University of Southern Queensland

Faculty of Engineering and Surveying

Evaluating the Potential to Impose Partial Root Zone Drying (PRD) on Clay Soils in Commercial Cotton Production Systems

A dissertation submitted by

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in fulfilment of the requirements of

Courses ENG4111 and 4112 Research Project

towards the degree of

Bachelor of Engineering (Agricultural)

Submitted: October, 2004

Abstract

This project investigated the ability to create effective partial root zone deficits for cotton on cracking clay soils. The project involved parameterising and validating the model by comparing simulated with measured results obtained from a partial root zone drying field trial. After validation, the model was used to simulate soil-water movement associated with the range of different irrigation frequencies and water volumes that could be applied commercially using low energy precision application nozzles fitted to centre pivots and lateral move machines.

From the validation, the predictive accuracy of the model simulation was found to progressively decrease from 69% to 64% and then 39% for increasing simulated growth periods of 17, 26 and 63 days. The simulated soil moisture content in the surface layers immediately under the plant row were found to be generally lower than the measured soil moisture in the field possibly due to difficulties in appropriately parameterising the root extraction pattern. Similarly, the simulated soil moisture at profile depths greater than 100 cm were slightly under-predicted presumably due to parameterisation errors in the soil hydraulic properties for this layer. Based on the requirement for a soil water gradient of at least 100 kPa, none of the irrigation strategies simulated on the soil produced a soil moisture potential gradient large enough to induce partial root zone drying effects without causing deficit irrigation.

A second investigation collected soil data for use in the model, however the model would not run using this data. The results of this project suggest that it may be difficult to implement PRD strategies on cracking clay soils for commercial cotton production. However further work is required to confirm the simulated soil-water movement under field conditions and to assess the impact of other local environmental conditions (eg. rainfall) on the potential to induce PRD responses.

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Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Student Number: 0011121697

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Signature

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Date

Acknowledgements

Throughout the course of this project, I have been fortunate to receive the assistance of many people. My thanks goes to all of these, however I would like to make special recognition of the following people for their support and willingness to share their invaluable knowledge and skills:

- All staff of the National Centre of Engineering in Agriculture (NCEA), The University of Southern Queensland (USQ), Toowoomba

- Mr Joseph Foley (Lecturer, USQ)

- Mr Simon White (PhD student, NCEA) for assistance with field work, providing me with lots to think about and for answering my endless questions.

- Associate Professor Steven Raine (Project Supervisor, NCEA) for his never-ending support and technical guidance.

- Cassie Deans, Renae Williams and everyone from G-Block (McGregor College, USQ) for continually picking up all the pieces and making me keep going.

My final thanks must go to the National Centre for Engineering in Agriculture and the Cooperative Research Centre for Irrigation Futures for providing me with the opportunity to undertake this project.

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1. Introduction

The aim of this project is to investigate the potential to impose partial root zone drying conditions on cracking clay soils used for commercial cotton production.

The cotton industry is a vital part of Australia's economy, selling $1.5 billion worth of exports annually. Approximately 400, 000 hectares of cotton, or approximately 80 to 90% of the land planted to cotton, is irrigated annually. This obviously consumes a large amount of water, extracting 1.5 million megalitres of water from the Murray Darling Basin alone. To ensure the long-term sustainability of Australia's water resources and farming land, smarter irrigation practices must be employed by many farmers. This can be quantified by increases in water use efficiency (the amount of cotton that can be produced per megalitre of water). Increases in water use efficiencies mean that farmers require less water to obtain their current yields. The extra water can then be traded, used to irrigate more land or returned to the river systems to maintain environmental flows.

Numerous field trials and industry adoption has proven that partial root zone drying (PRD) is an effective method of improving water use efficiencies for grape and citrus production in South Australia. The challenge is now to see if PRD can be expanded to cotton and other crops. Field trials are currently under way in south-east Queensland to investigate the possibility of improving water use efficiencies of cotton on cracking clay soils using PRD irrigation strategies.

The success of PRD is based on maintaining alternate regions of wet and dry soil within the crop root zone. The simple approach of watering alternate sides of the plant induces the plant to set up a hormonal/chemical response that increases crop water use efficiency. A key component of the success of PRD strategies is the magnitude and timing of the alternation of the water depletion within the crop root zone.

While recent research has indicated that cotton may respond to PRD under certain conditions, the potential to apply the necessary soil moisture stresses to alternate sides of the plant under commercial conditions is a function of both the soil textural and structural properties and the irrigation regime imposed. Unfortunately on heavy cracking clay soils, anecdotal evidence suggests that substantial lateral movement of water via crack fill can be expected when applying deficit irrigation strategies. Similarly, where one side of the plant is kept moist by frequent irrigation, it is likely that there will also be substantial lateral soil-water movement reducing the stress gradient imposed across the plant line, and therefore hindering the effects of PRD.

This project used a soil water movement model, HYDRUS-2D, to investigate the potential to impose partial root zone drying (PRD) conditions on cracking clay soils used for commercial cotton production. It involved of two investigations, each validating HYDRUS-2D and applying a broad range of irrigation schedules.

For the preliminary investigations, model parameterisation data was obtained from appropriate research literature (both published and unpublished). In order to validate HYDRUS-2D, soil moisture content and climatic measurements were required. By using data obtained from a PRD field trial on commercial cotton, the model was validated for the relevant soil type, irrigation application method and crop species.

Once the model and combination of soil type, irrigation method and plant species were validated, the investigations began. By applying a broad range of irrigation frequencies and volumes to the validated soil, soil water potential values throughout the profile were found with time. From these values (chosen spatially either side of the plant root system), the soil water potential differences across the plant roots were calculated over time. From these values of soil water potential difference, the irrigation scheduling practices that created substantial gradients were identified.

A second investigation into the ability to impose PRD on cracking clay soils under cotton production was undertaken. This investigation undertook field and laboratory tests on the soil at the validation site to determine the parameters required for HYDRUS-2D.

2. Literature Review

With the increasing pressures being placed upon the nation's water resources, the adoption of water saving techniques and improvements in water use efficiency are essential for the long-term sustainability of the irrigation industry and Australia's fresh water supplies. Partial root zone drying is a relatively new irrigation technique, but one that has produced significant increases in water use efficiency throughout numerous field trials and commercial applications. The ability to impose partial root zone drying conditions on the cracking clay soils typical of commercial cotton production is yet to be determined. Field trials are currently under way, however investigation using an appropriate soil water movement model will allow for a greater range of scenarios (water application volumes and timing) to be considered.

In completing such a project, the objectives are therefore:

1. To validate an appropriate soil water movement model to investigate the potential to impose partial root zone drying conditions on cracking clay soils.

2. To identify and evaluate whether partial root zone drying conditions can be produced on cracking clay soils using irrigation strategies that can be applied to commercial cotton production systems.

3. To provide recommendations regarding the ability to impose partial root zone drying conditions on cracking clay soils used for commercial cotton production.

2.1. Partial Root Zone Drying (PRD)

Partial root zone drying is the practice of applying water to only one side of the plant root mass in order to create a 'wet' and 'dry' side of the plant, as shown in Figure 2.1. The 'dry' side of the plant then induces a hormonal response that limits plant water use. During periods of water deficiency, plants show a reduction in plant growth and stomatal conductance (ie the stomatal aperture is reduced) (Hartung et al. 2002; Kang et al. 2000; Stikic et al. 2003; Wilkinson & Davies 2002). When exploited via PRD irrigation techniques, the irrigated and non-irrigated ('wet' and 'dry') sides of the plant must be alternated to maintain the plant hormonal responses. PRD trials have found that these hormonal responses reduce excessive vegetative growth and significantly increase water use efficiencies by using less water to produce similar yields (Gu et al. 2000; Kriedemann & Goodwin 2003; ' Less Water, More Grapes, Better Quality' 1997; *New irrigation method could halve agricultural water consumption* 2002; Wiley 1997).

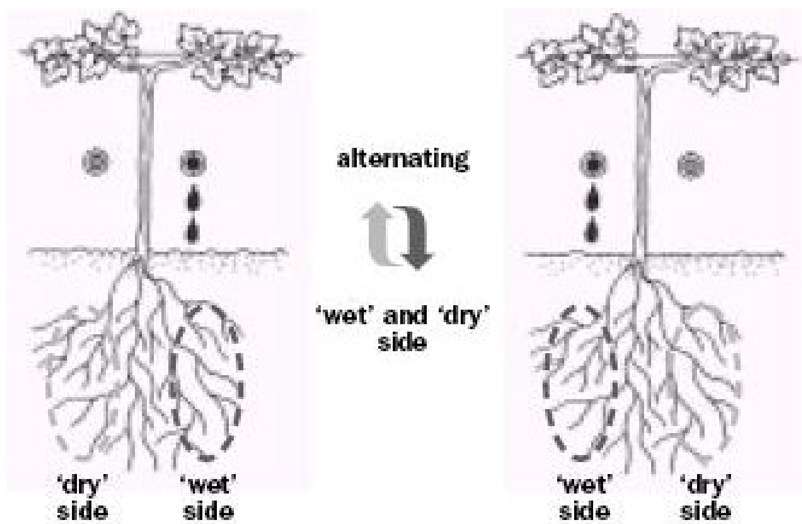

Figure 2.1. Physical overview of PRD

(Kriedemann & Goodwin 2003, Figure 12)

2.1.1. How PRD Works

The reduction in stomatal conductance during periods of water deficiency is thought to be due to many different and sometimes interdependent factors, including both hydraulic and chemical signalling (Comstock 2002; Garcia-Mata & Lamattina 2003; Hare et al. 1997; McCarthy et al. 2001; Wilkinson & Davies 2002). Whilst contradicted by some researchers (Hare et al. 1997; Hartung et al. 1998; S.Q. Zhang et al. 2001), extensive research indicates that these reductions in stomatal aperture are primarily due to chemical signalling of abscisic acid (ABA) travelling from the roots to the shoots (Comstock 2002; McCarthy et al. 2001; Wilkinson & Davies 2002; S.Q. Zhang et al. 2001).

As soil dries out, the associated plant roots synthesise more ABA (Comstock 2002; Hartung et al. 2002; Seo & Koshiba 2002; Wilkinson & Davies 2002; Zhang & Davies 1990, cited in S.Q. Zhang et al. 2001). The ABA then enters the xylem sap and travels from the plant roots up to its shoots (Comstock 2002; Hartung et al. 2002; Jones 1980, cited in Stikic et al. 2003; Zhang & Davies 1990, cited in S.Q. Zhang et al. 2001). The increased concentration of ABA in the xylem increases the ABA content in the guard cells of the leaves (S.Q. Zhang et al. 2001). This in turn reduces guard cell and leaf turgor, which closes the leaf stomata (Assmann 1993, cited in Hartung et al. 1998; Raschke 1987, cited in Henson & Turner 1991; McCourt 2002?). Closure of the leaf stomata reduces leaf transpiration and photosynthesis by reducing the flow of water vapour and carbon dioxide into the leaf (McCarthy et al. 2001). This can result in significant decreases in crop water use because transpiration and photosynthesis accounts for over 95% of plant water use (Comstock 2002).

Whilst not proving the cause and effect aspects of this chain of events leading from soil drying to stomatal closure, many experiments have been conducted that affirm the existence of relationships (causal or otherwise) between various parts of the chain. In summarising these events, studies by Tardieu (1996, cited in Lacape et al. 1998) found relationships between soil water potential, xylem ABA content and stomatal conductance.

The closure of stomata with increasing soil water deficits has been confirmed many times (Hartung et al. 2002; Kang et al. 2000; Torrecillas et al. 2000; S.Q. Zhang et al. 2001). Experiments conducted by Hartung, Sauter and Hose (2002) and S.Q. Zhang, Outlaw and Aghoram (2001) showed that this occurred whilst leaf water potential was still unaffected, therefore suggesting that the signal was root-based. In the experiments by S.Q. Zhang et al. (2001), root ABA content increased as the soil water deficit was induced. The maximum root ABA content, maximum guard cell

ABA content and minimum leaf conductance of water deficit plants all occurred at approximately the same point in time. Throughout the experiment it was found that 'leaf conductance was inversely proportional to guard cell ABA content' (S.Q. Zhang et al. 2001). This experiment did however, only show a weak relationship between estimated delivery rate of ABA to the leaflet and guard cell ABA content. This suggests that root ABA is only one source of guard cell ABA. Other sources of ABA include that synthesised by plant leaves and by the guard cells themselves. Once leaf water potential reduces, and after significant lag times following soil drying, leaf biosynthesis of ABA occurs (Hartung et al. 1998; S.Q. Zhang et al. 2001), which may play a role in the accumulation of ABA in the guard cells.

