric head on the wet side of the inflection point, h_w, and the dry side, h_d, for each soil were substituted into **Eqns [38]** and **[39]** to obtain the appropriate relative water contents, Θ_w and Θ_d, after tracing from the WRC's, example of which is shown on **Figure 4.2**. These were then converted to volumetric water contents, θ_w and θ_d, using the saturated volumetric water content, θ_s, as follows:

$$\theta_w = \Theta_w \times \theta_s \qquad \text{and} \qquad \theta_d = \Theta_d \times \theta_s \qquad [40]$$

All volumetric water contents were subsequently converted to gravimetric water contents so that the plant experiments could be conducted on a gravimetric basis (i.e. constant pot weight).

Conversion of volumetric to gravimetric water contents was achieved using a re-arranged version of **Eqn [37]**, *viz.*

$$\theta_m = \theta_v \times \frac{\rho_w}{\rho_b} \qquad [41]$$

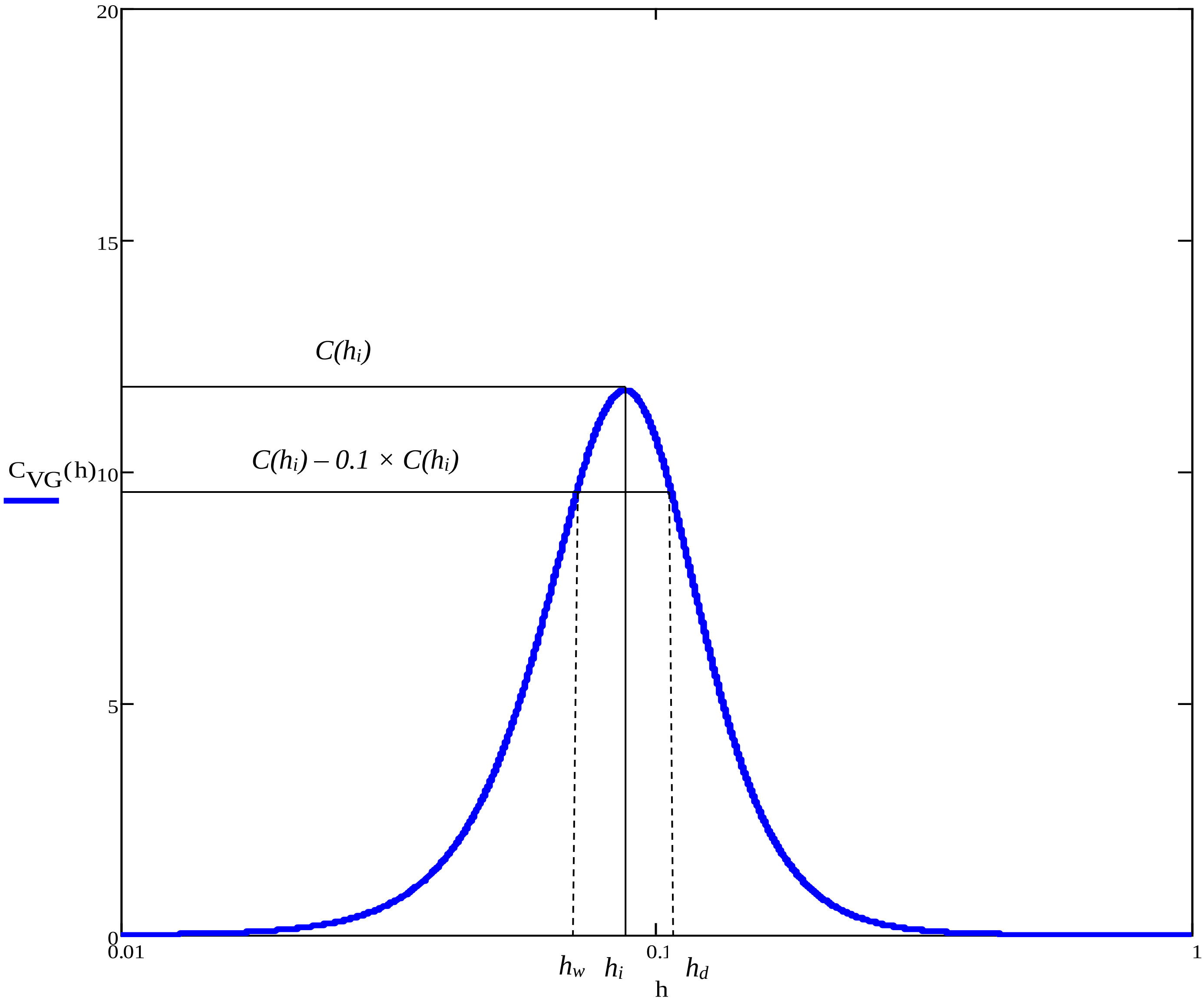


Figure 4.1: Water capacity function for sand with nominal particle size 0.75 mm, illustrating the matric suctions below (h_w) and above (h_d) the matric suction at the inflection point (h_i). The maximum peak in the C(h) curve marks the inflection point of the water retention curve (θ_i, h_i); the thin broken lines mark the matric heads where C(h) is 10% less than its maximum on both the wetter side (θ_w, h_w) and the drier side (θ_d, h_d). The y and x-axes of the graph are water capacity (m^{-1}), denoted as C_{VG} (h) and matric suction, also denoted as h, m.

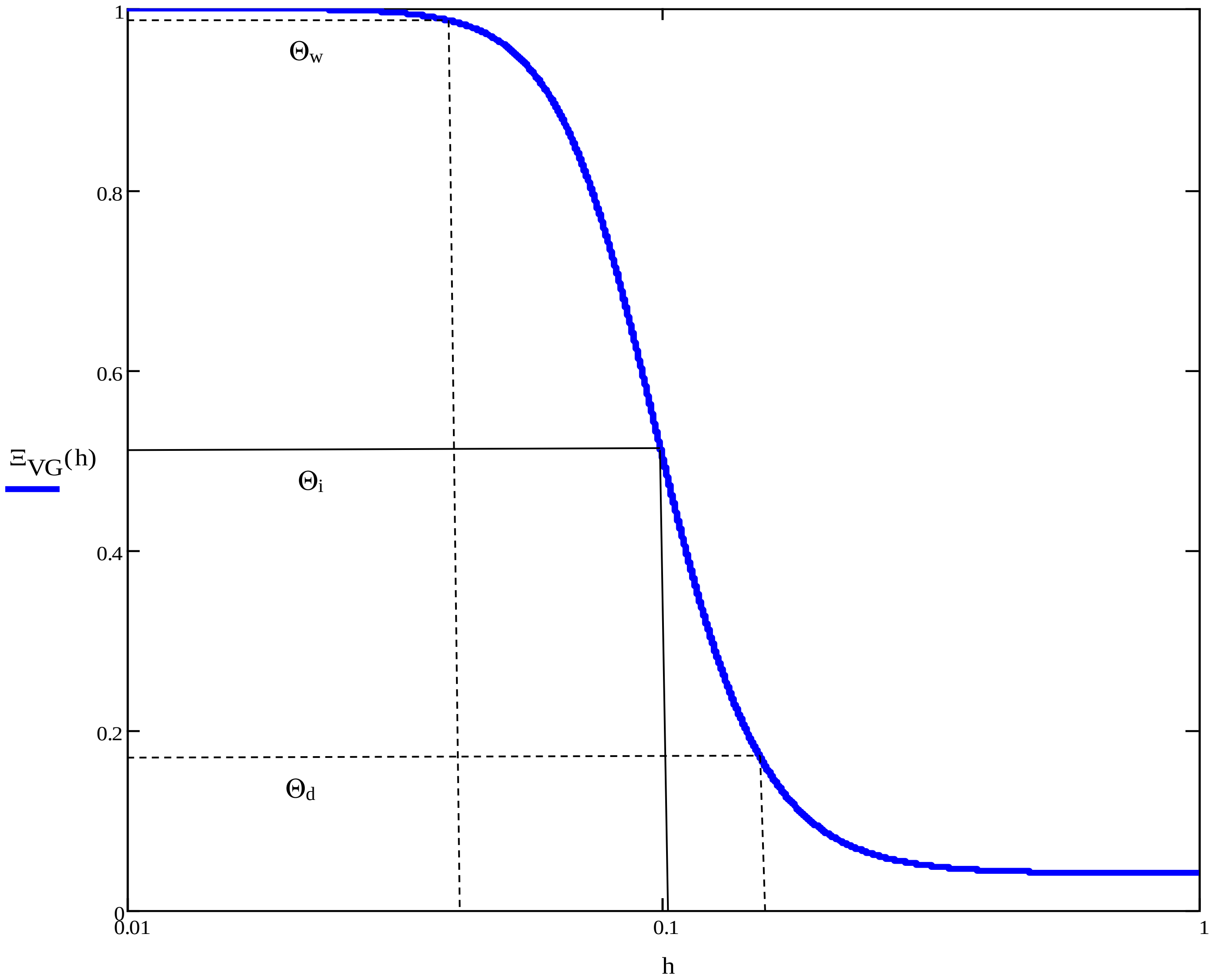


Figure 4.2: Average water retention curve fitted for CS using the VG water retention. In the WRC's depicts the trace of relative water content (Θ_r) estimates for the wet (Θ_w) and dry (Θ_d) side of the inflection point, converted to volumetric water contents using **[40]**. Indicating, this on the WRC's is black broken lines. The label for the y-axis and x-axis of the graph are relative water content, and matric suction denoted as Ξ_{VG} (h) and h, m respectively.

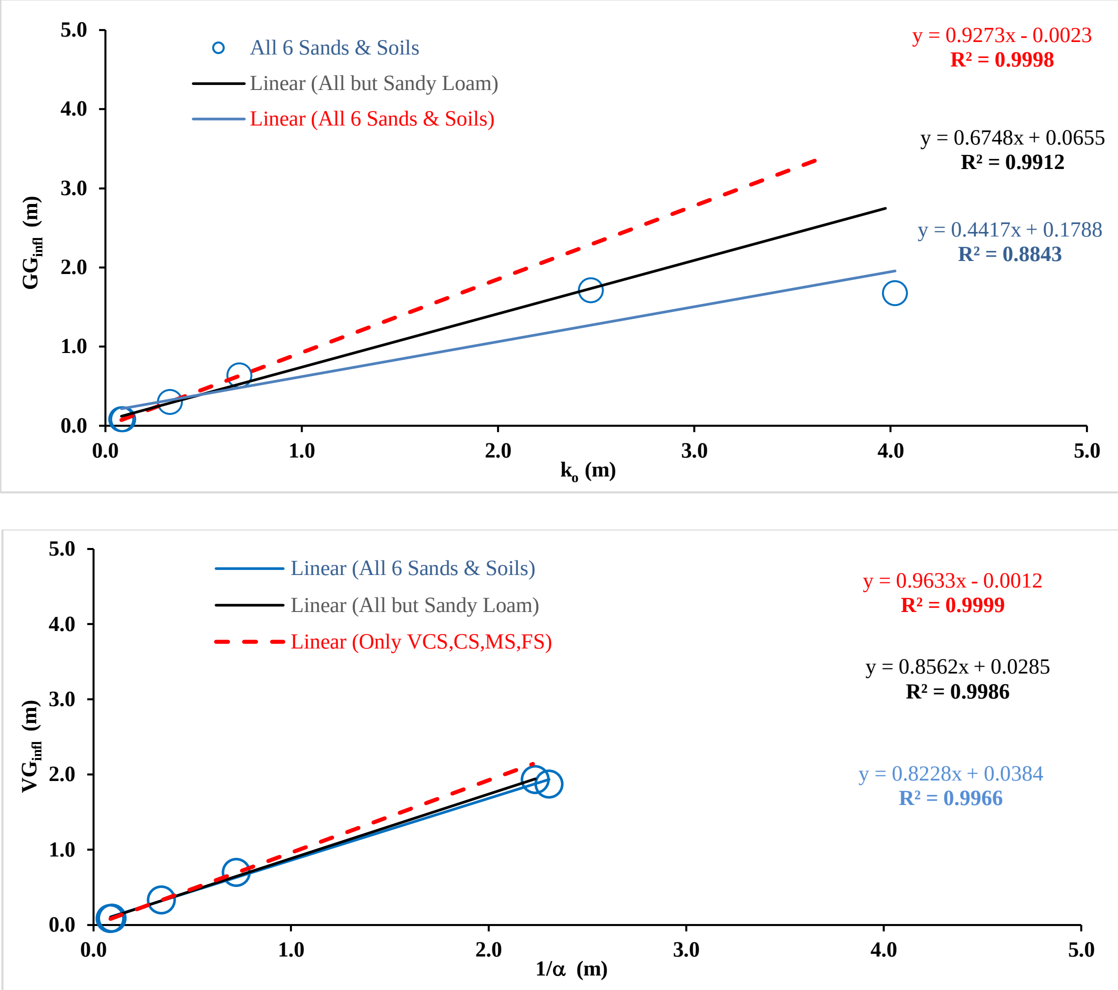
4.5 Results and discussion

The water retention data, as well as the fitting parameters, for all replicates of the 6 sands and sandy soils are all shown in **Appendix 1** of the thesis. The mean fitting parameters (their standard deviations, S.D., and the number of water retention curves for each soil, η) for each soil are shown in **Table 4.1**. Also, shown in the table are the matric head for each model where the differential water capacity, $d\theta/dh = C(h)$, reaches a maximum (or the slope of that curve, $dC(h)/dh$, equals zero – this matric head marks the point of inflection on the water retention curve). Of particular interest in this study is the extent to which k_o in the Groenevelt-Grant equation (as well as $1/\alpha$ in the Van Genuchten equation) coincide with the matric head at the respective inflection points. If k_o and $1/\alpha$ identify the inflection points precisely, they would be identical to the matric heads where *C(h)* reaches its maximum as described in **Figure 4.1**. The additional two rows (red type) in **Table 4.1** show the difference between the estimated and actual matric heads (k_o – GG_{infl} or $1/\alpha$ - VG_{infl}) at the inflection point for both models.

Table 4.1 Mean water retention curve-fitting parameters for the 6 different sands or sandy soils.

Parameter	Texture of Sand or Sandy soil (n = number of replicate water retention curves)											
	VCS (η = 20)		CS (η = 20)		MS (η = 20)		FS (η = 18)		VFS (η = 13)		SL (η = 20)	
	Mean	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**
θ_s	0.330	0.025	0.340	0.026	0.317	0.012	0.396	0.010	0.370	0.010	0.367	0.056
Values for GG equation parameters, Eqn [38]												
k_1	0.315	0.027	0.330	0.033	0.308	0.033	0.329	0.021	0.343	0.141	0.353	0.187
n	7.207	5.047	3.209	1.861	3.565	1.041	3.630	0.751	2.169	1.703	1.527	1.471
k_0 (m)	0.081	0.006	0.090	0.015	0.329	0.043	0.683	0.025	2.474	0.683	4.023	2.400
GG_{infl} (m)	0.078	0.008	0.079	0.020	0.299	0.030	0.633	0.036	1.707	0.559	1.670	1.719
Difference k_0 – GG_{infl}	0.003m		0.012m		0.030m		0.050m		0.767m		2.353m	
Values for the VG equation parameters, Eqn [39]												
θ_r	0.017	0.003	0.014	0.010	0.016	0.019	0.073	0.012	0.072	0.099	-0.017	0.263
N	11.252	6.763	4.853	2.518	5.416	1.187	5.760	1.032	4.534	2.215	2.967	2.329
α	11.692	0.775	10.907	2.072	2.929	0.284	1.382	0.052	0.487	0.193	0.778	0.555
$1/\alpha$ (m)	0.086	0.005	0.095	0.018	0.344	0.034	0.724	0.027	2.237	0.524	2.306	1.767
VG_{infl} (m)	0.084	0.007	0.089	0.021	0.329	0.030	0.697	0.032	1.929	0.635	1.869	1.895
Difference $1/\alpha$ – VG_{infl}	0.002m		0.006m		0.016m		0.027m		0.308m		0.438m	

It is clear from **Table 4.1** that the parameters k_o and $1/\alpha$ are in many cases similar to their respective suctions at the inflection points but they are certainly *not* precisely identical to them. Furthermore, this similarity applies only to the coarser materials (VCS, CS, MS and FS); the differences, k_o–GG_{infl} and $1/\alpha$–VG_{infl}, become increasingly greater for the finer soils (VFS and SL). The correlation between the parameters and the inflection point are shown for the Groenevelt-Grant (GG) equation in **Figure 4.3a** and for the Van Genuchten (VG) equation in **Figure 4.3b**.



Figures 4.3. Correlation between the calculated matric head at the inflection point and **a)** the fitting parameter, k_o, in the GG-model, or **b)** the fitting parameter $1/\alpha$ in the VG-model.

As the finer materials are sequentially removed from the correlations for the GG-equation in **Figure 4.3a** the regression coefficient, R^2, increased from 0.8843 (including all 6 soils), to 0.9912 (excluding only the Sandy loam), to 0.9998 (excluding both the Sandy loam and the Very fine sand). The same approach with the VG-equation (**Figure 4.3b**) resulted in very little change in the regression coefficients (i.e. R^2 goes from 0.9966 to 0.9986 to 0.9999). Of course, none of these R^2 values is particularly poor; it is simply that the R^2 values for the VG equation are greater than those for the GG equation.

The other important observation is that, and this is relatively intuitive, the inflection point of the water retention curves shifts to greater matric heads across the soils examined (from Very Coarse Sand to Sandy Loam). That is, k_o and $1/\alpha$ are large for the fine materials and they decline rapidly for the coarser materials (**Figure 4.4**).

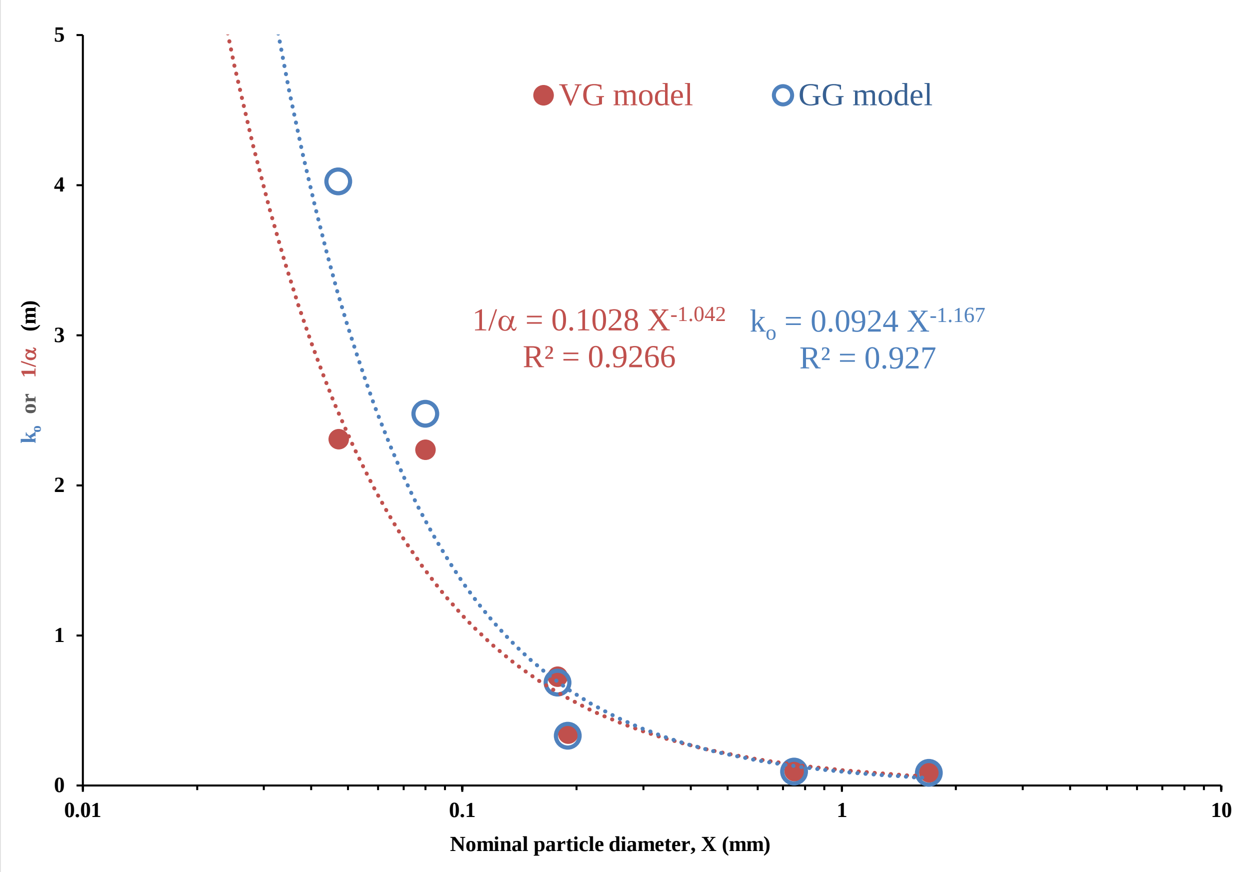


Figure 4.4 Correlation between particle size and the matric head at the inflection point on the water retention curve as indicated by k_o or $1/\alpha$.

The coordinates of the inflection points for the different sands and sandy soils (and their indicator parameters, k_o and $1/\alpha$) are shown in **Table 4.2** along with the 95 % confidence intervals. Importantly, the confidence intervals surrounding the parameters and the coordinates are similar for both GG- and VG-models. However, for every sand and sandy soil the matric head at the inflection point is predicted by the VG equation to be greater than that of the GG equation. This means the volumetric water content at the inflection point is invariably smaller for the VG equation than it is for the GG equation. It is therefore critical to the success of the plant experiments reported in subsequent chapters that the best estimates of the inflection point be used. To obtain the best estimates of the inflection point, the water retention model that fits the data most closely must be chosen. **Table 4.3** shows the mean sum of squared errors (SSE) between the measured and predicted water contents for the 6 sands and sandy soils using both the Groenevelt-Grant (GG) and van Genuchten (VG) models. On average, the sum of squared errors is greater for the GG-model than for the VG-model, suggesting that for light textured (sandy) soils, the VG-model provides a superior fit to the measured data relative to the GG-model.

Table 4.2 Coordinates of the inflection points on the water retention curves for the 6 sands and sandy soils, (h_i, θ_i), their 95 % confidence intervals, and their indicator parameters, k_o (for GG equation) and $1/\alpha$ (for VG equation).

Soil textures	Groenevelt-Grant (GG) equation output					
	k_o	(± 95 % CI) (m)	h_i	(± 95 % CI) (m)	θ_i	(± 95 % CI) ($m^3\ m^{-3}$)
VCS	0.081	(0.078 to 0.084)	0.078	(0.074 to 0.082)	0.236	(0.226 to 0.246)
CS	0.090	(0.083 to 0.097)	0.079	(0.069 to 0.089)	0.260	(0.250 to 0.270)
MS	0.329	(0.309 to 0.349)	0.299	(0.285 to 0.313)	0.236	(0.226 to 0.246)
FS	0.637	(0.619 to 0.655)	0.637	(0.618 to 0.656)	0.305	(0.295 to 0.315)
VFS	2.337	(2.012 to 2.662)	1.670	(1.331 to 2.009)	0.305	(0.285 to 0.325)
SL	4.023	(2.900 to 5.146)	1.670	(0.866 to 2.474)	0.334	(0.304 to 0.364)
Soil textures	**Van Genuchten (VG) equation output**					
	α^{-1}	(± 95 % CI) (m^{-1})	h_i	(± 95 % CI) (m)	θ_i	(± 95 % CI) ($m^3\ m^{-3}$)
VCS	0.086	(0.084 to 0.088)	0.084	(0.081 to 0.087)	0.197	(0.187 to 0.207)
CS	0.094	(0.085 to 0.103)	0.089	(0.079 to 0.099)	0.229	(0.219 to 0.239)
MS	0.344	(0.328 to 0.360)	0.329	(0.315 to 0.343)	0.205	(0.195 to 0.215)
FS	0.724	(0.710 to 0.738)	0.697	(0.681 to 0.713)	0.271	(0.261 to 0.281)
VFS	2.237	(1.920 to 2.554)	1.929	(1.545 to 2.313)	0.281	(0.251 to 0.311)
SL	2.063	(1.236 to 2.890)	1.869	(0.982 to 2.756)	0.326	(0.293 to 0.359)

Table 4.3. Sum of squared errors, SSE, for the water retention data using GG and VG models for 6 different sands and sandy soils.

Soil Texture	Mean Sum of Squared Errors, SSE			No. water retention curves
	GG model		VG model	
Very Coarse Sand	4.2E-02	>	3.0E-02	20
Coarse Sand	1.7E-02	>	1.1E-02	20
Medium Sand	8.3E-03	>	5.0E-03	20
Fine Sand	1.7E-02	>	1.3E-02	13
Very Fine Sand	7.8E-03	>	6.6E-03	18
Sandy Loam	2.0E-03	>	1.9E-03	20
Average all soils	1.6E-02	>	1.1E-02	

4.6 Conclusions

Contrary to claims by Grant and Groenevelt (2015) and others that the inflection point on the water retention curve can be identified precisely from the fitting parameter k_o in the GG-model and by $1/\alpha$ in the VG-model, the evidence in **Tables 4.1** and **4.2** plus **Figures 4.3** and **4.4** suggests that this is not correct. The GG- and VG-model parameters are good estimates of the matric head at the inflection point but they are not precisely the same. If identifying the precise location of the inflection point is important, it would therefore be better to simply differentiate the water capacity and find the precise matric head by setting $dC(h)/dh = 0$.

Furthermore, evidence presented here suggests the VG fitting parameter, $1/\alpha$, more closely approximates the matric head at the inflection point, and furthermore the VG model provides a superior fit to the water retention data relative to the GG model. The VG model may therefore be superior to GG-model for the purposes of identifying the inflection point in very sandy soils. The VG water contents shown in the right-hand column of **Table 4.2** will therefore be used for the studies outlined in **Chapters 5**.

CHAPTER 5

Wheat response to soil moisture conditions at and surrounding the point of inflection in the soil water retention curve for coarse textured soils

5.1 Introduction

In recent times, the response of crops including wheat to soil moisture contents at varying degrees has been evaluated for different kinds of soils (Izanloo et al. 2008; Meyer and Green 1981). The majority of these studies are conducted either to determine plant response to water stress or how water is use efficiently by plants (Asare et al. 2011; Rampino et al. 2006; Siddique et al. 2000). This abiotic factor is usually measured by using different indicators, some of which measures specific physiological function of plant that determines whether growth and development is advancing or not. Others also measure specific soil physical properties, which are known to control water movement from the soil pores within the matrix to plant roots for absorption (Chahal 2010; Jones 2007). To mention is hydraulic conductivity, aeration, pore size distribution, soil strength and matric suction. Among these the latter property provides the needed water potential (energy) gradient to cause water to move from one point to another within the soil system. It is an important determinant in the sense that a default in its function prevents the soil matrix to release water for it to be transported to the roots for uptake.

For this reason, many water predictive models, such as the IWC (Groenevelt et al. 2001), LLWR (Da Silva et al. 1994), and NLWR (Letey 1985) have considered this basic property in quantifying the amount of water required by crops to mitigate crop water stress. These models, for instance the IWC, incorporates it by considering the soil water retention curve and other dynamic soil physical properties. However, the challenge here has been where to start weighting the water capacity on the WRC to calculate PAW using the IWC, especially for very coarse textured soils, which is known with abrupt hydraulic restriction to PAW. On a more serious note, the matric suction at the inflection point was proposed to solve this problem. However, the non-existence of plant information linking this unique matric suction has been a subject for investigation in the literature. Thus, no work has been done to really evaluate the water potential (matric suction) at the inflection point on the WRC to real plant response for authentication as hydraulic stress point for plants. This idea per say, came into been when the relative diffusivity was used theoretically to reduce the water capacity function to almost 50 % to calculate PAW for Rijtema's (1969), light loamy medium coarse sand, No. 6 soil (Grant and Groenevelt 2015).