The increase in ABA synthesis and the contents present in roots and the xylem sap during soil drying are well reported and accepted (Seo & Koshiba 2002). For example studies by Shashidar et al. (1996, cited in Hare et al. 1997) found that moderate soil drying caused increases in xylem ABA concentration and delivery rate in sunflowers. Experiments conducted by Tardieu et al. (1993, cited in S.Q. Zhang et al. 2001) and Henson and Turner (1991) then found that experimental increases in xylem sap ABA concentration resulted in decreased stomatal conductance. In experimental work conducted by S.Q. Zhang and Outlaw (2001), as soil water potential dropped, guard cell ABA concentration and whole leaf ABA concentration increased and leaf conductance decreased.

The existence of increased ABA levels and decreased stomatal conductance in plants experiencing partial root zone drying was confirmed in a PRD field trail on grapevines (Stoll et al. 2000). During this trial it was found that, compared to well-watered control plants, plants experiencing PRD had a significant increase in the ABA concentration of the xylem sap and a 23% decrease in stomatal conductance. Other PRD trials (Loveys et al. 2000, cited in Stoll et al. 2000) found a ten to forty fold increase in the ABA concentration of the drying roots.

The PRD trial on grapevines (Stoll et al. 2000) also measured reduced levels of cytokinin in the plant roots, shoot tips and buds. This reduction is consistent with findings on numerous trials involving water deprived sunflowers (Hare et al. 1997).

Along with ABA, cytokinins are considered by many researchers to be one of the most important plant hormones in the root to shoot signalling processes (Hare et al. 1997). Cytokinins are growth promoting hormones and therefore work against ABA in its efforts to induce dormancy (restrict vegetative growth) and decrease stomatal conductance (Hare et al. 1997; Postlethwait & Hopson 1995; Wilkinson & Davies 2002). In cotton, cytokinins in the xylem sap have been shown to decrease the sensitivity of stomata to xylem ABA (Radin et al. 1982, cited in Wilkinson & Davies 2002). Consequently, when attempting to induce a partial root zone drying response in cotton, a decrease in cytokinins in the xylem sap would magnify the effect of increased levels of xylem ABA on stomatal conductance.

Stomatal sensitivity to xylem ABA can be effected by many other things (J. Zhang et al. 1997), including leaf water potential (J. Zhang et al. 1997; S.Q. Zhang et al. 2001). Xylem sap pH also has an effect on stomatal closure (Jackson 2002). An increase in pH in the transpiration stream increases the sensitivity of leaf stomata to ABA (Wilkinson & Davies 2002; J. Zhang et al. 1997). Some experimental results have shown an increase in xylem pH as soil dries (J. Zhang et al. 1997), including a trial of PRD on grapevines (Stoll et al. 2000).

Ethylene, salicylic acid and methyl jasmonates are other plant hormones that are known to interact during plant water deprivation and stomatal closure (Hare et al. 1997; Suhita et al. 2003). For example, ABA is known to be an inhibitor of ethylene production (Sharp & LeNoble 2002) and ethylene production due to cytokinin actions appear to be of particular importance during periods of plant water stress (Hare et al. 1997). Jackson (2002) also lists auxins and gibberellins as being important hormones involved in root to shoot signalling. As well as these plant hormones, root to shoot signalling is effected by inorganic materials (eg hydrogen ions, nitrates and calcium), mainstream metabolites (eg ethanol) and water and solutes situated outside of the plant roots (Jackson 2002). Nitric oxide is another component of ABA induced stomatal closure, known to affect stomatal closure and interact with the ABA signalling pathways (Garcia-Mata & Lamattina 2003).

The effect of PRD on cotton development is of some concern. Research by Gokani and Thaker (2001) suggests that ABA plays an inhibitory role in boll development, although its effects on fibre length were undetermined. It has also been suggested that fibre strength may be reduced by increases in the ABA content of cotton fibres during the secondary thickening phase (Timpa et al. 1991, cited in Gokani & Thaker 2001).

The closure of the stomata and the increased presence of ABA in the shoots, combined with the decreased amounts of cytokinins, reduces excessive vegetative growth (Hartung et al. 2002; Seo & Koshiba 2002; Wilkinson & Davies 2002) and encourages fruiting (*New irrigation method could halve agricultural water consumption* 2002). This could be due to the impacts of ABA and cytokinins on ethylene production. Increased ABA (Sharp & LeNoble 2002) and decreased cytokinins (Hare et al. 1997) both act to decrease ethylene production. Ethylene is a growth promoting hormone in young seedlings (Sharp & LeNoble 2002), therefore a reduction in ethylene would result in restriction of vegetative growth.

A reduction in excessive vegetative growth is advantageous because it enhances the availability of excess plant sugars and nutrients required for fruit set and development (*New irrigation method could halve agricultural water consumption* 2002; Stikic et al. 2003). Less vegetative matter also results in less water being required to sustain the crop, less opportunity for pest and disease and increased expose of the fruits to light (Kang et al. 2000; ' Less Water, More Grapes, Better Quality' 1997; Wiley 1997). The increase in the amount of light exposed to the fruits results in decreased season lengths, which decreases the potential for negative impacts on fruit quantity or quality due to adverse weather or pest infestations. A PRD trial on grapevines at Hanwood, in the Murrumbidgee Irrigation Area of New South Wales, found that the grapevines under the PRD irrigation regime produced grapes that were ready for harvest one week before the control grapevines (Kriedemann & Goodwin 2003). A PRD trial in Turkey produced cotton that was ready for harvest two weeks before that growing on the control plants (*New irrigation method could halve agricultural water consumption* 2002).

Typically, stomatal closure and ABA increases are associated with decreases in plant tissue water content, which infers a detrimental plant stress due to water deficiency. In PRD however, the plant does not become stressed because of the plentiful supply of water on the irrigated side of the plant. In PRD, the plant therefore saves water by implementing 'drought techniques' (reducing stomatal aperture), however it doesn't experience the detrimental side effects of a drought.

Unfortunately, if the same side of the plant is kept dry for extended periods of time, it no longer continues its biosynthesis of ABA, therefore the stomata re-opens and the plant reverts back to its normal water consumption (Hare et al. 1997; Hartung et al. 2002; Wilkinson & Davies 2002). By alternating the wet and dry sides of the plant, it was found that the production of ABA continued (McCarthy et al. 2001). The amount of time between these alternations is dependant on environmental conditions, soil type, plant species and other site-specific details. Values for grapevines have ranged from about 3-5 days (Kriedemann & Goodwin 2003) up to approximately three weeks (*New irrigation method could halve agricultural water consumption* 2002).

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2.1.2. In-Field Application of PRD

Successful application of PRD requires appropriate selection of an irrigation method and soil type. To accurately determine whether or not gradients are being achieved and to schedule irrigation volumes and timings requires soil moisture monitoring equipment (Currey 2003; Kriedemann & Goodwin 2003; McCarthy et al. 2001).

Precise application of the irrigation water is essential to ensure that 'wet' and 'dry' sides of the plant can be developed. This eliminates the use of sprinklers for partial root zone drying. Previous trials have used surface and sub-surface drip emitters, furrow irrigation and hand watering. The second requirement of a suitable application method is its ability to apply small volumes of water accurately and uniformly. This is especially important on deep clay soils with a large potential for lateral soil water movement. These soils not only require small application volumes to limit lateral movement, but they are less satisfactory for partial root zone drying (Kriedemann & Goodwin 2003) and therefore have a smaller margin for error.

Whilst some overseas trials have investigated partial root zone drying using furrow irrigation, on the soils and furrow set-ups typically used for growing cotton in Australia it is believed that furrow irrigation would not meet the second requirement of a suitable irrigation method. The cotton industry is typically associated with long furrow lengths that require large volumes of water to be applied. These large volumes generate substantial soil water pressure head gradients, causing significant lateral soil water movement on the cracking clay soils. Normally this application method also results in non-uniformities due to the beginning of the furrow being exposed to more water and water ponding at any furrow dykes.

One irrigation method potentially suitable to apply partial root zone drying within the Australia cotton industry is the use of centre pivot and lateral move machines fitted with low energy precision application (LEPA) equipment. Centre pivot and lateral move irrigators are essentially large, moving machines fitted with multiple sprinklers. This allows for the application of small, reasonably accurate irrigation quantities. By fitting the irrigators with LEPA equipment the water is directed down onto the soil between the plants as a stream, rather than as an encompassing spray.

Unfortunately adoption of centre pivot and lateral move irrigation machines is still considerably low within the Australia cotton industry. Studies conducted in 2001 indicate that only approximately 4 % of the average area under cotton is irrigated using these machines (Foley & Raine 2001). This means that adoption of partial root zone drying would involve a change in irrigation practises and considerable cost for most cotton farmers. If partial root drying of cotton is achievable, a mechanism would need to be developed and fitted to the irrigation machines to ‘turn-off’ every second LEPA tube. In order to alternate the wet and dry sides, the mechanism would need to capable of swapping those water outlets turned on and off.

A PRD field trial in the Langhorne Creek district of south-east South Australia showed a large range of results due to the variations in soil type and grapevine species. It was found that the soil type had a profound effect on the water use efficiencies of the grapevines and on the effect of the PRD techniques. As the infiltration rate of the soil increased, so too did the water use efficiency of the PRD grapevines in comparison to the well-watered grapevines (Kriedemann & Goodwin 2003). On the soils with low infiltration rates (predominantly clay soils) the changes in the water use efficiencies of the PRD grapevines (in comparison to the well-watered grapevines) were low (increases of 21% and10%, and a decrease of 13%) (Kriedemann & Goodwin 2003).

2.1.3. Results from PRD Trials

Numerous field trials and industry adoption has proven that PRD is an effective method of improving water use efficiency for various industries internationally. In Australia, the notable areas of implementation have been to grape and citrus production in southern areas. The challenge is now to see what other crops and soil types this irrigation practise can successfully be expanded to.

Partial root zone drying trials on grapevines have shown positive results. The general results show no, or limited, yield decreases, reduced vegetative growth, no change or higher fruit quality and significantly lower water use efficiencies (Gu et al. 2000; Kriedemann & Goodwin 2003; ' Less Water, More Grapes, Better Quality' 1997; Wiley 1997). Over three seasons, trials in southern Australia found that the fruit from the grapevines under PRD irrigation treatments had better wine making qualities; higher titratable acidity, lower pH and greater concentrations of colour, phenols and glycosyl-glucose (Wiley 1997).

Trials over two seasons on Riesling around Waikerie in South Australia resulted in an approximately 85% increase in water use efficiency on the vines under partial root zone drying (Dry et al. 2001, cited in Kriedemann & Goodwin 2003). Mixed results were received from a PRD field trial on Shiraz in the Sunraysia region of north-west Victoria. Over four seasons, the increases in water use efficiency for the grapevines under PRD irrigation treatments were 58%, 65%, 33% and 58% (Kriedemann &

Goodwin 2003). Irregardless of the variation, all four seasons still resulted in significant increases in water use efficiency.

Extensive PRD trials have been completed on tomatoes at the University of Lancaster, as well as some comprehensive trials in India. These results were very similar to those found in grapevines; namely reduced plant growth, limited yield losses, increased sugar contents and increased water use efficiencies (Stikic et al. 2003). Some of the work at the University of Lancaster involved physically separating the plant roots (ie putting half into a plastic bag and the other half into another plastic bag) to ensure that two distinct wet and dry sides of the plant could be established in the experiments. These experiments showed significant reductions in vegetative growth; a 26% reduction in plant height, 10% reduction in the number of leaves per plant, a 22% reduction in the leaf area and a reduction in the shoot and root dry weight (29% and 23% respectively). The fruit sugars increased by 13% in the PRD tomatoes, however there were no significant changes in the fruit dry weight, lycopene or total minerals. The water savings resulted in a 59% increase in water use efficiencies of the plants that underwent the PRD treatments.

PRD techniques have also shown potential on citrus crops, pears and stone fruit in the Riverlands of South Australia. Successful trials with pears have also been conducted in Hong Kong (Kang et al. 2003). Red raspberries have also been sucessfully grown using PRD strategies in both Scotland (Stoll et al. 2002) and the United Kingdom (Grant et al. 2004; *New irrigation method could halve agricultural water consumption* 2002). The European Union have formed a consortium named IRRISPLIT to investigate the effects of PRD on a range of crops around the Mediterranean. These crops include olives, tomatoes, citrus fruits and cotton. (*New irrigation method could halve agricultural water consumption* 2002).