As the focus, this chapter of the thesis reported on the findings of an experiment conducted to determine whether matric suctions predicted for the inflection point on WRCs developed for sands and sandy soils (**see chapter 4**) served as an identifier of hydraulic or water stress in wheats.

5.2 Materials and Methods

5.2.1 Experimental materials

The six different coarse textured soils described in **Chapter 4** were used to grow two different wheat genotypes up to the Zadoks' growth stage 21, which describes the tillering stage, main shoot and one tiller (Zadoks et al. 1974). The names of the soils are listed here in order from largest average particle size to smallest: Very coarse sand (VCS), Coarse sand (CS), Medium sand (MS), Fine sand (FS), Very fine sand (VFS) and Sandy loam (SL). All materials will be referred to by their alpha-codes in this chapter.

Plastic pots of 1-litre capacity (118 mm diameter across top; 100 mm diameter across bottom; 120 mm tall) were filled with oven-dry-equivalent weights of soil producing bulk densities shown in **Table 5.1**. Plastic beads (i.e. 84.84 ± 3.90 g per pot) were used as mulch on the soil surface of the pots to minimise water loss through evaporation after seeding the pots with wheat genotypes supplied by Associate Professor Matthew Gilliham, *Plant Transport & Signalling Group*, University of Adelaide.

Table 5.1 Weights and bulk densities of sandy materials used in pot study.

Sand or sandy soil	Equivalent oven-dry weight placed into pots, g	Dry bulk density of soil in pot, g cm^{-3}
VCS	1403	1.52
CS	1357	1.47
MS	1455	1.58
FS	1258	1.36
VFS	1292	1.40
SL	1371	1.49

5.2.2 Experimental factors and design

The factors were Soil texture (6, described above), Wheat genotype (2, Kukri and Excalibur, referred to above) and soil matric head (3, at the inflection point, and on the wet and dry sides of the inflection point, as described in **Chapter 4**, section **4.3**. There were five replications laid out in a 6 × 2 × 3 completely randomised factorial design (**Table 5.2**).

Table 5.2: Description of the 6 × 2 × 3 completely randomised factorial design for soils (S1 - VCS, S2 - CS, S3 - MS, S4 - VFS, S5 - FS, S6 - SL), wheat genotypes (W1 Kukri, W2 Excalibur), and soil matric heads on the wet side of the inflection point, WET, at precisely the inflection point, INFLECTION, and on the dry side of the inflection point, DRY. With 5 replicates of each combination there were 120 pots in the study.

S1 **W1** WET INFLECTION DRY	**S1** **W2** DRY WET INFLECTION	**S2** **W1** INFLECTION DRY WET	**S2** **W2** WET INFLECTION DRY
S3 **W1** DRY WET INFLECTION	**S3** **W2** WET INFLECTION DRY	**S4** **W1** INFLECTION DRY WET	**S4** **W2** WET INFLECTION DRY
S5 **W1** INFLECTION DRY WET	**S5** **W2** WET INFLECTION DRY	**S6** **W1** DRY WET INFLECTION	**S6** **W2** INFLECTION DRY WET

5.2.3 Soil water contents

The soil water content in each pot was set and maintained gravimetrically according to the volumetric water contents and soil matric heads predicted from the water retention curves (WET, INFLECTION and DRY). As explained in **Chapter 4**, I fitted the water retention data for the 20-odd replicates of the six soils (*viz.* $\Theta(\mathrm{h}) = \frac{\theta(h)}{\theta_s}$ and h), individually to the VG-model (Van Genuchten 1980) to obtain the fitting parameters: α (m^{-1}), θ_{res} and N (dimensionless). Rather than averaging the VG parameters to create a single curve, I differentiated the individual WRC for each replicate to obtain 20-odd relative water capacity curves, $\frac{d\Theta}{dh} = C(h)$. I then used the peak in each individual water capacity curve to identify the matric suction at the inflection point, h_i, where $\left(\frac{d}{dh}\right)^2 \Theta = 0$. To calculate the magnitude of C(h) equal to 90 % of the maximum C(h), I then multiplied each $C(h_i)$ by 0.9. Points having this magnitude occurred on both sides of the maximum C(h), so for each of the 20-odd replicates, I found the suction at 0.9 x $C(h_i)$ on the left of the maximum, h_{wet}, and on the right of the maximum, h_{dry}. Then I found the corresponding values of $\Theta(h_{wet})$, $\Theta(h_i)$ & $\Theta(h_{dry})$ for each set of water retention data by substitution into the individual (inverted) water retention curves, $h(\Theta)$ (*or by using the "trace" function on the WRCs in Mathcad software*). I converted the values of Θ into their respective volumetric water contents (cm^3 water per cm^3 total volume), θ_{wet}, θ_i, & θ_{dry} via their individual saturated water contents, θ_s. I then calculated the mean values for the three points: $(\overline{\theta_{wet}}, \overline{h_{wet}})$

, $(\overline{\theta_{infl}}, \overline{h_{infl}})$, and $(\overline{\theta_{dry}}, \overline{h_{dry}})$ and converted the volumetric water contents to gravimetric water contents using **Equation [41]** (shown in **Chapter 4**), to obtain gravimetric units (Hanks 1992; Hillel 1998), which were combined with the soil masses reported in **Table 5.1** to obtain the total mass for each pot (**Table 5.3**).

Table 5.3: Mean planned (predicted) matric suctions, $\bar{h}$, volumetric water contents, $\bar{\theta}$, and volumes or masses of water, Q, required to maintain constant soil water conditions at the inflection point as well as wetter and drier than the inflection point (WET, INFLECTION, DRY) for the 6 soils.

Sand or sandy soil	$\bar{h}$, m	$\bar{\theta}$, m^{3}m^{-3}	Q, cm^3 or g
	WET		
VCS	0.078	0.248	226
CS	0.075	0.270	247
MS	0.286	0.252	225
FS	0.619	0.313	268
VFS	1.531	0.315	288
SL	1.545	0.345	311
	INFLECTION		
VCS	0.089	0.193	175
CS	0.089	0.227	207
MS	0.329	0.205	181
FS	0.688	0.274	233
VFS	1.929	0.280	256
SL	1.869	0.326	293
	DRY		
VCS	0.091	0.149	135
CS	0.104	0.179	163
MS	0.376	0.157	137
FS	0.764	0.233	195
VFS	2.033	0.240	219
SL	2.120	0.300	269

A more ideal approach (which I did not use; reasons explained below[1]) might have been to calculate the mean values of the VG parameters, α, θ_{res} and N, that were determined for the 20-odd WRCs, and use them to create a single relative WRC, rather than using multiple WRCs as I did. In this ideal approach the single WRC would be differentiated, $\frac{d\Theta}{dh} = C(h)$, and the peak in C(h) identified to mark the location of the inflection point. The values for h_{wet}, h_i, & h_{dry} would then be determined from a single curve, and the corresponding values for $\Theta(h_{wet})$, $\Theta(h_i)$ & $\Theta(h_{dry})$ extracted using the inverted WRC and converted to volumetric water contents θ_{wet}, θ_i, & θ_{dry}.

[1] I did not use this 'ideal' approach because I had to start my pot experiments when (limited) glasshouse space became available; this time occurred before I had a complete set of WRCs for all the soils. I had the information for all the sands but the WRCs for the SL soil took much longer to equilibrate, which meant I didn't have information at the drier end of the SL-WRCs, and had to proceed with only a partial data set. I therefore used the available SL data to identify the approximate location of the inflection point (and the wetter and drier points) for each individual WRC, then averaged them.

5.2.4 Wheat establishment in pots

I conducted a preliminary growth experiment to determine the relative magnitudes of (gradually increasing) plant mass and the mass of the pots, which allowed a correction for the pot weights during watering. The water content predicted at the wet side of the inflection point for each soil was used to grow wheat plants over a period of three weeks, during which the fresh mass of plant material was weighed (destructively) at regular intervals up to 21 days. Masses were plotted as a function of time (days after emergence, DAE) and cubic polynomials fitted to describe the relationships (**Figure 5.1**), which were used daily to adjust the (upward) mass of water required to keep the soil matric head constant during the main experiment.

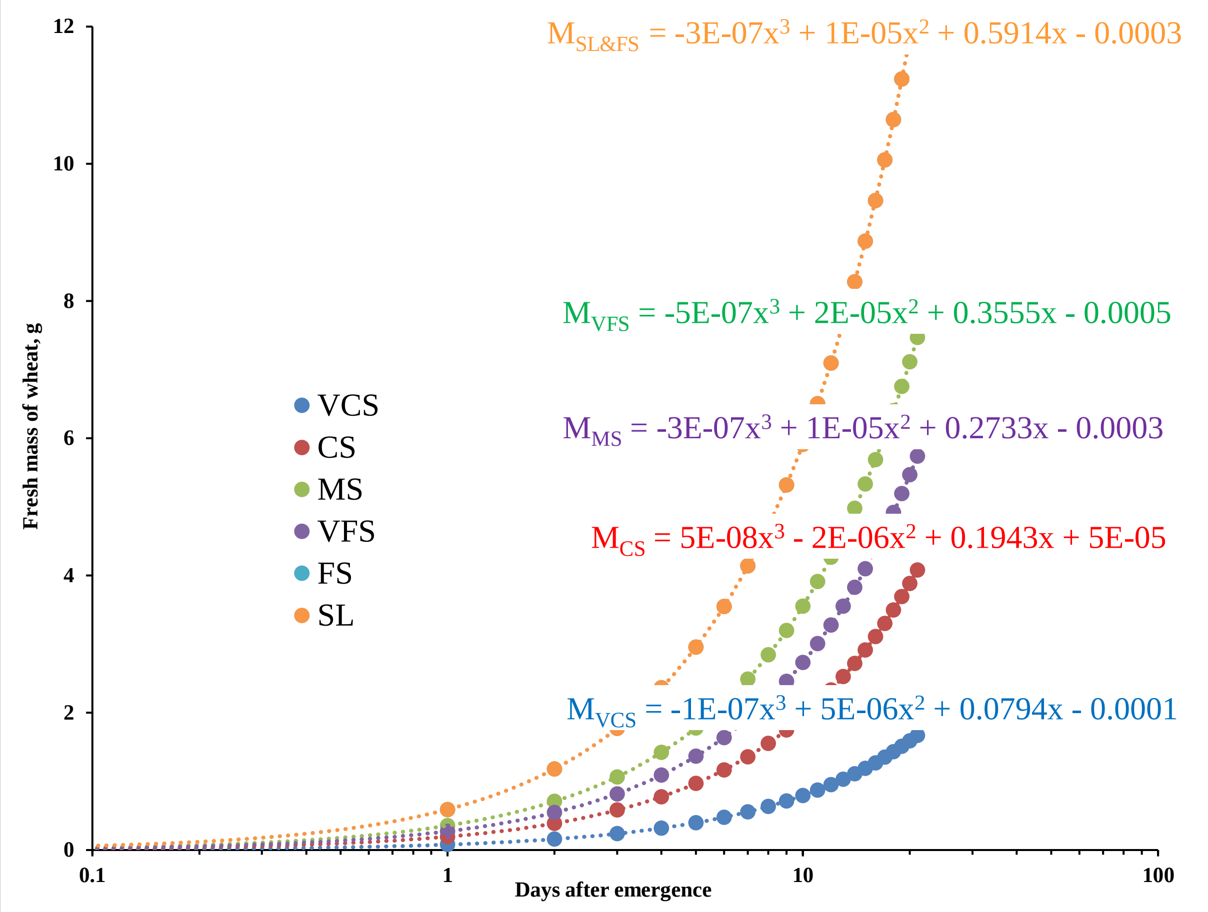


Figure 5.1: Calibration equations describing the (cubic polynomial, R^2 = 1) relationship for each soil between fresh mass of wheat as a function of time, used to correct the daily pot weights for plant biomass, so the predicted water contents could be kept constant.

5.2.5 Conditions in glasshouse

The experiment was conducted in Glasshouse No.7 of the *South Australian Research and Development Institute* at the Waite Campus. Maximum and minimum temperatures were recorded in the glasshouse (**Table 5.4**) and when the average daytime temperature fell below 25 °C heating lamps were used to raise the temperature.

Table 5.4: Pot watering date and time, plus temperature conditions in the glasshouse.

Date	Watering time	Temperatures		
		Min °C	Mean °C	Max °C
15/03/2016	-	-	-	-
16/03/2016	-	-	-	-
17/03/2016	-	-	-	-
18/03/2016	11:40	17	23	44
19/03/2016	12:18	17	23	44
20/03/2016	10:53	17	24	44
21/03/2016	11:55	17	25	44
22/03/2016	12:08	17	25	44
23/03/2016	11:45	17	22	44
24/03/2016	12:52	17	25	44
25/03/2016	11:38	17	26	44
26/03/2016	11:36	17	23	44
27/03/2016	12:01	17	23	44
28/03/2016	13:30	17	23	44
29/03/2016	11:41	17	26	44
30/03/2016	11:52	17	22	44
31/03/2016	12:01	16	27	44
1/04/2016	12:01	16	24	44
2/04/2016	12:40	16	27	44
3/04/2016	13:46	16	27	44
4/04/2016	11:30	16	29	44
5/04/2016	10:30	16	26	44

5.2.5.1 Seeding and nutrient application

I arranged the pots on large tables in a glasshouse following the experimental layout described in **Table 5.2**. I recorded an initial weight for each pot after the required amount of water was added according to **Table 5.3** (the water added to each pot contained 0.6 g of fertilizer: 11% N, 2% P, 9% K and 1% Ca). Samples of the soil were taken to measure electrical conductivity (EC) and pH (**Table 5.5**). Two seeds of the appropriate wheat variety were then placed in each pot along with a small amount of water to establish good seed-soil contact until they germinated, after which a plastic bead mulch was placed over the soil surface. The total weight of each pot was then recorded and maintained throughout the experimental period (after correcting for plant weight according to the relations shown in **Figure 5.1**).

Table 5.5: Electrical conductivity and pH of soils used in the study.

Soil textures	Nominal particle size (mm)	[1]$EC_{1:5}$ ± s.d.	[2]EC_e	[3]pH ± s.d.	[4]pH ± s.d.
VCS	1.7	0.052 ± 0.001	0.854	6.77 ± 0.01	6.78 ± 0.02
CS	0.75	0.035 ± 0.007	0.545	6.78 ± 0.11	6.67 ± 0.01
MS	0.19	0.049 ± 0.004	0.847	6.76 ± 0.03	6.70 ± 0.03
VFS	0.08	0.171 ± 0.009	2.381	7.74 ± 0.12	7.61 ± 0.01
FS	0.178	0.161 ± 0.005	2.071	6.93 ± 0.12	6.86 ± 0.15
*SL	0.048	0.367 ± 0.004	5.418	7.94 ± 0.00	7.76 ± 0.01

[1,2] $EC_{1:5}$ measured using 10 g of soil to 50 g distilled water, then converted to paste extract EC_e using procedure of (Slavich and Petterson 1993; Smith and Doran 1996).
[3,4] pH measured in water then $CaCl_2$ using procedures after(Smith and Doran 1996).
*SL was saline, as shown on **Figure 3.1**.

5.2.5.2 Daily watering regime

To ensure my pots of soil were held at the "predicted" or "planned" values of θ and h, I measured the soil water content gravimetrically every day separately for Kukri and Excalibur pots until the plants reached the desired stage of growth (Zakoks' scale 21). During the experiments, adjustments were made daily to the amounts of water added based upon preliminary experiments to calculate the increasing weight of plant material in each soil type. To assist in this, I also placed eighteen additional pots randomly among the experimental pots to account for any evaporation that occurred through the plastic bead mulches; this information was included along with plant fresh weights to calculate the amount of water to add to each pot daily.

From the daily measured pot weights, I determined the gravimetric water contents for each pot, w_{wet}, w_i & w_{dry} (g water per g dry soil) and converted them to volumetric water contents using the bulk densities of the different soils in the relevant pots, thus obtaining multiple values of θ_{wet}, θ_i, & θ_{dry} for Kukri and Excalibur, respectively. In detail, I converted the daily pot weights to volumetric water contents, θ_v, using the relation:

$$\theta_v = \frac{[M_T - (M_B + M_{FP} + M_F + M_P)] - M_{OD}}{M_{OD}} \times \frac{\rho_b}{\rho_w} \qquad \textbf{[41]}$$

where M_T is the total mass of moist soil, beads, fresh plant and fertilizer (g), M_B is the mass of the plastic beads, M_{FP} is the mass of fresh plant tissue, M_F is the mass of fertilizer added, M_P is the mass of the empty pot, M_{OD} is the mass of oven dry soil in the pot, ρ_b is the bulk density of the soil in the pot, and ρ_w is the specific gravity of water. The values of θ_v were converted to relative volumetric water contents, $\Theta(h_{wet})$, $\Theta(h_i)$ & $\Theta(h_{dry})$, from which the corresponding matric heads for Kukri and Excalibur, respectively, were obtained as explained in **Section 5.1.3**. Mean values of the measured $\overline{\theta_v}$ and $\bar{h}$ were calculated and compared with those predicted.

5.2.6 Harvest measurements

When the wheat plants reached Zadoks' growth stage 21, they were carefully removed from the pots, separated into roots and shoots and their fresh weights measured. The roots and shoots were then dried in an oven set at 65 °C for three days and then dry weights measured. A small sample of soil was retained for analysis of EC following procedures described in Smith and Doran (1996) and Slavich and Petterson (1993).

5.2.7 Statistical analysis

F-test analysis of variance was performed on the dry weights of wheat. Averages of dry weights determined for the shoot and root biomass were separated using the least significant difference test (LSD). Also, an orthogonal contrast comparison was performed for dry weight of shoots obtained for wheats growth at water potentials of wet plus inflection point ($h_w + h_i$) as against the dry end (h_d). All statistical analysis and computations in this chapter were done using the GenStat software and Microsoft Excel, edition eighteen and 2016, respectively.

5.3 Results and discussion

5.3.1 Soil water contents and matric heads during growing period

For all but one soil, the planned and measured soil water suctions were generally quite close (**Figure 5.2**). All 'measured' soil water suctions were inferred from the relevant water retention curves based on the water contents calculated from the daily pot weights. The measured soil water suctions for the SL soil turned out to be signficantly smaller than the planned values, which is why six points in **Figure 5.2** lie below the 1:1 line. Two technical problems beyond my control were responsible for this and caused the watering regime to be compromised for the SL soil: First, as explained in the footnote in **Section 5.1.3**, I had incomplete water retention data for the SL soil when I needed to start my pot experiments; this meant I had inaccurate data for the SL soil to estimate the amounts of water to add. Second, because of the dispersive nature of the SL soil, infiltration of water into the pots of soil was extremely slow, so I had to add additional water to account for unmeasured evaporation during the set-up phase. Fortuitously, however, I ended up adding larger amounts of water added to the pots and this turned out to be relatively close to what should have been added (after I had more complete information), so the planned and measured water contents for the SL soil shown in **Figure 5.3** fall indistinguishably on the 1:1 line along with all the other soils for which no technical problems were encountered! The volumetric water contents maintained in the pots of soil during the growing period (wet side, inflection point, and dry side) are shown in **Table 5.6**, and assured me that the planned and measured status of water in the pots was satisfactory.

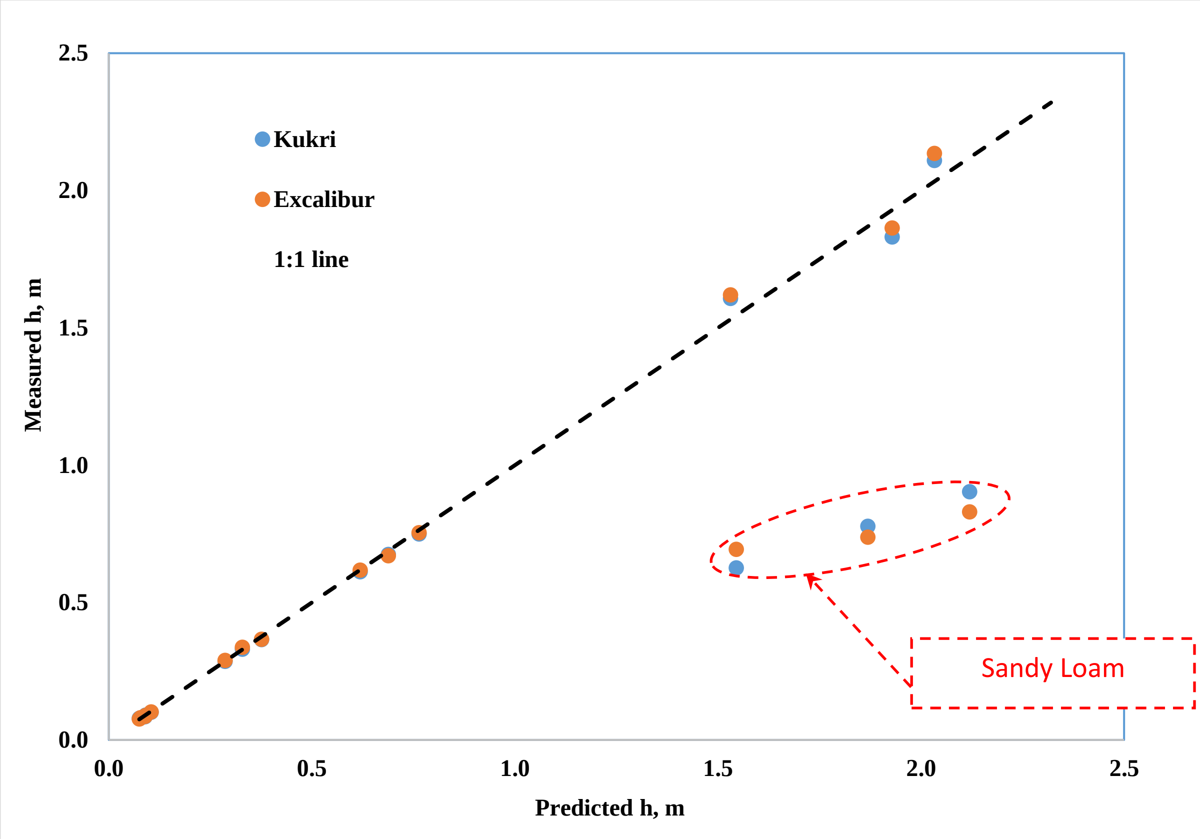


Figure 5.2. Soil matric suction measured in pots of different soils growing Kukri or Excalibur wheat verses that planned, superimposed on a 1:1 line.

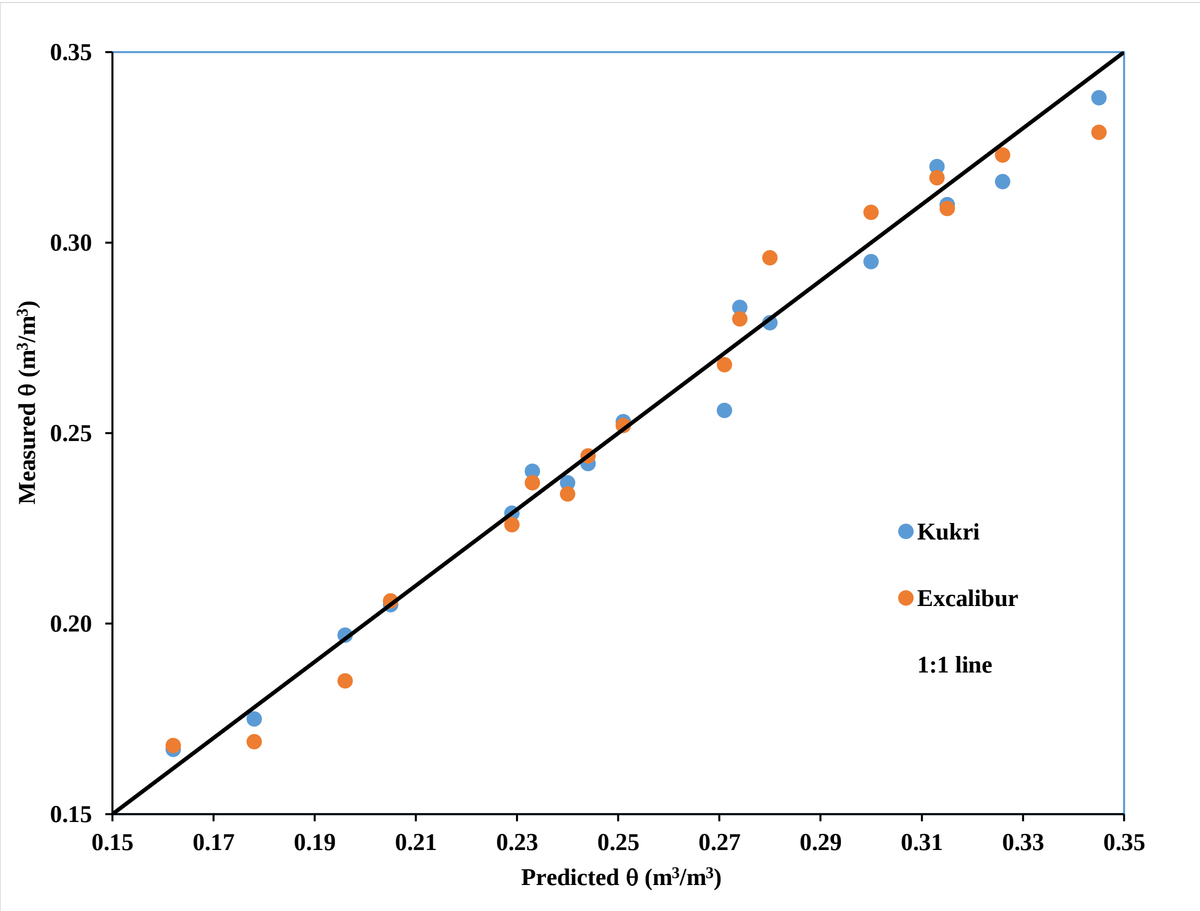


Figure 5.3. Soil volumetric water content measured in pots of different soils growing Kukri or Excalibur wheat verses that predicted, superimposed on a 1:1 line.

Table 5.6 Volumetric water contents planned (predicted) and mean measured water contents in pots of different textured soils used to grow wheat (var. Kukri and Excalibur) over 21 days.

Soil texture	Planned (predicted) water content (m^3 m^{-3})	Experimentally measured water content in pots (m^3 m^{-3})	
		Kukri	Excalibur
	Wet side	**Wet side ± s.e.**	
VCS	0.244	0.242 ± 0.001	0.244 ± 0.001
CS	0.271	0.256 ± 0.001	0.268 ± 0.002
MS	0.251	0.253 ± 0.001	0.252 ± 0.001
FS	0.313	0.320 ± 0.003	0.317 ± 0.003
VFS	0.315	0.310 ± 0.001	0.309 ± 0.001
SL	0.345	0.338 ± 0.004	0.329 ± 0.004
	Inflection	**Inflection ± s.e.**	
VCS	0.196	0.197 ± 0.001	0.185 ± 0.001
CS	0.229	0.229 ± 0.002	0.226 ± 0.001
MS	0.205	0.205 ± 0.001	0.206 ± 0.001
FS	0.274	0.283 ± 0.003	0.280 ± 0.003
VFS	0.280	0.279 ± 0.001	0.296 ± 0.001
SL	0.326	0.316 ± 0.005	0.323 ± 0.002
	Dry side	**Dry side ± s.e.**	
VCS	0.147	0.144 ± 0.001	0.151 ± 0.001
CS	0.178	0.175 ± 0.001	0.169 ± 0.001
MS	0.162	0.167 ± 0.001	0.168 ± 0.002
FS	0.233	0.240 ± 0.002	0.237 ± 0.003
VFS	0.240	0.237 ± 0.001	0.234 ± 0.001
SL	0.300	0.295 ± 0.004	0.308 ± 0.002

5.3.2 Shoot and Root responses

The ANOVA output suggested there were several significant factors influencing both shoot and root growth (**Tables 5.7** and **5.8**). For example, Soil texture and its interactions with Matric suction and with Wheat variety had significant effects on shoot growth, while both Soil texture and Wheat variety (and some interactions) had significant effects on root growth. The significant F-values are highlighted in bold-face type in **Tables 5.7** and **5.8**.