It has been attempted to create partial root zone drying in furrow irrigated cotton in both north Africa (Kriedemann & Goodwin 2003) and in the Cukurova region of Turkey (*New irrigation method could halve agricultural water consumption* 2002). Whilst the work completed by the Cukurova University alternates the side of the plant on which the irrigations are applied (by either furrow or drip irrigation), only half of the water is applied to these plants in comparison to the fully watered control plants (Topcu et al. 2002). This means that the 'wet' side of the plants may not have been moist enough, and therefore the plants may have benefited from deficit irrigation effects. Water use efficiencies of approximately 90% were recorded for both the furrow and drip irrigation trials (Topcu et al. 2002).

2.2. Soil Water Movement

Soil water movement is driven by gravitational, pressure, osmotic and matric forces and occurs as either saturated, unsaturated or vapour flow (Raine 2003; Singer & Munns 1999). The hydraulic conductivity (speed of soil water movement) and infiltration capacity of a soil are functions of both the soil properties and the initial moisture content (Raine 2003; Singer & Munns 1999). Soil water movement models use internal water balances to calculate changes in soil moisture content. Whilst the more recent soil water movement models are capable of dealing with most situations that exist in the field, the problem is now with accurately parameterising them (Denisov et al. 2002; Gerakis & Zalidis 1998). Because of the difficulties in parameterising cracking clay soils and the lack of complete data sets to verify them, the accuracy of models that claim to handle cracking clay soils is yet to be determined (ed. Bethune & Kirby 2001).

2.2.1. Soil Water Retention Curves

A soil's water content, also referred as its moisture content, is the amount of water in the soil (Singer & Munns 1999). This is usually expressed as a percentage of either the soil mass or volume (Raine 2003; Singer & Munns 1999). When it is derived as a proportion of the soil's volume, it is known as the volumetric moisture content. When the soil water content is calculated as the amount of water per unit mass of dried soil, it is known as the gravimetric moisture content. These two concepts are related such that the volumetric moisture content is equal to the gravimetric moisture content multiplied by the bulk density of the soil (Raine 2003).

There are a number of ways to measure soil water content, each with their own advantages and disadvantages. These include direct sampling, using a neutron moisture meter (NMM) (also referred to as a Neutron Probe (NP)), using equipment based on time domain reflectometry (TDR) and using equipment based on capacitance (otherwise known as frequency domain) principles (Charlesworth 2000; George 1994; Raine 2003).

The neutron moisture meter is a probe that is placed into an aluminium access tube buried vertically in the ground. The probe emits fast neutrons and then counts the slow neutrons. As shown in Figure 2.2, the fast neutrons collide with hydrogen atoms in the soil (ie water) and loose considerable energy, therefore becoming slow neutrons (Charlesworth 2000; George 1994; Raine 2003). Whilst the neutron moisture meter is relatively quick and easy to use, the initial capital is quite expensive and it requires a license to use and store it (because it is a radioactive source). The NMM must also be calibrated for each soil type due to field variation in bulk density and the presence of other forms of hydrogen (eg those ions presence in clay particles and organic matter) (Raine 2003).

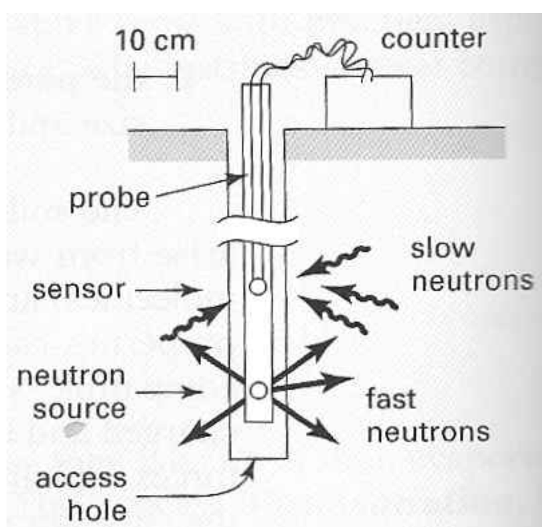


Figure 2.2. Method of a neutron moisture meter

(Singer & Munns 1999, p. 110)

Increasingly, soil moisture monitoring equipment is capacitance based. The enviroSCAN is a common commercial system consisting of a series of capacitance sensors located at different depths within a plastic access tube (Charlesworth 2000). These sensors are linked to a data logger, therefore enabling 'continuous' soil water monitoring (ie measurements can be taken automatically at pre-set time intervals). Capacitance units must also be calibrated for the soil type. Whilst capacitance based measurement is not as accurate as a correctly calibrated NMM, these units are normally cheaper to purchase and require less time to use (the values are automatically determined and recorded).

Direct measurement of soil moisture content is undertaken by gravimetric oven drying. This is the most accurate method, however it is very labour intensive, destructive, time consuming and does not provide instantaneous results. It is therefore mostly used to calibrate other methods and for research purposes. Soil cores are taken from the field and samples are oven dried at approximately 110 °C for 48 hours (Charlesworth 2000). The mass of water in the sample is determined as the oven-dried mass of the soil subtracted from the initial mass of the soil (Singer & Munns 1999).

Soil water potential is the relative amount of energy of the water in a soil system (Hillel 1971; Raine 2003; Singer & Munns 1999). It is commonly described as a measure of how much work a plant must do to extract the water from the soil (Raine 2003). Most instruments used to measure soil water potential are based on the equilibrium principle (Raine 2003). These instruments are saturated and placed in the soil to exchange water with the soil until an equilibrium is reached between the two (Raine 2003). These measurement instruments include tensiometers and electrical resistance blocks (including gypsum blocks) (George 1994; Raine 2003). Soil psychrometers, which measure wet and dry bulb temperature in order to determine soil water vapour relative humidity, can also be used to derive soil water potential (Raine 2003). Unfortunately, the equation to derive soil water potential is very sensitive to the value of relative humidity (Raine 2003), which only varies between approximately 98.5 and 100% (Singer & Munns 1999), therefore greatly limiting the accuracy of the estimated soil water potential.

The relationship between soil water potential and moisture content is known as the soil moisture characteristic or the soil water retention curve (Minasny & McBratney 2003; Raine 2003; Singer & Munns 1999). This curve is a unique function for each soil, however it is primarily regarded to be a function of the soil texture and structure, as well as of whether the soil is wetting or drying (hysteresis) (Raine 2003). The creation of a soil moisture characteristic curve involves applying a known potential to the soil, waiting for the system to equilibrate, and then determining the soil moisture content. This can be completed using suction plate (include Haines) or pressure membrane apparatus (Singer & Munns 1999).

The relative porosity of a soil is indicated by its volumetric moisture content at saturation (ie a soil with a low porosity will have a low moisture content) (Singer & Munns 1999). Similarly, the pore size distribution of a soil is represented by the slope and shape of the soil moisture characteristic curve (Singer & Munns 1999). As shown in Figure 2.3, in comparison to clayey soils, because sandy soils have a lower porosity they tend to have lower moisture contents at saturation (soil water potential equal to zero) (Raine 2003). The dominance of macro pores in sands means that they drain rapidly and have relatively low moisture contents at high values of suction (ie large negative values of soil water potential) (Raine 2003).

Soil Water Retention Curve

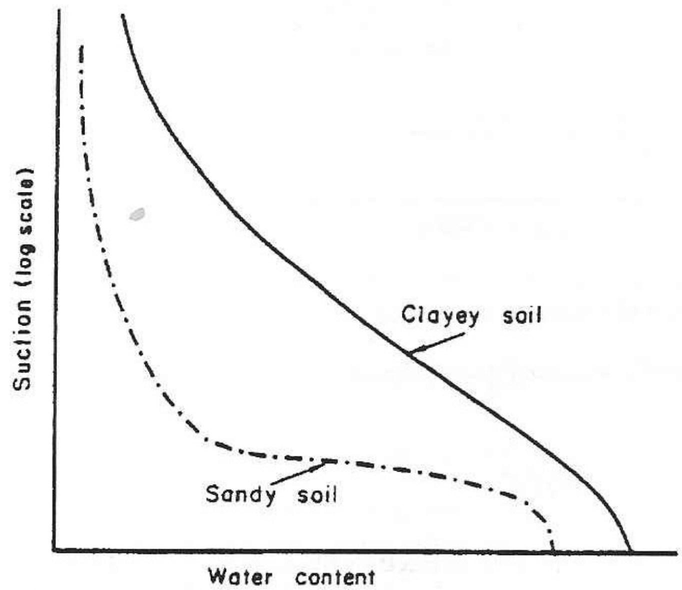


Figure 2.3. Soil water retention curves for different soils

(Hillel 1971, p. 64)

2.2.2. Hydraulic Conductivity Curve

Hydraulic conductivity is the speed at which water can move through a soil. This is function of both the soil properties and the initial soil moisture content (Raine 2003). As shown in Figure 2.4, the hydraulic conductivity of a soil is at its maximum when the soil profile is saturated. In this state, sandy soils will typically have a higher hydraulic conductivity then clayey soils because of the dominance of large pores in the sand (McLaren & Cameron 1996).

Hydraulic Conductivity Curves

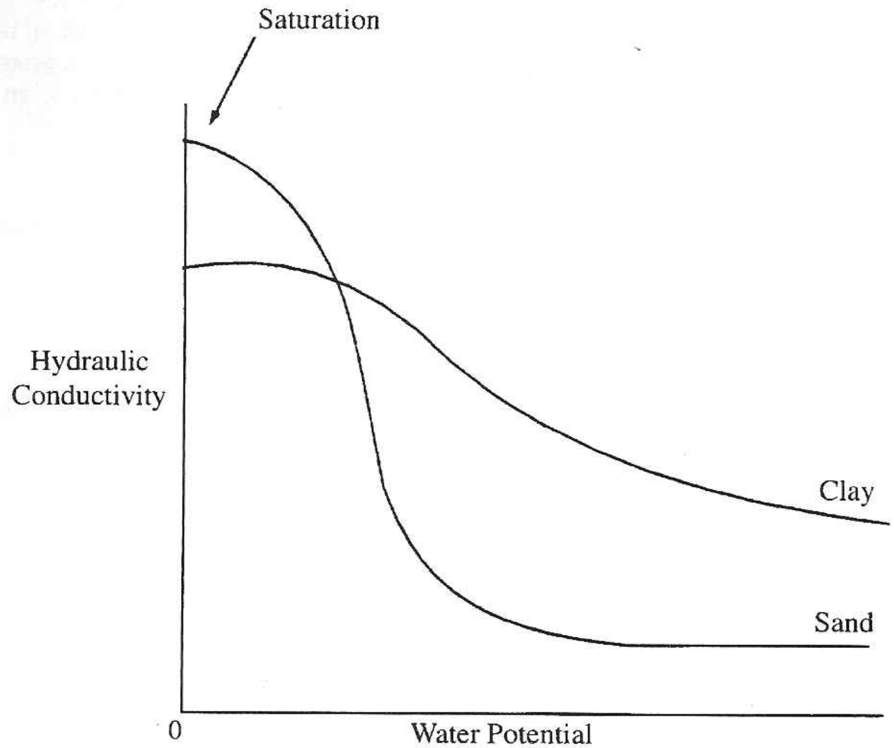


Figure 2.4. Hydraulic conductivity curves for different soil types

(Raine 2003, Figure 9.2)

As a soil dries out, the hydraulic conductivity drops due to a number of retarding factors. The flow paths become obstructed by either dislodged soil particles, or more commonly by air (as the water leaves the larger pores, it is replaced by air) (Raine 2003; Singer & Munns 1999). This obstruction means that many flow paths are no longer direct and the water now needs to take a longer path to reach its final destination (Singer & Munns 1999). Friction between the water and the soil also increases because as the soil dries, the water remains in the smaller pores and as thin films on the soil particles, therefore increasing the soil surface area (boundary) to fluid ratio (Singer & Munns 1999). In cracking and swelling clays, these actions greatly alter pore size distribution and flow paths, therefore possibly creating dramatic changes in the hydraulic conductivity of the soil (Raine 2003).

The benefits of reducing hydraulic conductivity with soil moisture content are large reductions in drainage and evaporation times (ie soil water losses are minimised) (Singer & Munns 1999). Since hydraulic conductivity is highly dependant on the porosity and pore size distribution of a soil, the rate at which it decreases with decreasing soil moisture content is a function unique for each soil (Raine 2003; Singer & Munns 1999). During the unsaturated state, hydraulic conductivities for clay soils are typically greater than those for sandy soils due to the higher proportion of medium-sized pores in clayey soils (Raine 2003).

When water enters the soil profile it either remains in the soil pores or moves through them in response to a variety of forces (Raine 2003). These forces include gravitation forces (water flows downwards), pressure forces (water flows so as to too loose pressure (ie from high pressure areas to low pressure areas)), osmotic forces (water flows from solute dilute regions to solute concentrated regions) and matric forces (flow from larger to smaller pores, flow from wetter to drier areas) (Singer & Munns 1999).