Table 5.7 Analysis of variance (ANOVA) for shoot growth response, including the comparison of wet plus inflection point verses dry matric suction shoot dry weight.

Source of variation in shoot dry mass	**df**	**SSE***	**MSE****	**VR*****	**F-value**
Replication	4	0.2500	0.063	1.13	-
Soil texture	5	11.929	2.386	42.98	< **0.001**
Wheat variety	1	0.1539	0.154	2.77	0.098
Matric suction	2	0.2129	0.106	1.92	0.151
Wet+Inflection vs Dry	1	0.0061	0.006	0.11	0.741
Soil texture × Wheat var	5	0.999	0.200	3.60	**0.004**
Soil texture × Matric suction	10	2.618	0.262	4.72	< **0.001**
Soil × (Wet+Inflection vs Dry)	5	0.0535	0.011	0.19	0.965
Wheat var × Matric suction	2	0.1046	0.052	0.94	0.392
Wheat var × (Wet+Inflection vs Dry)	1	0.0015	0.002	0.03	0.869
Soil texture×Wheat var×Matric suction	10	1.795	0.180	3.23	< **0.001**
Soil×Wheat var × (Wet+Inflection v Dry)	5	1.093	0.219	3.94	**0.002**
Residual	138****	7.661	0.056	1.00	-
Total	177****	25.65	0.063	1.13	-

* SSE = Sum of squared errors
** MSE = Mean squared error = (SSE ÷ df)
*** VR = Variance ratio = MSE ÷ Residual MSE
**** 2 missing values

Table 5.8 ANOVA for root growth response.

Source of variation in root dry mass	**df**	**SSE**	**MSE**	**VR**	**F-value**
Replication	4	0.046	0.012	0.44	-
Soil texture	5	5.804	1.161	44.34	< **0.001**
Wheat variety	1	0.215	0.215	8.21	**0.005**
Matric suction	2	0.046	0.023	0.88	0.419
Soil texture × Wheat var	5	0.308	0.062	2.35	**0.044**
Soil texture x Matric suction	10	0.290	0.029	1.11	0.360
Wheat var × Matric suction	2	0.026	0.013	0.50	0.609
Soil texture × Wheat var × Matric suction	10	0.295	0.029	1.13	0.348
Residual	138	3.613	0.026	1.00	-
Total	177	10.559	-	-	-

The texture of the soil had an impact on shoot and root growth of both wheat varieties, but the effects were neither large nor consistent in trend, such that, for example, there was no indication that yields were consistently smallest in the VCS and largest in the SL (**Figures 5.4 and 5.5; Table 5.9 and 5.10)**.

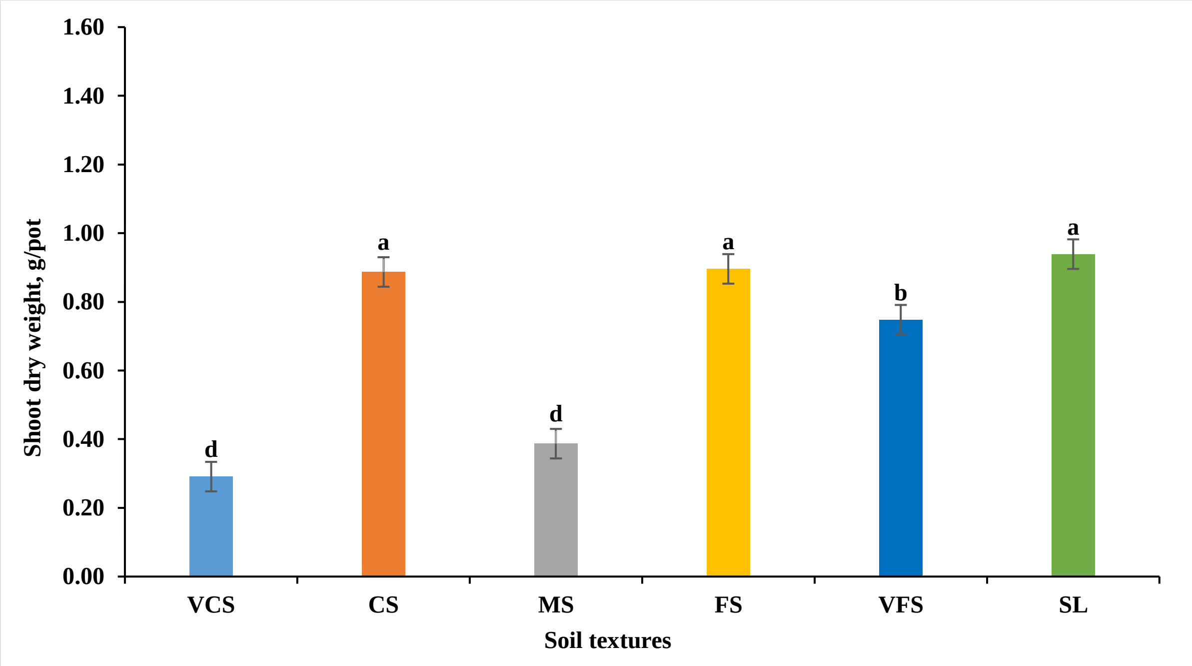


Figure 5.4: Soil texture effect on mean shoot dry weight produced from 6 different soils.

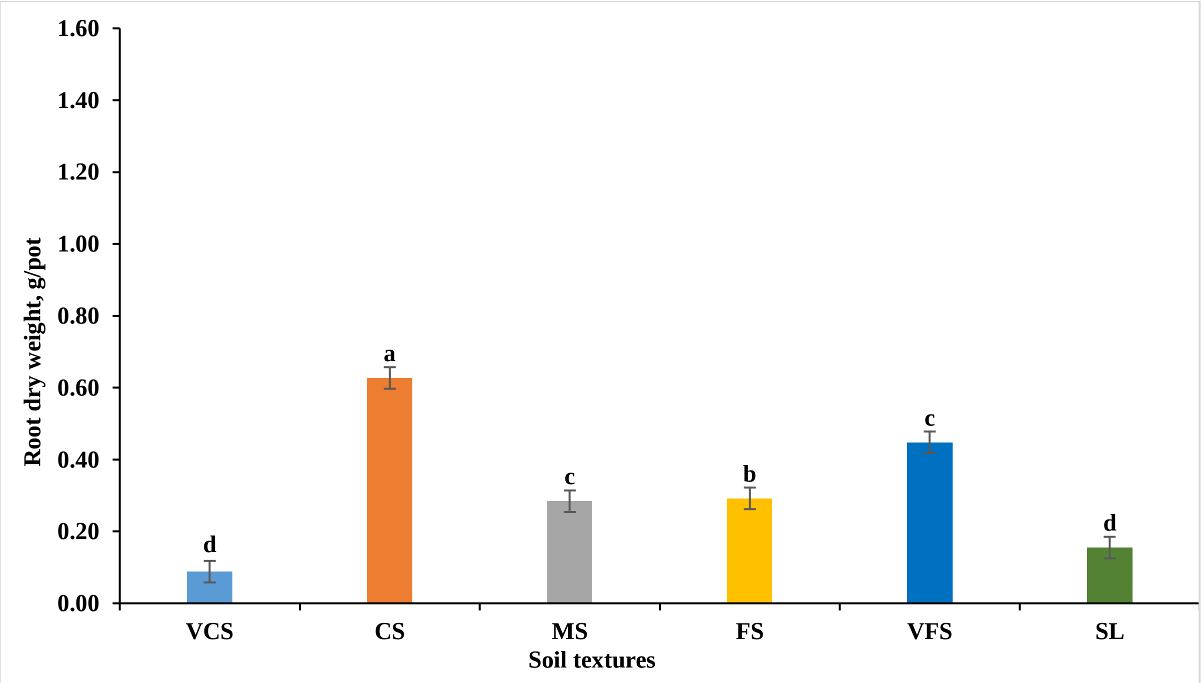


Figure 5.5: Soil texture effect on mean root dry weight produced from 6 different soils.

In addition, (and more importantly) there was no consistent effect of soil matric suction on either shoot or root yield (**Tables 5.9** and **5.10**). Even when the data for the Wet side and Inflection point were averaged and compared to the Dry side data, yields were not consistently greater for the Wet side + Inflection point than for the Dry side, though significant differences existed for the planned comparison performed for shoot dry weight (**Figure 5.6 and Table 5.7**). Similarly, the three-factor interaction effect showed some significant differences in mean shoot dry weight among wheat genotypes, soil moisture conditions and soil textures but no universally consistent trends emerged (**Tables 5.7**). There were some significant differences in root growth between soil textures but very few significant differences between wheat varieties in a given soil texture (**Table 5.11**).

Table 5.9 Shoot dry mass for wheat varieties, Kukri and Excalibur, grown for 21 days under soil moisture conditions on Wet side, Inflection point, and Dry side in 6 different soil textures.

Soil texture	Mean shoot dry mass, g ± s.e. *					
	Kukri			Excalibur		
	Wet side	Inflection	Dry side	Wet side	Inflection	Dry side
VCS	0.268b ± 0.074	0.186bc ± 0.040	0.288c ± 0.037	0.376b ± 0.090	0.316c ± 0.046	0.312b ± 0.043
CS	1.038a ± 0.188	0.886a ± 0.126	0.658b ± 0.220	0.944a ± 0.227	0.762b ± 0.096	1.036a ± 0.105
MS	0.306b ± 0.038	0.376b ± 0.022	0.334c ± 0.039	0.380b ± 0.068	0.462c ± 0.009	0.462b ± 0.010
FS	0.748a ± 0.150	1.006a ± 0.074	0.882b ± 0.069	0.914a ± 0.048	0.892b ± 0.060	0.932a ± 0.056
VFS	0.780a ± 0.096	0.488b ± 0.035	0.534bc ± 0.050	0.862a ± 0.069	0.854b ± 0.036	0.970a ± 0.007
SL	0.796a ± 0.138	1.140a ± 0.204	1.202a ± 0.093	0.434b ± 0.200	1.474a ± 0.066	0.586b ± 0.212

* ***Means compared within columns & rows; values with same letter not significantly different at P = 0.05; otherwise significantly different.***

Table 5.10 Root dry mass for wheat varieties, Kukri and Excalibur, grown for 21 days under soil moisture conditions on Wet side, Inflection point, and Dry side in 6 different soil textures.

Soil texture	Mean root dry mass, g ± s.e.					
	Kukri			Excalibur		
	Wet side	Inflection	Dry side	Wet side	Inflection	Dry side
VCS	0.082 ± 0.017	0.064 ± 0.016	0.078 ± 0.020	0.110 ± 0.027	0.120 ± 0.022	0.072 ± 0.022
CS	0.688 ± 0.183	0.770 ± 0.074	0.434 ± 0.217	0.620 ± 0.177	0.612 ± 0.121	0.636 ± 0.110
MS	0.166 ± 0.020	0.248 ± 0.023	0.272 ± 0.033	0.280 ± 0.020	0.366 ± 0.015	0.374 ± 0.014
FS	0.230 ± 0.051	0.206 ± 0.010	0.236 ± 0.033	0.388 ± 0.026	0.342 ± 0.014	0.348 ± 0.012
VFS	0.506 ± 0.014	0.290 ± 0.099	0.260 ± 0.054	0.528 ± 0.077	0.564 ± 0.008	0.538 ± 0.009
SL	0.121 ± 0.033	0.198 ± 0.054	0.208 ± 0.057	0.088 ± 0.024	0.230 ± 0.027	0.086 ± 0.034

Although not all factors had a significant impact on plant response the wheat variety, Excalibur, generally produced greater mean shoot biomasses than Kukri in all soils and in most of the soil moisture conditions (**Table 5.9**). This is consistent with the greater vigour associated with Excalibur relative to Kukri (Izanloo et al. 2008), although the mean root growth was essentially the same for both wheat varieties (**Table 5.11**). Any differences in shoot and root growth between the two varieties of wheat are not considered to be influenced by the moisture treatments in this study (**Table 5.7 and 5.8**).

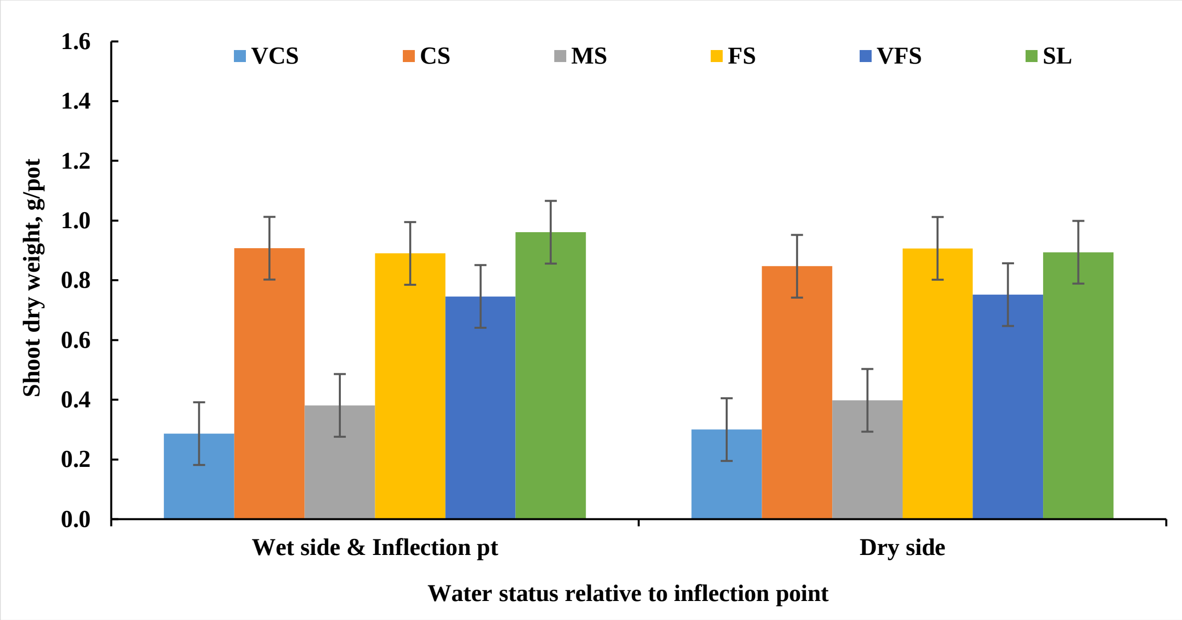


Figure 5.6 Mean shoot growth of wheat (both varieties) grown under moist (Wet side + Inflection point) versus Dry side soil water conditions.