Gravitational and pressure forces are the dominant forces in saturated soil water movement, whereas matric forces, also referred to as suction and/or tension, is the dominant force in unsaturated soil water movement (Singer & Munns 1999). Osmotic forces are the driving force behind plant soil water uptake via the root system (Hillel 1971; Singer & Munns 1999). In line with the above effects on soil water due to various forces, soil water moves to equilibrate the potential energy in the system (ie from high energy to low energy regions of the profile) (Raine 2003; Singer & Munns 1999). The rate of flow, also known as the flux, is dependant on the soil's hydraulic conductivity (ease at which water flows through the soil) and the potential gradient (which determines the magnitude of the driving force) (McLaren & Cameron 1996; Raine 2003; Singer & Munns 1999).

Soil water movement can be classified as either saturated flow, unsaturated flow or vapour flow (Raine 2003; Singer & Munns 1999). Theoretically, in saturated flow all of the soil pores are contributing because they are all filled with water (Raine 2003). Realistically, the very small pores of the soil contain entrapped air and therefore don't contribute towards the soil water movement (Raine 2003). This is especially the case in soils with high clay contents. Saturated soil water flow occurs in aquifers, flooded soils and in the lower layers of soils with inadequate drainage (Singer & Munns 1999). They are also approximated in the upper layers of a soil during heavy rainfall or irrigation (Singer & Munns 1999).

In unsaturated soil water flow, some of the soil pores have been drained of their water, therefore not all of the pores contribute towards the soil water movement (Raine 2003). Due to the lower hydraulic conductivities in unsaturated soil, soil water movement is much slower in this state. Because of the stillness of air in the soil system, vapour flow is not usually significant in the soil system, except near the surface where temperature gradients drive movement throughout the day (Raine 2003; Singer & Munns 1999).

Soil water is retained in the soil because of adsorption (water molecules attaching themselves to the solid soil particles). The amount of water that a soil can hold is a function of the total particle surface area (required for adsorption), the pore size distribution and how the pores are interconnected. Losses to the soil water system, including plant extraction, evaporation and deep percolation, are exacerbated at high moisture contents (Singer & Munns 1999). During initial soil water evaporation at the ground surface the soil is dried down in the top few centimetres to such an extent that a very dry crust forms (Singer & Munns 1999). This crust is so dry that soil water does not rise up through this (the hydraulic conductivity is too low), therefore evaporation stops (Singer & Munns 1999). Deep percolation is the process whereby gravitational forces drive soil water down below the plant root zone. Plant uptake via their root system is the main loss to the soil water system (Singer & Munns 1999). Extraction begins near the surface and progresses downwards with time. The exact pattern of soil water uptake is dependant on the weather, crop species and the plant growth phase.

Infiltration is the entry of water into the soil system. This process is driven by matric forces (ie the attraction of water to soil surfaces and pores), however if the infiltration is downwards, it is also assisted by gravitational forces (McLaren &

Cameron 1996; Turner et al. 1984). There are three main types of infiltration; one-dimensional (eg. rainfall, sprinklers, basin irrigation), two-dimensional (eg. furrow irrigation) and three-dimensional (eg. sub-surface drip and trickle irrigation) (Raine 2003).

As shown in Figure 2.5, the infiltration capacity of a soil is dependent on the soil's physical properties and the amount of time since infiltration began (McLaren & Cameron 1996; Singer & Munns 1999; Turner et al. 1984). The relevant soil properties are those that influence hydraulic conductivity at high moisture contents (ie texture, structure and other macro pore properties) (McLaren & Cameron 1996; Singer & Munns 1999). As time passes during a period of infiltration, the infiltration capacity decreases because water must move further in order to find unsaturated soil (ie to increase the wetting front) (Singer & Munns 1999). In some soils, the swelling and dispersion of clay blocks pores and closes cracks, therefore reducing the hydraulic conductivity of the soil (Singer & Munns 1999; Turner et al. 1984). In other soils, the infiltration capacity is severely limited by the presence of impervious, compacted or high clay content soil layers (ie soil horizons with very low hydraulic conductivities) (McLaren & Cameron 1996; Singer & Munns 1999).

Infiltration Rates

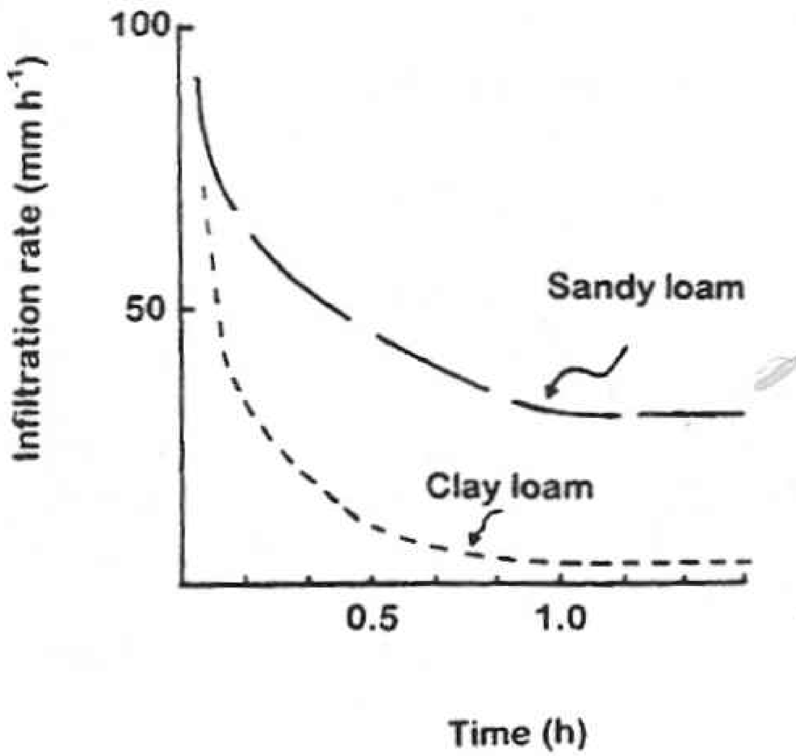


Figure 2.5. Infiltration rates for different soil types

(McLaren & Cameron 1996, Figure 7.9)

The infiltration rate of an event is the actual rate of water infiltration into the soil and is governed by either the infiltration capacity or the water application rate (whichever is the limiting factor) (Singer & Munns 1999). Consequently, the infiltration rate is always either less than or equal to the infiltration capacity (Singer & Munns 1999). If the water application rate is greater than the infiltration capacity, then ponding of the water on top of the soil surface will occur (Singer & Munns 1999; Turner et al. 1984). This can lead to runoff, erosion and uneven wetting of the soil profile (Singer & Munns 1999).

2.2.3. Application to Irrigated Agriculture

In irrigated agriculture, water losses include soil water evaporation, deep percolation and runoff (Singer & Munns 1999). Whilst some irrigation practises (eg furrow irrigation) require some runoff, excess runoff is also caused by other irrigation methods when application rate exceeds infiltration capacity (Singer & Munns 1999). In some circumstances, deep percolation is also a design feature (eg salt leaching), however in other instances it is due to soil and water application non-uniformities (Singer & Munns 1999).

Furrow irrigation applies water to the areas between row crops, however due to lateral soil water movement, the area directly underneath the crop also receives moisture (Singer & Munns 1999). Because of the small wetted area through which infiltration occurs, infiltration times are often very long (can be up to a few days) (Singer & Munns 1999). In furrow irrigation it is important to match the application rate to the infiltration capacity of the soil carefully (Singer & Munns 1999). The application rate needs to be large enough to pond water on the soil surface, but not too large that adequate infiltration does not occur near the application point.

If the correct application rate is applied, there should be no runoff associated with sprinkler or drip irrigation. When irrigating via a sprinkler, this should also theoretically ensure a uniform application of water, however due to equipment limitations this is not the case. A poorly designed system may require deep percolation to occur in some areas in order to apply an adequate amount of water to other areas. Sub-surface dripper systems eliminate most losses due to evaporation, although, depending on the system, capillary rise often draws some of the soil water into the top few centimetres of the soil where it can be evaporated out of the soil system.

2.2.4. Soil Water Modelling

Soil water movement models show changes in either soil water potential or moisture content, as calculated using a water balance in each region. The complexity of these water balances vary with the model, however most now involve many possible losses and additions to the soil water system. The magnitude of each of these losses and additions is computed using scientifically derived formula.

Soil water movement models have undergone extensive development, especially as the processing power of the standard desktop computer has increased. A number of soil water movement models are now able to deal with things such as profile non-uniformity (ie different soil layers), user-defined ground water table levels (and their effect on deep percolation and capillary rise) and a variety of water application methods (eg rainfall, furrow irrigation, drip irrigation, etc). Despite these, and many other, additions to soil water models, the complex nature of soils (with many qualitative and unknown aspects) dictates that every model is still based on many simplifications (Denisov et al. 2002).

Whilst the more recent soil water movement models are capable of dealing with most situations that exist in the field, the problem is now with accurately parameterising them (Denisov et al. 2002; Gerakis & Zalidis 1998). Unfortunately, as the complexity, and hence realism, of the model increases, so to do the number of variables required to be entered by the user. Many of these parameters (particularly soil parameters) are difficult and expensive, if not impossible, to obtain accurately (Denisov et al. 2002; Gerakis & Zalidis 1998). To obtain initial soil moisture content values (or values to compare with the model's output) is either expensive (NMM, TDR, etc) or time consuming (direct samples) (Gerakis & Zalidis 1998; Raine 2003).

An accurate soil moisture characteristic curve is often required in a soil water movement model. Whilst this can be obtained using pressure chamber apparatus, laboratory-derived soil water retention curves aren't always representative of conditions in the field (Gerakis & Zalidis 1998). It is very difficult to represent a field with a single (or numerous) soil core (Gerakis & Zalidis 1998), especially for those with well-developed and complex structures. The need to provide models with a full soil moisture characteristic curve has been somewhat alleviated by the creation of pedotransfer functions. Schapp et al (1998, cited in Minasny & McBratney 2003) found that by providing one or two points along this curve and basic soil properties (eg bulk density and sand, silt and clay fractions), the van Genuchten soil water retention curve parameters (two curve shape parameters) could be reliably estimated.

2.2.5. Modelling Cracking Clay Soils

There is currently some concern surrounding the ability of models to accurately compute soil water movement in cracking clay soils (ed. Bethune & Kirby 2001). Because these soils shrink and swell over time, their water holding capacity is not constant (ed. Bethune & Kirby 2001). During a heavy irrigation or rainfall event, these changes may occur very quickly and must therefore be accounted for in a soil water movement model. Alternative views see cracks merely as internal reservoirs, allowing the water to sit in the cracks, rather than on the soil surface, while it infiltrates into the surround soil (ed. Bethune & Kirby 2001). Unfortunately this view also requires analyse of the cracks, because the geometry of them will influence where the water infiltrates to (ie water infiltrating from a crack may have a narrower and deeper wetted zone than that achieved by surface ponding).

The role of cracks in soil water movement, particularly in regularly irrigated soil parcels, has not been adequately identified. Whilst there is some theoretical knowledge about swelling soils, there is very little field measurement of these factors and properties (especially hydraulic properties) (ed. Bethune & Kirby 2001). Cracks are a qualitative concept that vary both spatially and temporally. The importance of cracks in soil water movement is dependent on their ability to influence water storage and flow (ed. Bethune & Kirby 2001). This is determined by the number, size, depth and connectivity of the cracks and the environment in which they are situated (ie irrigation practices) (ed. Bethune & Kirby 2001). For example, if cracks extend beyond the root zone of a crop, water may enter the crack, travel down to the bottom of it and therefore be lost from the root zone (ed. Bethune & Kirby 2001).

The corrections to changes in storage (and hence water balance) must be measured in order to effectively parameterise a shrinking and swelling soil. In order to predict the effects of cracks on soil water movement, the amount of flow proportioned into the cracks and the soil matrix must be identified, as well the movement of soil water between the two (ed. Bethune & Kirby 2001). To determine this requires knowledge of the rate of closure of cracks in various situations and also the wetting pattern of each crack (ed. Bethune & Kirby 2001). Soil shrinkage properties are one way to predict crack presence and volume (ed. Bethune & Kirby 2001). Unfortunately, plant roots, cropping and irrigation practises, climate factors and the wetting and drying history of the soil will all have an impact on when and where cracks will form (ed. Bethune & Kirby 2001; Wells et al. 2003). The effect of water properties on the shrinking and swelling of soils is not well documented in Australia (ed. Bethune & Kirby 2001).

Current models are restricted by the lack of complete sets of Australian field data required to verify the output of these models (ed. Bethune & Kirby 2001). Such data sets need to measure all possible components of the internal water balance and identify the effect of shrinking and swelling on the water holding capacity and crack volume (ed. Bethune & Kirby 2001). Another limitation is that pedotransfer functions have not yet been developed for these soils (ed. Bethune & Kirby 2001), therefore increasing the amount and complexity of the parameterisation required. The use of these models has also been hindered because users are unsure of when (ie under what field circumstances), or how, to include cracks in the model (ed. Bethune & Kirby 2001).

Drainage and saturated hydraulic conductivities in the upper layers of cracking clay soils are values of high uncertainty. Traditional theories are that clay soils have very low saturated hydraulic conductivities due to their fine texture. This theory was supported by research undertaken by Connolly et al. (2002), which found saturated hydraulic conductivities in the top ten centimetres of a cracking clay soil to be approximately 50 mm/day. Due to the soil structure, recent studies have found saturated hydraulic conductivities in the top layers of some cracking clay soils to be significantly higher than this. Vervoort, Cattle & Minasny (2003) found the saturated hydraulic conductivity of a soil with a similar mineralogy (sand, silt and clay particle size fractions) to be approximately 8.4 m/day (8 400 mm/day) below the surface crumb layer.

All soil water movement models require an increasing array of parameterisation for factors such as soil, plant and climatic properties (Denisov et al. 2002; Gerakis & Zalidis 1998). When dealing with cracking clay soils, existing models are yet to be verified for Australian soils due to a lack of appropriate data sets (ed. Bethune & Kirby 2001). The continual improvement of soil water models allows for increased theoretical investigation of a wide range of realistically possible soil-water-plant systems and their interaction with the surrounding environment.

2.3. Investigating PRD Using Soil Water Movement Models

To date, there is little or no literature available on the use of soil water movement models to investigate and evaluate the use of partial root zone drying techniques. This may be due to the focus of most field trials on finding quantitative water use and yield differences between crops that have been fully watered and those that have been irrigated using partial root zone drying techniques. So far, the focus of PRD research has primarily been on determining the mechanisms by which it works and evaluating its use for a particular crop. Very little work has been done on evaluating the potential to impose PRD on different soil types.

Whilst field trials are one way to evaluate the potential for PRD on different soil types (this was the method chosen for investigations by Kriedemann & Goodwin (2003) and some current researchers), the use of properly parameterised soil water movement models allow for a wider range of investigation scenarios (soil types and irrigation schedules) (ed. Bethune & Kirby 2001). If access can be gained to relevant soil parameterisation data, a single model can be used many times to investigate different soils. Each of these soils can then be exposed to a wide range of irrigation scheduling and application techniques.

Whilst the use of such models doesn't allow for yield quality or quantity assessment of a particular crop, they can guide the need for field trials and experimental work in particular areas of possible success (ed. Bethune & Kirby 2001). For example, if used correctly, the use of a model may determine whether or not distinct wet and dry regions around a plant can be obtained on a particular soil type. If the results indicate that it is possible, they will also dictate the conditions required in order for it to happen. This therefore allows researchers and experimenters to focus their efforts on the soils and irrigation techniques and scheduling practices that give the greatest possible chance of producing a PRD response. In the long term, it allows for research funds to be spent more effectively, therefore achieving more useful outcomes for the irrigation industry (ed. Bethune & Kirby 2001).

3. Overview of HYDRUS-2D

HYDRUS-2D is a two-dimensional soil water movement model. It has extensive capabilities and options, therefore only the details relevant to this project are discussed in this section. The model requires the user to input details regarding the plants' soil water uptake pattern and root distribution, the soils' hydraulic conductivity and water holding ability and time variant data such as rainfall, evaporation and transpiration. Mathematically significant data can also be altered from the given default, for example the maximum number of iterations and tolerance levels can be set to solve the differential equations created by the boundary conditions. Note that HYDRUS-2D is capable of vertical flow, horizontal flow and axisymmetric flow, however this project only used vertical flow.

3.1. Setting-up Simulations

The first step was to identify the components of the model required using the 'Main Processes' screen shown in Figure 3.1. In all simulations, both 'Water Flow' and 'Root Water Uptake' were selected.

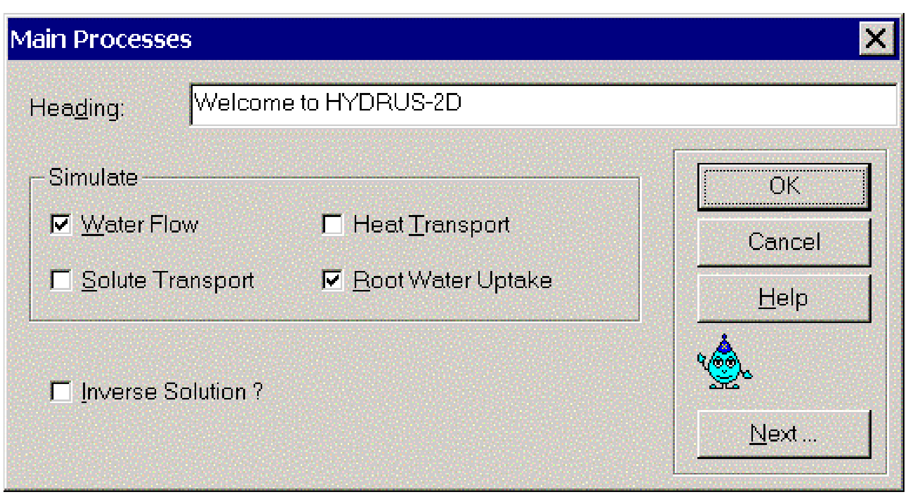


Figure 3.1. Main Processes

Next, the basic geometry is determined using the 'Geometry Information' screen in Figure 3.2. For this project, all of the lengths (including depths) were given to and calculated by HYDRUS-2D in metres. This meant that all pressure heads were also given in metres, where one metre equates to ten kilopascals. The flow type was always in the vertical plane and the geometry type was always selected to be 'General'. This means that the finite element mesh used to calculate the soil water redistribution is made up of many different shaped and sized triangles, rather than of equilateral triangles (as is the case with the rectangular option) (Rassam et al. 2003). The number of layers used doesn't effect the solution (Rassam et al. 2003) therefore it was left as one throughout this project. The number of materials refers to the number of soil layers, ie the number of different soils within the soil profile. The number of materials (herein referred to as soil layers) is distinct for each of the two investigations. How these layers are distributed within the profile is defined graphically within the final screen ('Voluntary Conditions and Domain Properties Editor').

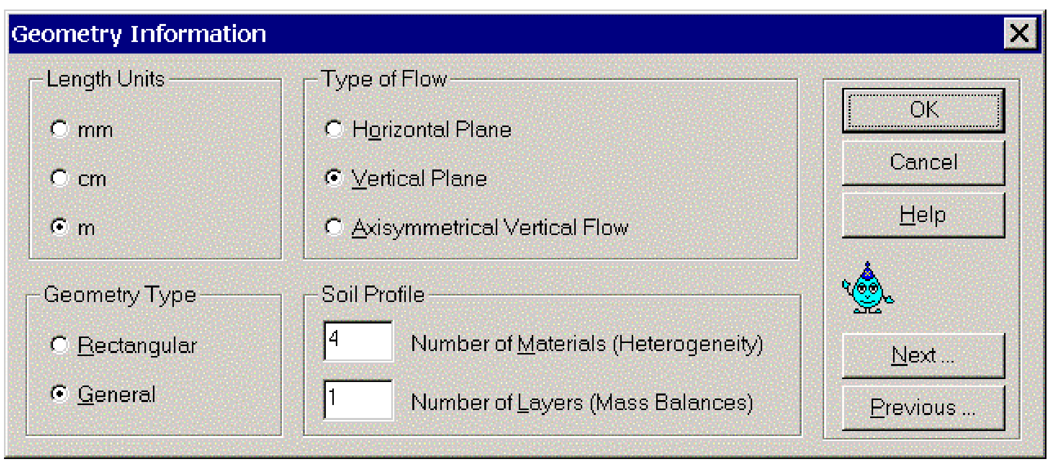


Figure 3.2. Geometry Information

Figure 3.3 shows the next screen shot, that is the 'Time Information' box. For this project the time units were days and there were always time-variable boundary conditions, although the number of these varied. The number of time-variable boundary conditions refers to the number of changes in irrigation volume, rainfall, evaporation and transpiration. The time discretization refers to developing the temporal basis of the model. The initial and final times vary with every simulation, however unless otherwise specified the initial, minimum and maximum time steps were 0.0001 days (8.64 seconds), 1e-006 days (0.0864 seconds) and 0.1 days (2.4 hours). Since the iterative solution process adjusts the time step according to the difficulty of convergence, it requires a starting point (the initial value) and an upper and lower limit (the maximum and minimum time steps) (Rassam et al. 2003).

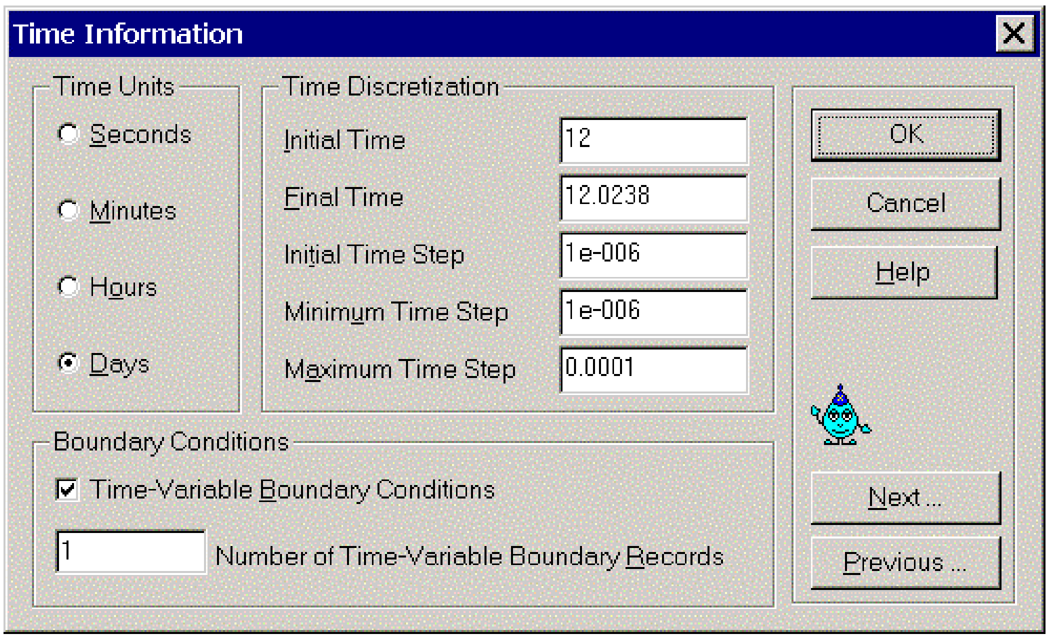


Figure 3.3. Time Information

The 'Print Information' screen (see Figure 3.4) was maintained at the default setting with all check boxes selected. The number of print times varied with each simulation. The specified print times are those times for which detailed results are available as output (eg the graphical soil moisture profile shot, mass balance details, etc).

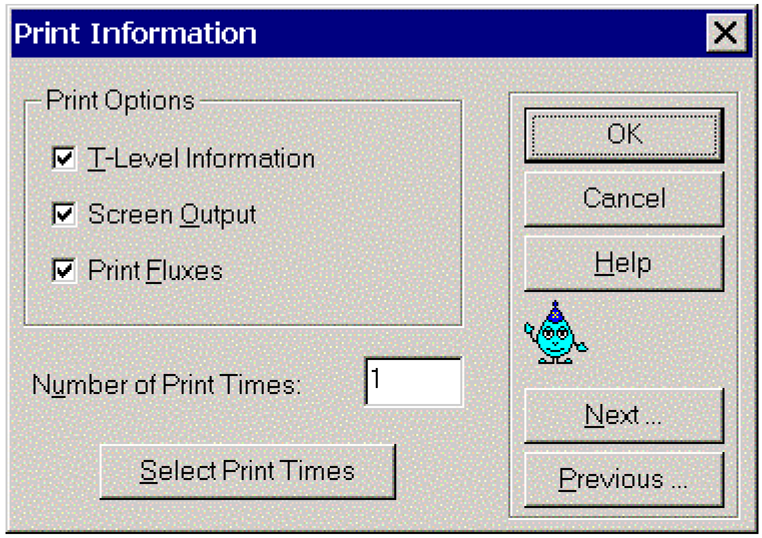


Figure 3.4. Print Information

The default values shown in Figure 3.5 were chosen for the 'Time Step Control' and 'Internal Interpolation Tables' sections of the 'Iteration Criteria' screen. The iteration criteria were altered. The maximum number of iterations was set to 50 and, unless otherwise indicated, the water content tolerance and the pressure head tolerance were both set to 0.001 . This tolerance is the maximum allowed change in the water content and the pressure head between successive iterations within each time step (Rassam et al. 2003). Whether the initial conditions were specified as water contents or pressure heads varied. For the part of the two validation simulations the initial conditions were specified as water contents. For the investigation simulations, the initial conditions were specified as pressure heads. In subsequent parts the initial conditions could be either, because they were determined from the previous simulation part's output.