Table 5.11: Mean root dry mass of wheat varieties, Kukri and Excalibur, grown in different sands and sandy soils for the interaction effect of soil texture and wheat genotypes.

Soil texture	**Kukri**	**Excalibur**
	(Mean of Wet side, Inflection, Dry side from Table 5.10)	
VCS	0.075c	0.101c
CS	0.631a	0.623a
MS	0.229b	0.340b
FS	0.224b	0.359b
VFS	0.352b	0.543a
SL	0.176bc	0.135c

Means are comparable within columns & rows; values with same letter are not significantly different at p = 0.05; otherwise significant
Estimate of average standard error was 0.042

On the surface of the evidence presented in this study, the inflection point on the water retention curve of sandy soils appears not to be a critical marker of soil moisture status to identify the onset of dynamic hydraulic stress for wheat plants. It is possible, however, that the soil conditions in the pots used in this study were not ideal to test the hypothesis. For example, if the root-length density of the plants growing in my pots were sufficiently great that the travel-distance for water from the soil matrix to the root surface was small, then dynamic hydraulic restrictions might not become apparent, even if the unsaturated hydraulic conductivity of the soil is low. Although I did not measure root length density, this is a distinct possibility in small pots. Future work would need to be conducted either in larger pots for shorter times, or else in the field.

Second, the soil moisture conditions on the dry side of the inflection point may not have been sufficiently dry. I hypothesised that so long as the dry point was outside the 95 % confidence interval for the mean water content at the inflection point, it would be sufficiently dry to test the idea. It is possible that the experiments should have been set up at matric heads corresponding to 80 % of the maximum water capacity instead of 90 %.

It is also possible that other experimental factors influenced the plant response to the soil moisture conditions. For example, all the pots of soil were handled multiple times every day during (transporting from benches, weighing, watering, re-weighing, and transporting back to benches). If all this handling caused disturbance of the soil in the relatively soft plastic pots, any tendency of the different sands to subside and densify would be enhanced during handling. No measurements of densification, or even penetrometer resistance, were taken on the pots so this cannot be verified but some sandy soils set hard and become very dense when disturbed (Agrawal 1991; Bengough et al. 1991; Chan 1995; Harper and Gilkes 1994; Mullins et al. 1987; Panayiotopoulos and Mullins 1985; Westman and Hugill 1930). A consequence of soil densification is that any treatment differences may have been masked.

5.4 Conclusions

Based upon the response of two wheat varieties grown in pots of different sands and sandy soil, the hypothesis that the inflection point of the water retention curve marks a critical matric head for the onset of dynamic hydraulic stress in plants must be rejected unless a better experimental protocol is considered. It is possible, for example, that the matric head corresponding with 90 % of the maximum water capacity was not sufficiently stressful for the plants examined here. A drier matric head corresponding with say 80 % of the maximum water capacity might reveal clearer evidence of water stress.

Another factor not considered in this study was the control of root-length density – it would be important to ensure that experiments be performed in volumes of soil large enough to ensure dynamic hydraulic properties were tested; in the present study, the pots may have been too small. Finally, if a pot study is considered in the future, it will be important to avoid any soil compaction brought on by daily handling – perhaps by using reinforced pots that remain rigid during movement and handling.

CHAPTER 6

Summary, conclusions and suggestions for future research

The research questions and hypotheses posed at the beginning of this study (see **Section 2.14**) can now be answered as follows:

In relation to the matric suction at the inflection point of the water retention curve, h_i, it was confirmed for a wide range of sands and a sandy loam to coincide closely (if not precisely) with the value of the fitting parameter, k_o, in the Groenevelt-Grant water retention model (an exponential function), and with α^{-1} in the van Genuchten water retention model (a power function). This confirms the findings of Van Lier (2014) and Grant and Groenevelt (2015). The two parameters, k_o and α^{-1}, both have the dimension length (m) and are strongly and linearly correlated. Furthermore, the hypothesis that the matric suction at the inflection point depends on the particle and/or pore size and is related to the water retention parameters k_o and α^{-1}, was confirmed. The value of h_i shifted inversely with mean soil particle size for soils ranging from very coarse sands to a sandy loam. **Figure 4.3**, showed a very good fit to the data for power functions of the type $Y= aX^{-b}$, where Y is either k_o or α^{-1}, and X is the nominal particle diameter, mm.

For reasons best explained by a statistical mathematician familiar with the properties of exponential functions and power functions, the Van Genuchten model was found to fit the measured water retention data for the sands used in this study (which bend rather sharply during drainage) more effectively than the Groenevelt-Grant model. Given that the shape of the function resulting from the chosen model can have a large influence on the location of the inflection point, the model that best fits the data must be used to identify the inflection point. On this basis, the Van Genuchten model was chosen to identify the inflection point and the surrounding points for the plant experiments in this study. No integral water capacities were calculated in this study because, as discussed below, the plant responses did not emerge.

An attempt was made in this study to use real plants to experimentally evaluate the idea postulated by Grant and Groenevelt (2015) that the soil water status at or around the inflection point marks the onset of dynamic hydraulic stress in plants. The work presented in **Chapter 5** of this study compels the reader to conclude that the postulated relationship is <u>not</u> yet confirmed. When wetter and drier points around the inflection point were selected to correspond with matric suctions aligned to 90 % of the maximum differential water capacity (i.e. at 0.9 x $C(h_i)$), there were no consistent and statistically significant differences in root and shoot growth between wheat plants grown at the inflection points (and above it and below it) in a wide range of different sands. Now one would expect no real difference between the response at and above the inflection point (where conditions were postulated to be ideal) but a difference might be expected below the inflection point, and this was not found to be the case. For this reason, no analysis of the diffusivity and plant sensitivity factors suggested by Grant and Groenevelt (2015) can be conducted from the results presented here.

Before dismissing the hypothesis of Grant and Groenevelt (2015), however, more attention needs to be placed on identifying the critical matric suctions involved. On the wet side, it would be imprudent to shift to a smaller matric suction, h_{wet}, because aeration problems would create anaerobic conditions that would interfere with plant performance. However, on the dry side of the inflection point, the matric suction, h_{dry}, was clearly not sufficiently different from that at the inflection point, h_i, to generate a dynamic hydraulic stress in the plants used in this study. A more effective approach (but one outside the scope of this study) would be to grow plants in exactly the same sands but to hold them constant at a set of soil moisture suctions increasing from the inflection point onward. In that way, it would be possible to evaluate whether dynamic soil water restrictions started to have an effect on plant growth at some point that could be related to the matric head at the inflection point (i.e. 85 %, 80 %, 75 %, 70 % of the maximum water capacity, etc.). In addition, it would be important for plants to grow to more mature stages so that any soil water stress could be manifest at critical growth stages, rather than simply during the early stages of growth. Having said this, the root length density of the plants in potted soil would need to be relatively small so that water would need to move greater distances toward the plant. Control of these factors would have to involve much larger volumes of sand and soil, and longer growth periods, which would constitute a significantly larger study than was possible here.

On the basis that effects were not found under non-saline conditions (**Chapter 5**), proceeding to a similar analysis under saline conditions (proposed at the beginning of this study) could not be justified, even though I used wheat plants of different sensitivities to salt (Kukri versus Excalibur) and found differences in growth habit. Of course, future work of a similar nature to that initially proposed might be possible if the approach outlined above proved fruitful. I still think the hypothesis that the degree of correlation between h_i and the matric head at which water stress begins in plants will diminish with increasing salt concentration is a valid idea. I also think that wheat plants with differing sensitivity to salinity, such as Kukri and Excalibur, should be involved in such a study.

Finally, if sometime in the future, it is found that plants are indeed sensitive to the prevailing hydraulic conditions at or around the inflection point, an interesting question should be posed:

"why is this so?" When Grant and Groenevelt (2015) proposed the inflection point as a good starting matric suction for their weighting function, they were less interested in "why" than they were in "what" the function might look like. If viewed dispassionately, however, the inflection point is simply a static point on the water retention curve at which the largest amount of water is released per unit suction. There is no *a priori* reason why something dramatic should happen at this point, and unless it can be shown that some dynamic hydraulic property (e.g. unsaturated hydraulic conductivity or diffusivity) changes markedly at the inflection point, there may be no basis for focussing our attention here. I will leave this to others to consider.

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APPENDIX

Appendix 1

Water retention data for different sands and sandy soils, filtered to remove outliers and to balance data surrounding inflection point

Table A1.1: Very Coarse Sand (VCS) (Particle size diameter range: 1.4 to 2 mm, nominally 1.7 mm)

Matric head, m	Volumetric water content, (m^3 m^{-3})																			
	Rep. No. 1	Rep No. 2	Rep No. 3	Rep No. 4	Rep No. 5	Rep No. 6	Rep No. 7	Rep No. 8	Rep No. 9	Rep No. 10	Rep No. 11	Rep No. 12	Rep No. 13	Rep No. 14	Rep No. 15	Rep No. 16	Rep No. 17	Rep No. 18	Rep No. 19	Rep No. 20
0.0001	0.367	-	-	-	-	0.345	-	-	0.371	-	-	-	-	0.368	-	-	-	-	-	-
0.01	0.351	-	-	-	0.344	-	0.336	0.331	0.369	-	0.324	0.337	-	-	-	0.350	-	0.336	-	-
0.02	0.328	0.325	-	0.333	0.338	0.332	-	-	0.359	0.324	0.321	0.327	-	0.346	-	0.343	0.329	0.332	-	-
0.03	-	0.324	0.320	0.329	-	-	0.322	0.323	-	-	-	0.312	-	-	-	-	0.326	-	0.312	-
0.04	0.302	0.309	0.315	0.324	0.322	0.309	-	-	-	-	-	0.307	0.281	-	0.290	-	0.324	-	0.300	-
0.05	-	0.309	0.308	0.310	0.309	-	-	0.302	0.314	0.296	0.285	-	-	-	-	-	-	-	-	0.284
0.06	0.273	0.283	0.286	0.288	-	0.287	0.294	-	-	0.290	0.263	-	0.281	-	0.284	-	0.286	0.272	0.274	-
0.07	0.257	0.258	0.257	0.262	0.257	-	-	0.280	0.288	0.281	0.208	-	-	0.273	0.275	0.275	-	-	-	-
0.08	0.202	-	-	-	0.186	0.255	0.262	-	-	0.246	0.166	0.277	0.259	0.237	0.240	0.239	0.231	-	-	0.272
0.09	0.173	0.212	0.221	0.220	0.147	0.183	0.213	0.225	0.214	0.200	0.054	0.221	0.193	0.175	0.168	0.141	0.195	0.208	0.193	0.213
0.10	0.065	0.068	0.074	0.073	0.075	0.072	0.082	0.077	0.116	0.072	0.022	0.058	0.059	0.051	0.060	0.056	0.064	0.073	0.056	0.056
0.20	0.022	0.022	0.025	0.017	0.019	0.023	0.033	0.030	0.033	0.028	-	0.020	0.018	0.020	0.023	0.031	0.027	0.029	0.033	-
0.30	-	0.022	0.022	0.017	0.019	0.023	0.023	0.018	0.017	0.016	-	0.018	0.017	0.018	0.020	0.020	-	-	0.026	0.020
0.40	0.012	-	0.022	0.017	0.019	0.016	0.013	0.012	-	0.016	0.018	0.018	-	-	0.020	-	0.025	0.024	0.020	0.020
0.50	0.016	0.019	0.018	0.014	0.019	0.016	0.017	0.008	0.014	0.013	0.018	0.015	0.017	0.015	-	0.017	-	-	0.016	-
0.60	0.012	0.016	0.015	0.011	0.016	0.013	0.013	0.005	0.014	0.010	0.015	-	0.013	-	-	0.017	0.015	0.018	-	-
0.70	0.012	-	-	-	0.016	0.013	-	-	0.011	0.010	0.015	-	0.010	-	-	-	0.015	0.018	-	-
0.80	0.012	-	-	-	-	0.016	-	-	-	0.010	-	-	-	-	-	-	-	-	-	-
0.90	-	-	-	-	-	0.013	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table A1.2: Coarse Sand (CS) (Particle size diameter range: 0.5 to 1 mm, nominally 0.75 mm).

Matric head, m	Volumetric Water Content ($m^3\ m^{-3}$)																			
	Rep No.1	Rep No.2	Rep No.3	Rep No.4	Rep No.5	Rep No.6	Rep No.7	Rep No.8	Rep No.9	Rep No.10	Rep No.11	Rep No.12	Rep No.13	Rep No.14	Rep No.15	Rep No.16	Rep No.17	Rep No.18	Rep No.19	Rep No.20
0.0001	0.386	-	-	-	-	-	0.376	0.391	0.390	0.386	-	-	-	0.362	-	0.366	-	0.373	-	0.363
0.01	-	-	0.343	0.339	-	0.325	-	-	-	0.344	0.343	0.334	0.346	0.336	0.350	0.350	0.338	-	0.343	0.341
0.02	0.331	-	0.330	0.322	-	0.325	0.328	0.343	0.344	-	0.333	0.328	0.337	0.330	0.337	0.341	0.332	0.357	0.330	-
0.03	0.317	-	-	0.308	0.296	-	-	-	-	0.313	-	0.320	-	-	-	-	-	-	0.322	0.317
0.04	-	0.285	-	-	0.294	-	-	-	-	0.302	-	-	-	-	-	-	0.306	-	-	-
0.05	0.296	-	0.291	-	0.291	0.302	0.296	0.297	0.305	0.276	-	-	0.294	0.294	0.295	-	-	-	-	-
0.06	0.260	0.282	-	0.290	0.275	-	0.283	0.275	-	0.263	-	0.299	-	-	0.272	0.270	0.290	0.306	0.298	-
0.07	-	-	0.250	-	-	-	-	0.249	0.274	0.244	0.279	-	-	0.259	-	0.251	-	0.270	-	-
0.08	0.222	-	-	-	-	-	0.229	0.230	0.235	-	-	-	0.253	0.243	0.244	0.173	0.252	-	0.283	-
0.09	-	-	0.188	-	0.240	0.248	-	0.204	0.222	0.222	-	-	-	0.227	0.224	0.140	0.213	0.238	-	-
0.10	0.199	0.267	0.156	0.259	0.204	0.153	0.144	0.158	-	0.209	0.208	0.258	0.221	-	0.188	0.130	-	0.209	0.257	0.268
0.20	0.034	0.035	0.038	0.036	0.035	0.036	0.040	0.035	0.039	0.037	0.034	0.033	0.032	0.033	0.034	0.034	0.033	0.035	0.033	0.033
0.30	0.025	0.029	0.029	0.024	0.024	0.021	0.030	0.020	0.023	0.028	0.027	0.021	0.026	0.019	0.027	0.028	0.027	0.025	0.024	0.022
0.40	0.019	0.025	0.025	0.020	0.019	0.019	0.029	0.020	-	0.025	0.025	0.020	0.026	0.019	0.026	0.022	0.025	0.022	0.022	0.020
0.50	0.019	0.025	0.024	0.021	0.019	0.019	0.026	0.018	-	0.024	0.021	0.020	0.022	0.019	0.022	0.021	0.024	0.021	0.021	0.019
0.60	0.017	-	0.018	0.020	0.016	0.019	0.023	0.016	0.023	0.022	-	0.018	0.018	0.019	-	0.017	0.017	0.021	0.018	0.019
0.70	0.015	-	0.016	0.020	0.016	0.019	0.023	0.016	0.022	-	-	0.017	0.018	0.017	-	-	0.017	0.021	0.018	0.018
0.80	0.016	-	0.015	0.017	0.015	0.019	-	0.014	0.019	-	-	0.016	-	-	-	-	0.013	0.019	0.018	-
0.90	0.016	-	-	-	-	-	-	-	-	-	-	0.016	-	-	-	-	-	0.019	0.018	-
1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.019	0.015	-

Table A1.3: Medium sand (MS) (Particle size diameter range: 0.125 to 0.25 mm, nominally 0.19 mm).

Matric head, m	Volumetric Water Content ($m^3 m^{-3}$)																			
	Rep No.1	**Rep No.2**	**Rep No.3**	**Rep No.4**	**Rep No.5**	**Rep No.6**	**Rep No.7**	**Rep No.8**	**Rep No.9**	**Rep No.10**	**Rep No.11**	**Rep No.12**	**Rep No.13**	**Rep No.14**	**Rep No.15**	**Rep No.16**	**Rep No.17**	**Rep No.18**	**Rep No.19**	**Rep No.20**
0.0001	-	-	-	-	-	-	0.344	0.346	-	0.340	-	-	-	-	-	-	-	-	-	0.331
0.01	-	-	-	-	0.300	0.328	0.335	-	0.335	-	0.330	0.323	0.324	0.326	-	0.337	0.325	0.316	-	0.325
0.02	-	-	-	-	-	0.325	-	0.330	-	0.328	0.326	-	-	-	0.295	0.330	0.322	0.313	0.322	-
0.03	-	0.313	0.314	0.313	0.283	0.322	0.327	0.329	0.329	0.327	0.325	-	0.321	0.318	0.295	0.321	0.320	-	0.322	0.319
0.04	-	-	-	-	-	-	-	-	-	-	-	0.323	-	-	-	-	-	0.310	-	-
0.05	0.308	0.310	0.311	0.311	0.280	0.310	0.320	0.324	0.325	0.325	0.319	-	0.315	-	-	-	0.316	-	0.316	-
0.06	0.307	-	0.311	0.311	0.279	-	-	-	-	0.323	-	-	0.316	-	-	-	0.316	0.308	0.316	-
0.07	-	-	0.310	0.311	0.279	-	-	-	-	-	-	-	0.314	-	-	-	-	0.308	-	-
0.08	-	-	-	-	-	-	0.319	0.323	-	0.321	0.318	0.323	-	0.317	-	0.320	-	-	-	0.319
0.09	0.306	0.310	0.310	0.311	-	0.306	-	0.322	0.323	0.322	0.317	0.322	-	0.316	-	-	-	-	0.314	0.319
0.10	0.306	0.309	0.307	0.308	0.275	0.305	0.318	0.316	0.320	0.320	0.313	0.319	0.315	0.314	-	0.316	0.313	0.307	0.310	0.316
0.20	0.299	0.294	0.302	0.287	-	0.291	0.295	0.296	0.278	0.298	0.295	-	0.300	0.282	0.294	0.290	0.307	0.288	0.278	0.295
0.30	0.243	0.235	0.244	0.209	0.220	0.245	0.259	0.263	0.196	0.268	0.263	0.293	0.254	0.207	0.225	0.214	0.248	0.220	0.222	0.229
0.40	0.132	0.121	0.123	0.081	0.079	0.121	0.148	0.168	0.108	0.190	0.174	0.195	0.153	0.086	0.114	0.113	0.140	0.112	0.101	0.105
0.50	0.066	0.068	0.070	0.052	0.040	0.069	0.082	0.103	0.065	-	0.096	-	0.090	0.063	0.074	0.080	0.094	0.073	0.068	0.075
0.60	0.034	0.036	0.034	-	-	0.039	0.040	0.060	0.052	-	0.050	0.071	0.045	0.037	0.042	0.038	0.045	0.030	0.029	0.036
0.70	0.034	-	0.031	0.026	0.024	0.033	-	-	-	0.108	-	0.031	0.032	-	0.012	-	0.029	0.023	-	-
0.80	0.034	-	-	-	0.024	-	0.030	0.044	0.046	-	0.027	-	-	0.020	0.012	0.021	0.019	0.017	0.026	0.026
0.90	0.030	0.029	0.024	0.026	0.024	-	-	-	0.042	0.030	0.027	0.025	0.019	-	0.012	0.021	-	-	0.026	-
1.0	0.027	0.029	0.024	0.026	0.024	0.023	0.030	0.038	0.042	0.030	0.027	0.025	0.015	0.017	0.012	0.018	-	-	0.026	-
1.1	-	0.029	-	0.022	-	0.023	0.027	0.038	-	0.030	0.027	0.025	0.015	0.014	-	-	0.016	0.014	0.026	0.023
1.2	-	-	-	-	-	0.023	0.027	0.038	-	-	0.024	-	-	-	-	-	0.016	0.014	0.022	-

Table A1.4: Very Fine sand (VFS) (Particle size diameter range: 0.075 to 0.09 mm, nominally 0.08 mm).

Matric head, m	Volumetric water content (m^3 m^{-3})																			
	Rep No.1	**Rep No.2**	**Rep No.3**	**Rep No.4**	**Rep No.5**	**Rep No.6**	**Rep No.7**	**Rep No.8**	**Rep No.9**	**Rep No.10**	**Rep No.11**	**Rep No.12**	**Rep No.13**	**Rep No.14**	**Rep No.15**	**Rep No.16**	**Rep No.17**	**Rep No.18**	**Rep No.19**	**Rep No.20**
0.0001	0.409	0.410	-	0.427	0.417	-	-	0.415	0.411	-	-	-	-	0.415	0.418	-	-	-	0.426	-
0.01	0.409	0.410	0.418	0.414	0.418	-	-	0.409	0.408	-	0.406	-	-	0.409	0.412	-	0.406	-	0.423	-
0.02	-	-	0.411	-	-	-	-	0.406	-	-	0.403	-	-	-	0.412	-	0.399	-	-	-
0.03	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.386	0.398	-	-	0.394
0.04	-	-	-	-	-	-	-	-	-	-	0.403	-	-	-	-	0.384	-	-	-	-
0.05	-	-	-	-	-	-	-	-	-	0.371	-	-	-	-	-	0.377	-	0.3468	-	-
0.06	-	-	-	-	-	0.379	-	-	-	-	-	-	-	-	-	0.378	-	-	-	-
0.07	-	-	-	-	-	-	-	-	-	-	-	0.378	-	-	-	-	-	-	-	-
0.08	-	-	-	-	-	-	-	-	-	0.370	-	-	-	-	-	-	-	-	-	-
0.09	-	-	-	-	-	-	-	0.392	0.391	-	-	-	-	-	-	-	-	-	-	0.391
0.1	-	-	-	-	-	0.377	0.370	-	-	-	-	-	0.358	-	-	0.373	-	0.3451	-	-
0.2	-	-	-	-	-	0.374	0.370	-	0.384	-	0.385	0.382	0.358	-	-	0.369	-	-	-	-
0.3	-	-	-	-	-	0.371	0.367	-	-	0.357	0.379	-	0.358	-	-	0.369	-	-	-	-
0.4	-	-	0.381	-	-	0.371	0.367	-	-	-	0.379	-	0.358	0.362	-	-	0.372	-	-	0.378
0.5	-	-	-	0.370	-	0.367	0.367	0.376	0.374	-	0.379	-	0.355	-	0.378	0.369	0.372	-	-	-
0.6	-	-	-	0.363	0.364	-	0.363	-	-	-	-	-	-	-	0.378	-	-	0.3419	-	-
0.7	0.362	-	-	-	-	-	-	0.369	-	-	-	0.376	-	-	0.375	-	0.365	-	0.370	0.368
0.8	-	-	0.338	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.3321	-	-
0.9	-	-	-	0.347	0.355	-	-	0.353	-	-	-	0.349	-	-	-	0.343	0.342	-	-	0.338
1	-	-	-	0.331	-	-	-	-	-	-	-	0.336	0.338	0.346	-	-	0.329	0.3255	-	0.332
1.1	0.332	-	-	-	-	-	-	-	-	0.347	0.343	-	-	-	-	0.333	0.326	-	-	0.325
1.2	0.323	-	-	-	-	-	-	0.340	-	0.340	0.336	-	0.329	0.336	-	-	0.323	0.3124	-	0.319
1.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.75	-	-	0.279	0.247	0.324	0.352	-	0.272	0.349	0.262	0.278	0.314	0.257	-	0.346	-	-	-	0.301	0.297
2	0.285	0.337	-	-	-	0.332	0.341	-	0.341	-	-	-	-	0.304	-	0.333	-	0.2752	0.284	-
2.5	0.257	0.316	-	-	-	0.310	0.309	-	0.330	-	-	0.314	-	0.272	0.328	0.332	-	-	0.267	-
3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3.3	0.117	0.193	0.257	0.103	-	0.242	0.260	0.182	-	0.162	-	-	0.054	0.066	-	-	0.277	0.1696	-	0.248
4	0.065	0.172	0.253	-	-	0.231	0.227	0.148	0.322	-	0.252	-	-	0.054	0.315	-	-	0.0633	0.249	0.216
5	0.064	0.140	-	0.082	0.231	0.216	0.213	-	-	0.114	-	-	0.043	-	0.310	-	-	-	0.247	0.214
6	-	0.089	-	0.076	-	0.208	-	-	-	0.066	-	0.312	-	0.048	-	-	-	0.0188	-	-
7	-	0.082	-	-	0.235	-	-	0.074	-	0.033	0.261	-	0.034	0.051	-	-	0.274	0.0103	-	-

Table A1.5: Very fine sand (VFS) before (Chahal, 2010), now fine sand (FS), with nominal particle size diameter of 0.178 mm.

Matric head, m	Volumetric water content (m^3 m^{-3})																			
	Rep No.1	**Rep No.2**	**Rep No.3**	**Rep No.4**	**Rep No.5**	**Rep No.6**	**Rep No.7**	**Rep No.8**	**Rep No.9**	**Rep No.10**	**Rep No.11**	**Rep No.12**	**Rep No.13**	**Rep No.14**	**Rep No.15**	**Rep No.16**	**Rep No.17**	**Rep No.18**	**Rep No.19**	**Rep No.20**
0.04	-	-	0.379	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.05	-	-	-	-	-	-	-	-	-	-	-	0.395	-	0.406	-	-	-	-	-	-
0.06	0.387	0.383	0.377	-	-	0.404	0.389	-	-	-	-	0.392	-	0.403	-	0.403	-	-	-	-
0.07	0.384	0.381	-	-	-	0.402	0.390	-	0.399	0.388	-	-	-	0.401	-	-	-	-	0.411	-
0.08	-	-	0.374	-	-	0.399	0.387	-	-	0.385	-	0.390	-	-	-	0.401	-	-	0.411	-
0.09	-	-	-	-	-	-	-	-	-	-	-	-	0.410	-	0.405	-	-	0.397	-	-
0.1	-	-	-	-	0.381	0.399	0.391	-	0.397	-	0.387	0.390	0.403	0.398	-	0.398	0.399	-	0.411	0.405
0.2	0.378	0.378	0.371	0.402	0.381	0.389	-	0.384	0.390	0.385	0.387	-	0.407	0.395	0.392	0.395	0.386	0.397	0.411	0.395
0.3	-	-	-	-	0.377	0.382	-	0.378	0.383	-	0.377	0.383	0.397	0.395	-	-	0.376	0.387	0.398	0.385
0.4	0.368	0.375	0.361	0.399	0.371	0.376	0.377	0.381	0.373	0.372	0.377	0.380	0.390	0.388	0.385	0.381	0.373	0.384	0.392	0.385
0.5	-	0.355	0.358	0.376	-	0.363	0.367	0.378	-	0.369	0.367	0.370	0.367	0.375	0.366	0.375	0.369	0.381	0.372	0.372
0.6	0.328	0.322	0.331	0.333	0.341	0.313	0.338	0.338	0.330	0.346	0.337	0.334	0.317	0.328	0.336	0.322	0.323	0.325	0.312	0.322
0.7	0.292	0.279	0.298	0.280	0.291	0.267	0.285	0.282	0.281	0.293	0.291	0.268	0.258	0.269	-	0.272	0.270	0.262	0.246	0.263
0.8	0.223	0.193	0.203	0.197	0.212	0.194	0.205	0.206	0.202	0.210	-	0.178	-	0.190	0.270	0.190	0.201	0.176	0.193	0.180
0.9	0.176	0.153	0.163	0.164	0.163	0.151	0.159	0.160	0.172	0.174	0.188	0.142	-	-	-	-	0.178	0.136	-	-
1	0.147	0.130	0.126	-	0.136	-	0.133	0.133	0.132	0.147	0.175	-	-	0.150	-	-	-	0.120	0.140	-
1.1	0.117	-	-	0.111	0.110	-	0.106	0.110	-	0.121	-	0.125	0.155	-	0.127	0.120	-	0.106	0.121	0.144
1.2	-	-	0.107	0.105	0.100	0.115	-	0.097	-	0.111	-	-	0.145	-	-	-	-	-	0.111	-
1.5	0.101	0.098	0.093	-	-	0.095	-	-	0.099	0.101	-	0.106	0.123	0.102	0.103	0.097	0.108	-	-	-
2	0.085	0.080	0.083	0.088	0.084	0.077	0.080	0.082	0.081	0.085	-	0.089	0.084	0.076	0.080	-	0.080	0.079	0.054	0.092
3.3	0.081	0.070	-	0.068	0.072	-	0.075	0.080	0.068	0.075	0.084	0.077	0.071	-	0.072	0.070	0.065	0.075	0.025	0.069
4	-	-	-	0.066	-	-	-	-	-	-	-	-	0.066	-	-	-	0.069	0.070	-	-
5	-	0.062	0.070	0.062	0.063	0.061	0.064	0.064	0.060	0.069	0.079	0.064	0.063	0.064	-	0.061	-	0.064	0.016	0.069