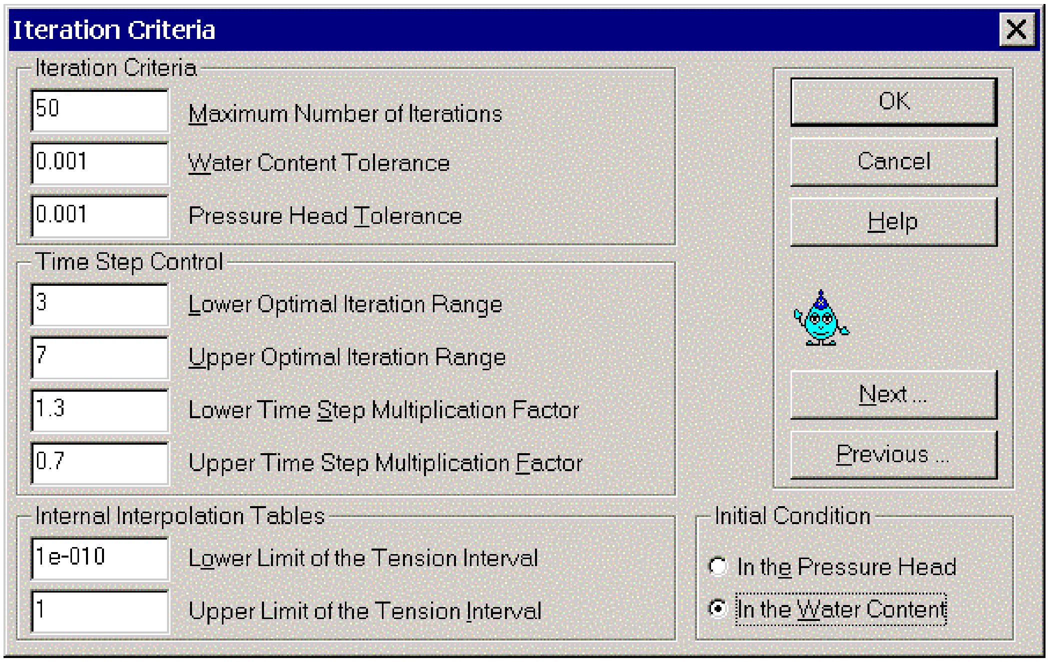


Figure 3.5. Iteration Criteria

After entering soil and plant parameters the 'Time Variable Boundary Conditions' screen (shown in Figure 3.6) is the next to appear. The number of rows in this table was defined earlier (in the 'Time Information' section shown in Figure 3.3). The time column contains the final time for which the data in that row is applicable. The second column contains the rate of rainfall, which in this case will be in metres per day. The third and fourth columns give the potential soil evaporation and plant transpiration rates (both in metres per day) based on the climatic conditions. The hCritA parameter refers to the minimum pressure head allowed at the soil surface. For clay soils this is recommended to be 3000 m, therefore this was the value used in all of the project simulations (Rassam et al. 2003). The rGWL column refers to a drainage flux, which wasn't used in this project. The GWL column refers to a head boundary condition, which was used in this project to simulate the LEPA irrigations.

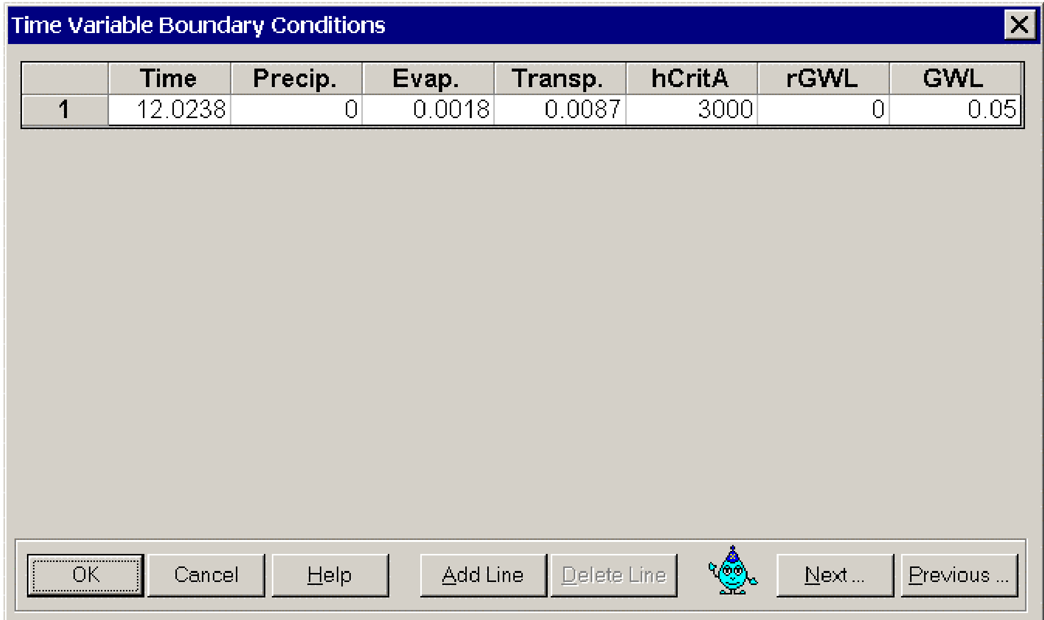


Figure 3.6. Time Variable Boundary Conditions

The physical boundaries and mesh creation are the next step in the process, however their properties are discussed in the relevant sections. HYDRUS-2D offers many physical boundary types, however only those used in this project are discussed below. Note that a boundary type may be used for all or only part of the soil profile boundary, as shown in Figure 3.7 below. The white no flux boundary is impermeable. It does not allow water into or out of the soil profile. In this project, the no flux boundary was used on the vertical side boundaries of the soil profile because the soil-water movement associated with the two half furrows should be symmetrical around these boundaries. The blue variable pressure boundary refers to the where the irrigation pressure head values (GWL) in the time variable boundary conditions screen shot are applied..

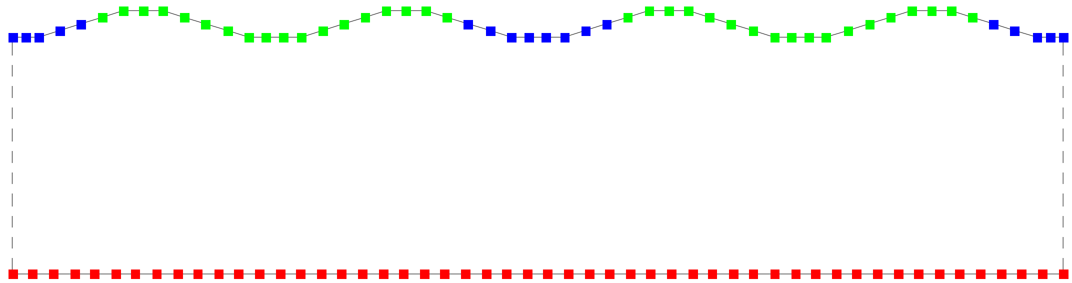


Figure 3.7. Irrigation boundary conditions

The red free drainage boundary is used at the bottom of the soil profile when the water table is too far below to effect drainage at the boundary (Rassam et al. 2003). This boundary type allows for deep drainage under gravity and is used on the bottom of all soil profiles used in this project. The bright green atmospheric boundary is usually placed along the top of the soil surface to allow for interactions between the soil and the atmosphere. These interactions include the rainfall, evaporation and transpiration (root uptake) given in the time variable boundary conditions.

3.2. Soil Parameters

The next part of HYDRUS-2D is selecting the appropriate soil hydraulic model to determine the soil water retention curve and the hydraulic conductivity curve. This is done using the screen shown in Figure 3.8. HYDRUS-2D determines the curves if parameters are provided for either the Brooks-Corey model, van Genuchten-Mualem model or the modified van Genuchten model (developed by Vogel and Cislerova) (Rassam et al. 2003). The van Genuchten-Mualem model was chosen because of the option to select the 'with air-entry value of –2cm' check box. The use of an air-entry value can become particularly important to the hydraulic conductivity function when modelling soils of a high clay content (Rassam et al. 2003), for example the 'Macquarie Downs" and Jondaryan soils used in this project. HYDRUS-2D can also incorporate the effects of hysteresis (the difference in the soil water retention curve between when the soil is wetting and when it is drying) however this was not considered in this project due to limited ability to appropriately parameterise for this.

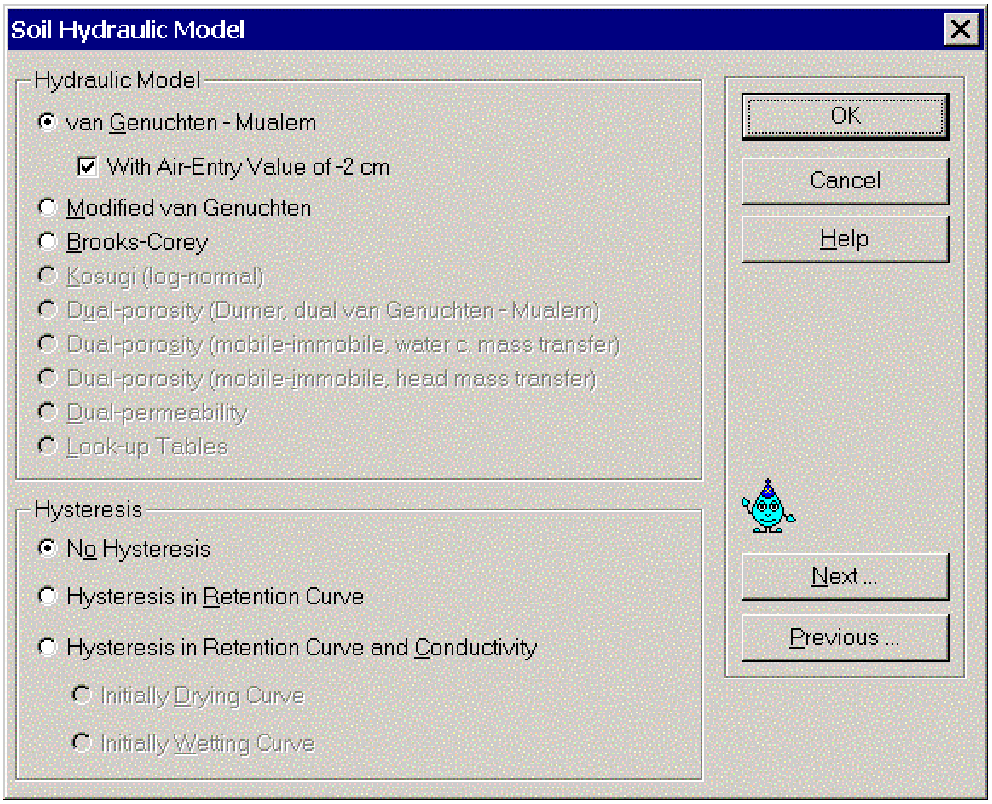


Figure 3.8. Soil Hydraulic Model

The van Genuchten-Mualem model (Rassam et al. 2003) is outlined in the following equations. The soil water retention curve (soil water potential versus volumetric soil moisture content) is given by equation 3.1 (Rassam et al. 2003).

$$S_e = \left(1 + |\alpha\psi|^n\right)^{-m} \qquad (3.1)$$

Where α, n and m are curve fitting parameters, ψ is the soil water potential and S_e is the normalised volumetric water content (also referred to as the effective saturation) defined in equation 3.2 (Rassam et al. 2003).

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (3.2)$$

Where: θ = volumetric soil moisture content equivalent to ψ

θ_r = saturated volumetric soil moisture content (ie at ψ = 0 kPa)

θ_r = residual volumetric soil moisture content (ie at ψ = 1500 kPa)

To simplify the equation defining the hydraulic conductivity curve and to minimise the parameters required, HYDRUS-2D uses the common correlation shown in equation 3.3 (Rassam et al. 2003).

$$m = 1 - \frac{1}{n} \qquad (3.3)$$

This reduces Mualem's equation for the hydraulic conductivity *k(h)*, to equation 3.4 (Rassam et al. 2003).

$$k(h) = K_s S_e^{\,l} \left[1 - \left(1 - S_e^{\,1/m} \right)^m \right]^2 \qquad (3.4)$$

Where: K_s = saturated hydraulic conductivity

l = pore connectivity parameter

From equations 3.1 – 3.4, it can be seen that in order to use the van Genuchten-Mualem model to derive the soil water retention curve and the hydraulic conductivity curve the parameters required are θ_r, θ_s, α, *n*, K_s and *l*. In HYDRUS-2D these are designated the symbols, Qr, Qs, Alpha, n, Ks and l. The parameters can be derived in a number of different ways, with the methods used in this project being described in the relevant sections. Note that in all simulations *l* was chosen to be 0.5 in accordance with Mualem's findings (Rassam et al. 2003).

3.3. Plant Parameters

The first step in defining the plant root water uptake is selecting a water uptake reduction model. This is done in the 'Root Water Uptake Model' screen shown in Figure 3.9. The two models available are the Feddes model and the S-shaped model (Rassam et al. 2003).

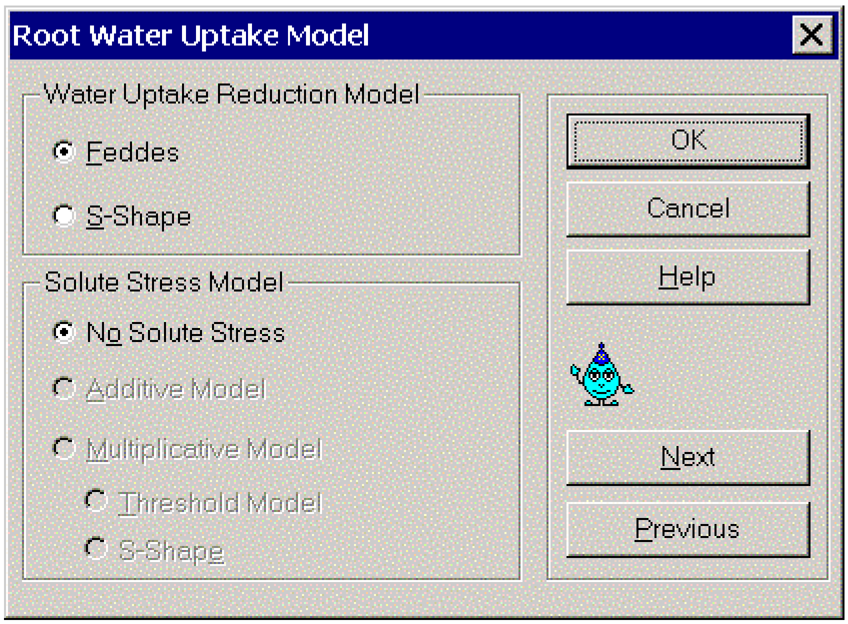


Figure 3.9. Root Water Uptake Model

The Feddes model, shown graphically in Figure 3.10, assigns plant water uptake at each point in the root zone according to the local pressure head conditions. P0 is the pressure head at which the plants begin to extract water. POpt is the pressure head at which the plants begin to extract water at the maximum possible rate (ie the potential transpiration values given in the time variable boundary conditions). For a potential transpiration rate of r2H, P2H is the pressure head at which the plant no longer extracts water at the maximum possible rate. For a potential transpiration rate of r2L, P2L is the pressure head at which the plant no longer extracts water at the maximum possible rate. Root water uptake ceases at P3, which is usually the permanent wilting point.

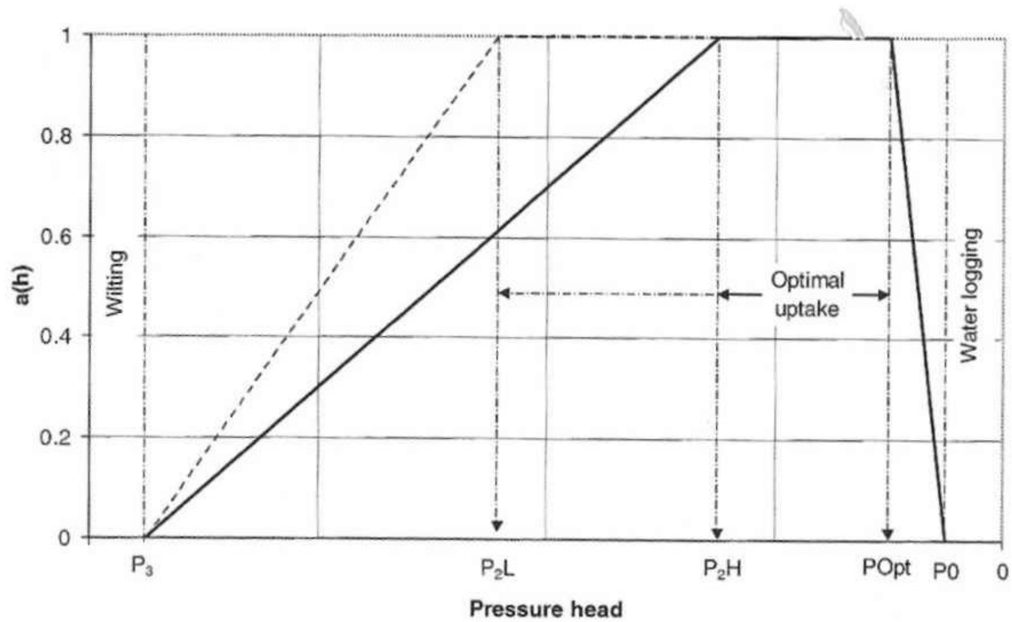


Figure 3.10. Feddes' plant root water uptake model

(Rassam et al. 2003, Figure III.1)

These values were obtained from a variety of sources. P0, POpt, P2H & r2H are all derived from the 2003-2004 cotton season regulated deficit and partial root zone drying field trial data near Jondaryan on the eastern Darling Downs. These parameters were calculated from a continuous plot of soil moisture content recorded by an enviroSCAN. P3 was taken to be the standard permanent plant wilting point of 1500 kPa. P2L and r2L are derived from local knowledge of cotton plants. These parameter values are shown in Figure 3.11.

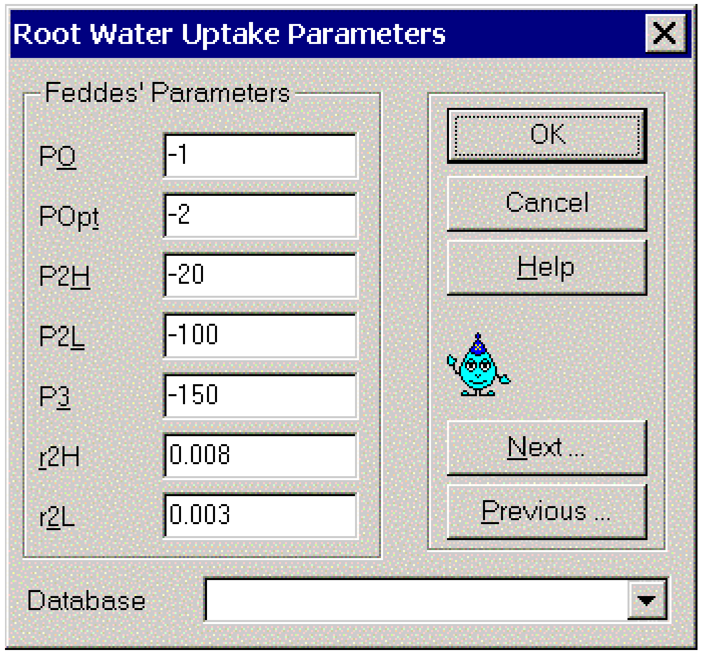


Figure 3.11. Root water uptake parameters

The root distribution pattern is graphically selected in a similar manner to the placement of the soil layers. Within the root distribution, each of the nodes are assigned relative density values. As indicated by Figure 3.12, these root density values provide a measure of the relative weighting for soil water extraction. The total volume of the root distribution is responsible for 100% of the plant soil water extraction as regulated by the transpiration demand of the plant. Each node then consumes its proportion of the transpiration relative to the other nodes' intensities. Further details regarding the method and determination of the weighting is given Rassam et al. (2003). Because of different rooting depths, the root distribution is varied throughout the simulations.

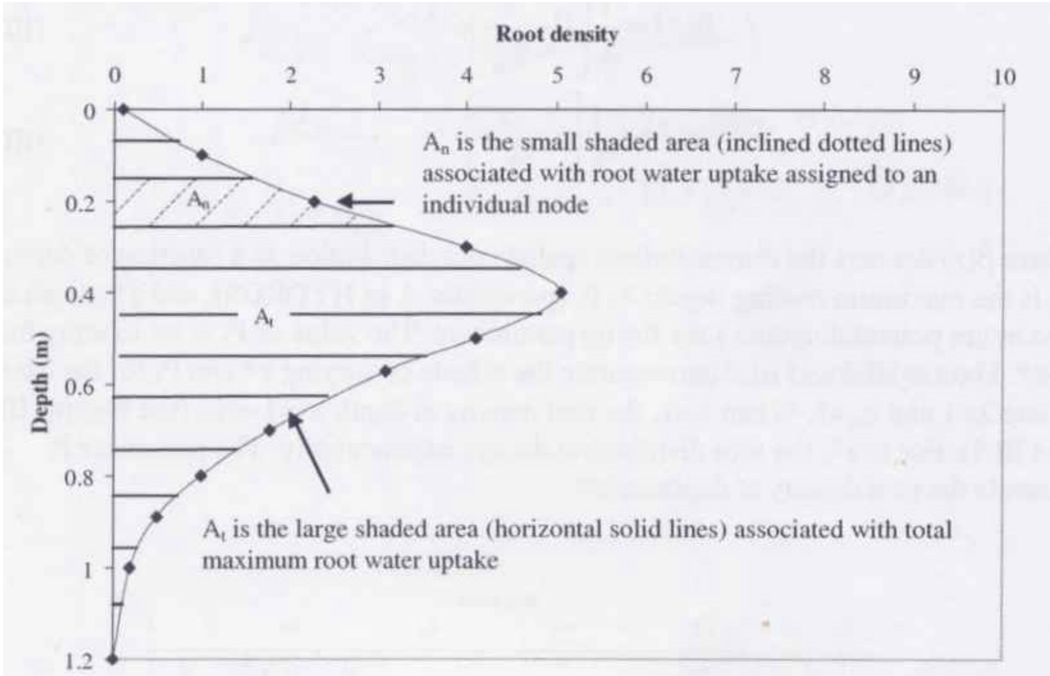


Figure 3.12. Physical depiction of root density
(Rassam et al. 2003, Figure III.3)

Originally the use of bulb shaped root zones (ie those in Figure 3.13) was investigated, however the laterally uniform distribution was eventually chosen. Due to the alternating dry furrows (if PRD can be achieved) the cotton roots will expand laterally in search of moisture, causing the roots of neighbouring plants to meet. The use of the laterally uniform distribution was also considerably easy and less time consuming to create and modify. Modifications of the distribution are important because they are required when the plant is growing throughout the season (ie their root distribution is expanding). Whilst the actual root distribution parameters vary depending on the simulation, they are all based on the common theory that approximately 40% of soil water extraction in the top layer, 30% is from the second layer, 20% is from the third layer and 10% is from the fourth layer.

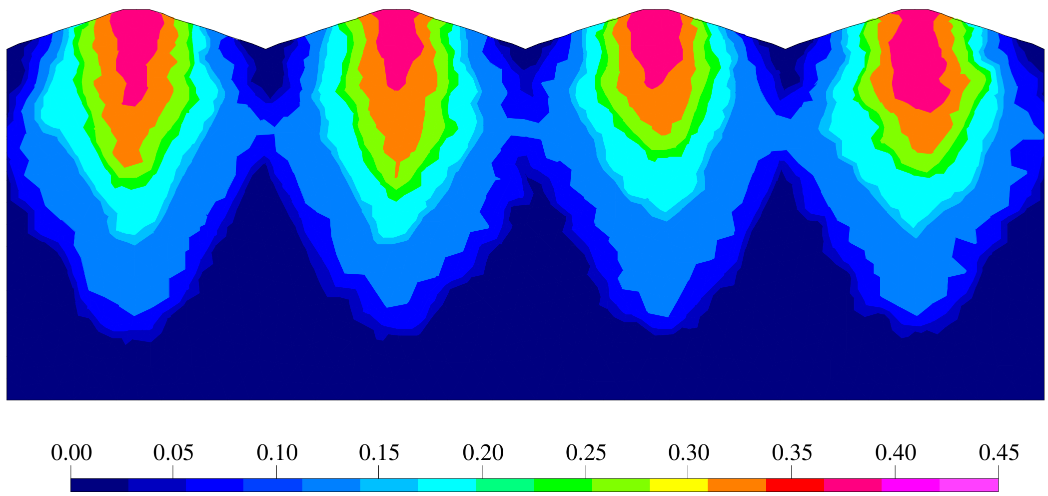


Figure 3.13. Bulb shaped root distributions

3.4. Irrigation Water Application

Irrigation applications in the simulations were applied through the variable pressure head boundaries located in every second furrow (as shown in Figure 3.7). When an irrigation was not being applied, these boundaries were replaced with the atmospheric boundary to allow for normal rainfall, evaporation and plant transpiration across the entire surface.