Table A1.6: Sandy loam (SL) *(Almond orchard soil),* with nominal particle size diameter of 0.048 mm.

Matric head, m	Volumetric water content ($m^3\ m^{-3}$)																			
	Rep No.1	**Rep No.2**	**Rep No.3**	**Rep No.4**	**Rep No.5**	**Rep No.6**	**Rep No.7**	**Rep No.8**	**Rep No.9**	**Rep No.10**	**Rep No.11**	**Rep No.12**	**Rep No.13**	**Rep No.14**	**Rep No.15**	**Rep No.16**	**Rep No.17**	**Rep No.18**	**Rep No.19**	**Rep No.20**
0.0001	0.502	0.527	0.529	0.510	0.483	0.531	0.514	0.498	0.477	0.493	0.454	0.485	0.527	0.476	0.468	0.480	0.430	0.410	0.470	0.467
0.5	0.353	0.367	0.385	0.354	0.342	0.376	0.373	0.338	0.346	0.364	0.362	0.359	0.359	0.355	0.362	0.352	0.343	0.336	0.348	-
1	-	0.334	0.348	0.323	0.311	0.332	0.335	0.300	0.323	0.360	-	0.326	0.321	0.331	0.325	0.323	-	0.308	0.320	0.353
3.3	0.267	0.233	-	0.231	-	-	0.211	0.208	0.271	-	0.277	0.212	0.254	0.252	0.236	0.204	0.288	0.188	0.204	-
4	-	0.215	0.220	0.212	0.219	0.213	-	0.195	0.239	0.293	0.239	-	0.233	-	0.217	-	0.263	-	0.187	0.258
5	0.214	-	-	0.180	0.191	0.188	-	0.170	0.196	-	-	-	0.213	0.217	-	0.173	-	-	-	0.243
6	0.170	0.186	0.182	0.175	0.167	0.168	0.170	0.150	0.168	0.224	0.189	0.167	-	0.180	0.178	0.166	0.206	0.157	0.161	0.213
7	-	-	-	-	0.147	-	0.161	-	0.158	0.201	0.182	-	0.167	-	-	-	-	0.148	0.152	0.199
8	0.154	-	0.168	-	-	-	0.158	-	-	0.186	-	0.155	0.167	0.153	-	0.152	0.179	0.140	0.147	0.176
9	0.154	0.168	0.168	0.160	0.146	0.164	-	0.127	0.147	0.181	0.173	0.155	0.167	0.148	0.146	0.153	0.170	0.136	0.144	0.170

Appendix 2

Analysis of variance (ANOVA) output for data collected on shoot dry biomass produced by Kukri and Excalibur wheat genotypes that grew at matric suctions predicted from the wet, inflection point and dry end of WRCs, developed for soils.

Table A2.1: Estimates of standard error (e.s.e), standard error of differences (s.e.d) and least significant differences used for comparing mean shoot dry biomass data collected on Kukri and Excalibur wheat genotypes.

Source of variation	Degree of freedom	Replication	*e.s.e, g	*s.e.d, g	$l.s.d_{0.05}$
Soil texture	138	30	0.043	0.061	0.120
Wheat genotype	138	90	0.025	0.035	0.069
Matric suction	138	60	0.030	0.043	0.085
Soil texture × wheat genotype	138	15	0.061	0.086	0.170
Soil texture × matric suction	138	10	0.075	0.105	0.208
Wheat genotype × matric suction	138	30	0.043	0.061	0.120
Soil texture × wheat genotype × matric suction	138	15	0.105	0.149	0.295

Coefficient of variation (CV %) = 34.1

**Errors are averages.*

Highlighted information on table was those used in the text of the thesis specifically, for chapter five in figures 5.4, 5.5, and 5.6.

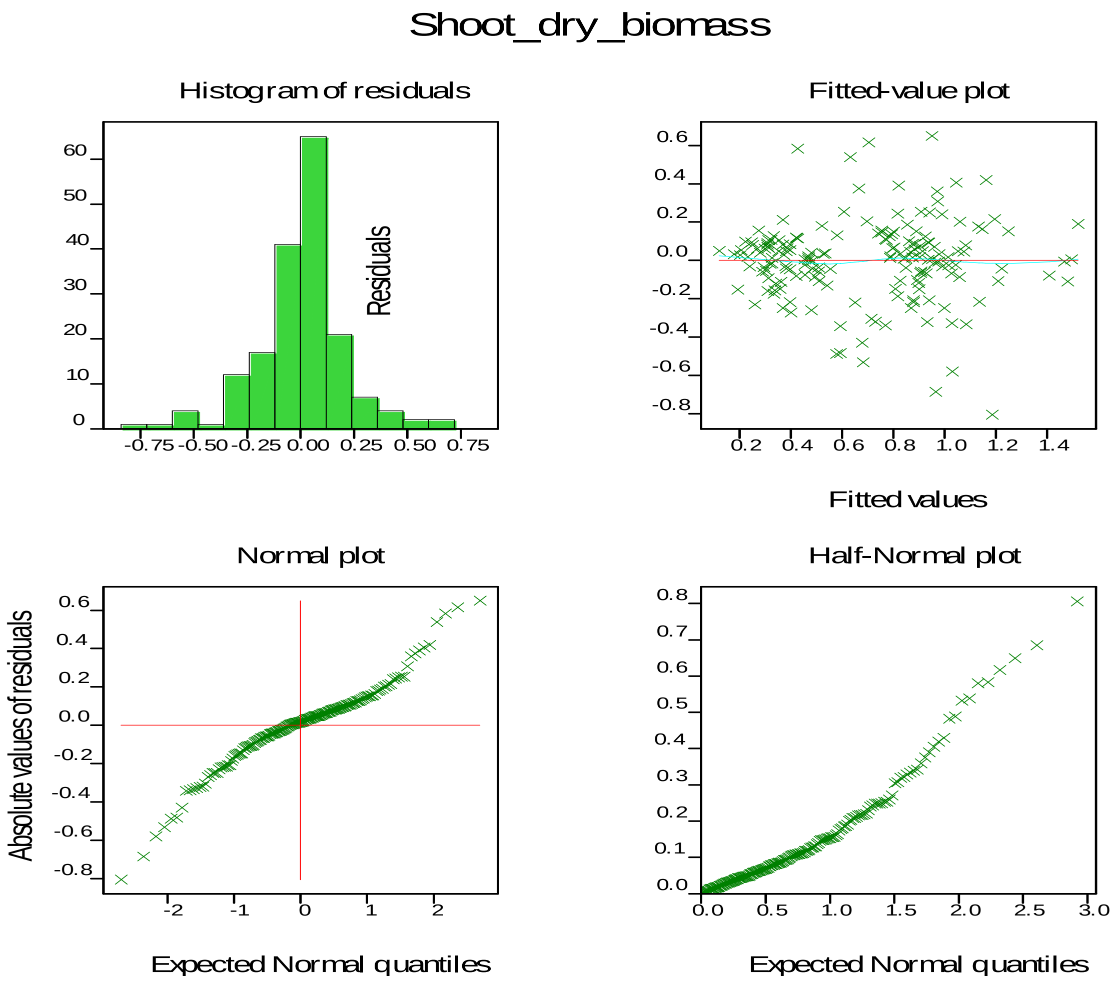

Figure A2.1: Histogram of residuals, fitted value plot, normal plot and half-normal plot used to check assumptions of analysis of variance for shoot dry biomass data collected for Kukri and Excalibur wheat genotypes that grew at the wet, inflection point, and dry end of WRC's developed for soils.

Appendix 3

Analysis of variance (ANOVA) output for data collected on root dry biomass produced by Kukri and Excalibur wheat genotypes that grew at matric suctions predicted from the wet, inflection point and dry end of WRCs, developed for soils.

Table A3.1: Estimates of standard error (e.s.e), standard error of differences (s.e.d) and least significant differences used for comparing mean root dry biomass data collected on Kukri and Excalibur wheat genotypes.

Source of variation	Degree of freedom	Replication	*e.s.e, g	*s.e.d, g	$l.s.d_{0.05}$
Soil texture	138	30	0.030	0.042	0.083
Wheat genotype	138	90	0.017	0.024	0.048
Matric suction	138	60	0.021	0.030	0.058
Soil texture × wheat genotype	138	15	0.042	0.059	0.117
Soil texture × matric suction	138	10	0.051	0.072	0.143
Wheat genotype × matric suction	138	30	0.030	0.042	0.083
Soil texture x wheat genotype × matric suction	138	15	0.072	0.102	0.202

Coefficient of variation (CV %) = 51.30
**Errors are averages.*

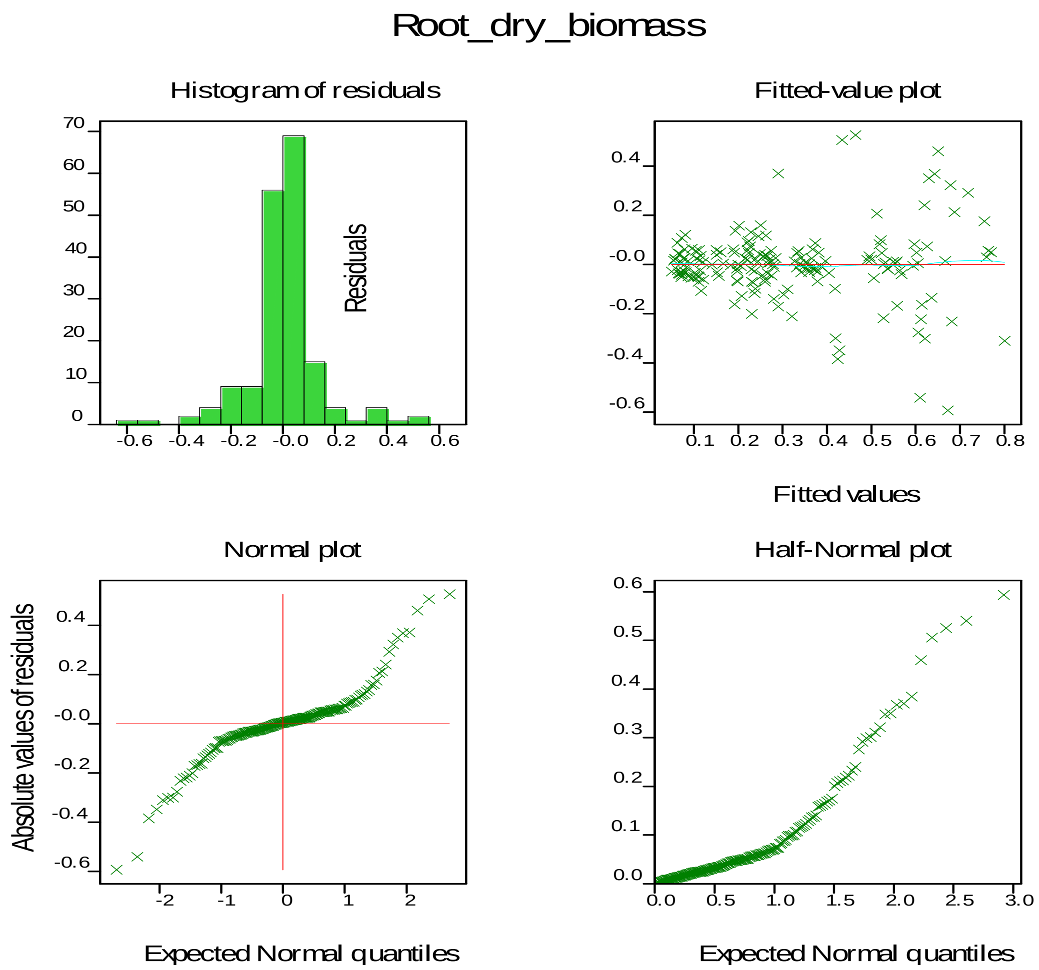

Figure A3.1: Histogram of residuals, fitted value plot, normal plot and half-normal plot used to check assumptions of analysis of variance for root dry biomass data collected for Kukri and Excalibur wheat genotypes that grew at the wet, inflection point, and dry end of WRC's developed for soil.