The pressure head boundaries were parameterized to enable infiltration based on the application of a constant head above the lowest point, ie above the furrow base. This height was equivalent to the height of an appropriate variable pressure head boundary node. In the 'Macquarie Downs" soil investigation this height was 100 mm (0.1 m) above the 150 mm deep furrow base, whereas in the Jondaryan soil investigation this height was only 50 mm above the 100 mm deep furrow base.

Initially when an irrigation was to be applied, the simulation would run for a period of time to produce an output graph of the cumulative infiltration through the variable pressure head boundary over time. The cumulative infiltration was given as a volume per metre in the third dimension. This equates to an area of water (m^2) in the two-dimensional viewing plane. To convert this to an equivalent depth of water infiltrated across the entire surface the computed area infiltrated was divided by the width of the soil section (ie 4 m). From this graph, the time required to apply the field measured irrigation volume could then be determined. Using this period of time, the simulated irrigation application was then run, applying the specified irrigation quantity through the variable pressure head boundary.

4. Investigation of PRD on the "Macquarie Downs" Soil

This section consists of two main parts; namely the parameterisation and validation of HYDRUS-2D and then simulations designed to reflect the range of different irrigation frequencies and volumes that could be applied commercially. Section 4.1 outlines the materials and methods consistent with both the validation and investigation. Section 4.2 covers the validation of HYDRUS-2D; including further simulation details, results and a subsequent analysis and discussion. The investigation of PRD effects is documented in Section 4.3 and also contains further simulation details, results and analysis. A final conclusion and summary can then be found in Section 4.4, with further project details located in Appendices B to E.

4.1. Common Materials

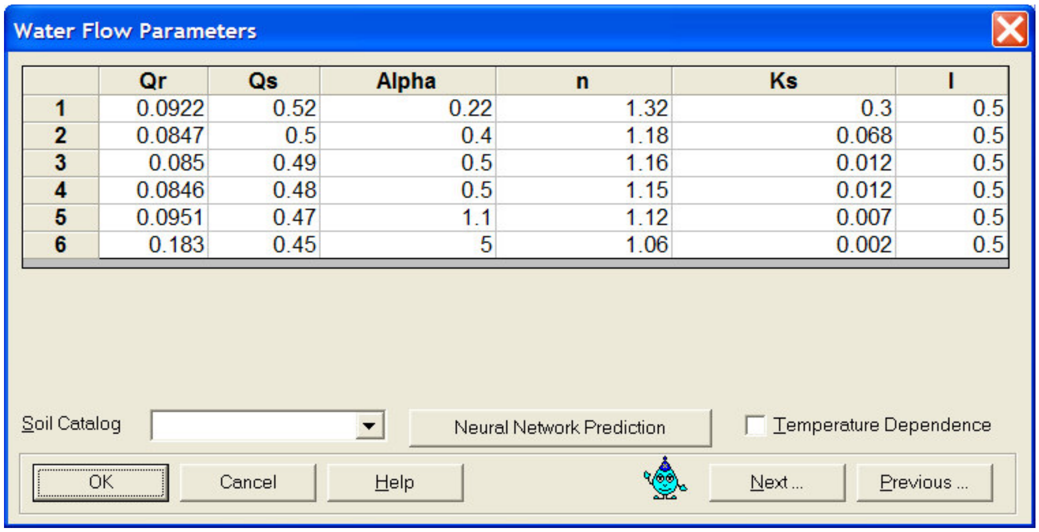
The common materials are those that are used in both the validation and PRD investigation simulations using the "Macquarie Downs" soil. These include details about the partial root zone field trial site, the soil parameters used and the geometry of the simulated soil profile.

4.1.1. Site

This project uses data based on soils and cotton production from the Darling Downs in South-East Queensland. In particular irrigation details, soil physical properties and moisture extraction data for this section were obtained from a partial root zone drying field trial on cotton at "Macquarie Downs". "Macquarie Downs" is located near Leyburn on the eastern Darling Downs (S27° 56.2', E151° 30.4'). The trial was conducted on a heavy black cracking clay soil using conventional commercial cotton (Sicot 80).

4.1.2. The Soil Parameters

The soil parameters used are shown in Figure 4.1 below. The meaning of these parameters is discussed in Chapter 3.



	Qr	Qs	Alpha	n	Ks	l
1	0.0922	0.52	0.22	1.32	0.3	0.5
2	0.0847	0.5	0.4	1.18	0.068	0.5
3	0.085	0.49	0.5	1.16	0.012	0.5
4	0.0846	0.48	0.5	1.15	0.012	0.5
5	0.0951	0.47	1.1	1.12	0.007	0.5
6	0.183	0.45	5	1.06	0.002	0.5

Figure 4.1. A HYDRUS-2D screen shot of the soil properties used

Values for *Qr*, *Alpha* and *n* were initially found using Rosetta, HYDRUS-2D's neural network prediction program. This program takes the soil property data in Table 4.1 and compares it to known soils in its database to estimate values for *Qr*, *Qs*, *Alpha*, *n* and *Ks* (the parameters in Figure 4.1). However Rosetta did not identify curve parameters (*Alpha* and *n*) that adequately fitted the measured points on the soil moisture characteristic curve (*TH33* and *TH1500* as defined in Table 4.1). The soil moisture characteristic curve parameters (ie. *Alpha* and *n*) calculated using Rosetta were subsequently modified to ensure that the soil moisture curve fitted the two known points (moisture content at field capacity and permanent wilting point). The differences in the soil moisture characteristics of the soils produced by Rosetta and the soils that I created by altering *Alpha* and *n* can be seen in Appendix B.

Table 4.1. Soil data used to produce the soil hydraulic parameters

Depth Below the Plant Row (cm)	***Sand*** (%)	***Silt*** (%)	***Clay*** (%)	***Bulk Density*** (g/cm^3)	***TH33***	***TH1500***
0-25	8.0	19.0	73	1.21	0.47	0.24
25-45	7.5	15.5	77	1.24	0.45	0.28
45-75	7.5	15.5	77	1.26	0.44	0.29
75-105	7.5	17.5	75	1.30	0.43	0.29
105-135	7.0	16.0	78	1.34	0.42	0.31
135-150	5.5	15.5	79	1.37	0.40	0.36

Where: *Sand* = Percent of sand (50 - 2000 µm) in the soil
Silt = Percent of silt (2 - 50 µm) in the soil
Clay = Percent of clay (< 2 µm) in the soil
Bulk Density = Bulk density of the soil layer (g/cm^3)
TH33 = Moisture content at 33 kPa (field capacity)
TH1500 = Moisture content at 1500 kPa (permanent wilting point)

This data was obtained from various sources. Particle size analysis data (categorised according to the International Union of Soil Science fraction sizes) was obtained from Goyne (2000, Appendix 5). This data was a soil chemical analysis conducted over the 1998-1999 season of an Endohypersodic, Self-mulching, Black Vertosol, which is very similar to the soil at "Macquarie Downs". This analysis split the soils into coarse sands (200-2000 µm), fine sands (20-200 µm), silt (2-20 µm) and clay (< 2 µm) sized fractions. To convert these fractions to the equivalent categories used in the United States and by HYDRUS-2D, it was assumed that half of the fine sand fraction (20-200 µm) as measured using the IUSS scheme would be included in the silt size fraction (2-50 µm) as defined by the US scheme.

Values for saturated moisture content (*Qs*), bulk density, moisture content at field capacity (*TH33*) and moisture content at permanent wilting point (*TH1500*) were taken from soil survey data found for "Macquarie Downs" (NRME, n.d.). Values for subsoil saturated hydraulic conductivity were obtained from an infiltration project on cracking clay soils (Connolly et al. 2002, Table 3). The saturated hydraulic conductivity values in the surface layers were based on earlier soil hydraulic studies (Connolly et al. 2001, Table 3). The final values used were increased due to findings by Vervoot et al. (2003, Table 3).

4.1.3. Model geometry

The two dimensional model geometry was developed to represent a typical furrow irrigation layout as used at 'Macquarie Downs" and within the local cotton industry (Figure 4.2). The furrows were 15 cm deep with row spacings of 1 m. The plant rows and furrow bases were both 20 cm wide. The depth of the soil profile was set to be 1.5 m below the top of the plant rows. As furrows were alternately irrigated (ie every second furrow), a profile width of 4 m was used to enable simulation of one full and two half wetted furrows. This layout enable the prediction of results associated with the wetted furrow, whilst ensuring that the correct amount of soil-water was present within the boundary limits.

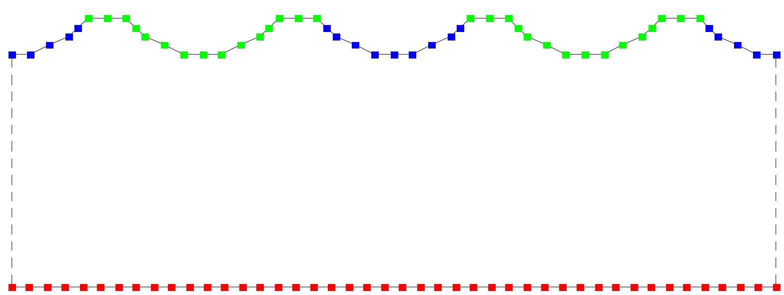


Figure 4.2. The shape of the soil profile used in HYDRUS-2D

4.2. Validation of HYDRUS-2D

Validation of the HYDRUS-2D model and soil hydraulic parameters was conducted to compare simulated soil-water movement results with local measured field data. Irrigation, climatic and soil-moisture data obtained during the middle of the 2002-

2003 season from the irrigated partial root zone drying cotton trial located at ‘Macquarie Downs” were used for the validation. Following simulation, the simulated soil moisture values were compared to the soil moisture data measured in the field.

The cotton was planted on 25th October 2002, with the simulations attempting to reproduce the soil moisture characteristic from January 2, 2003 until March 5, 2003. The simulation period was therefore 63 days, which included four irrigation events.

4.2.1. Materials and Methods

All model parameters used in the validation trial were the same as those indicated in Chapter 3, unless otherwise indicated in this section. Still to be defined are the atmospheric conditions (irrigation volumes and timings, rainfall, potential evaporation and potential transpiration), plant root distribution pattern and the initial conditions.

4.2.1.1. Atmospheric Conditions

The timing and size of the irrigation events can be seen in Table C.1 in Appendix C. Daily weather data during the trial period was obtained from a nearby weather station (located at Brookstead) and used to calculate daily evapotranspiration using the Penman-Monteith equation (Allen et al. 1998). The daily evapotranspiration values were assumed to consist of 1 mm of evaporation and the rest as crop transpiration. A total of 101.2 mm of rainfall was received at the site during the trial period and was applied in the simulation. The daily crop transpiration and rainfall values used are also shown in Appendix C.

4.2.1.2. The Plant Root Parameters

It was important to realise that the root density and the depth of the root zone changed as the cotton plant grew. The relative weighting of the soil water extraction by the roots was varied three times throughout the simulation to represent expected changes in root growth during this period. These changes are shown in Table 4.2.

Table 4.2 Relative weighting of root extraction used in the validation

Depth Below the Plant Row (cm)	**Root Density** (Day 0-20)	**Root Density** (Day 20-39)	**Root Density** (Day 39-63)
0-10	4	4	4
10-20	3	3	3
20-30	2	2	2
30-40	1	1	1
40-60	0.2	0.5	0.8

Whilst cotton roots can extend deep into the ground, under irrigated conditions it is believed that most extraction occurs in the top 40 cm of the root zone. Some plant water extraction may also occur at a depth of 40-60 cm, therefore a relatively small density value was placed at this depth.

4.2.1.3. Initial Conditions

The initial soil-moisture profile condition used in the validation simulation was set to be equivalent to that measured in the field at the start of the trial period. These values can be found in Table C.2 in Appendix C or they can be viewed pictorially in Figure 4.3. The soil moisture values at horizontal distances of 17, 50 and 83 cm away from the wetted furrow were interpolated as the average of the neighbouring soil moisture values.

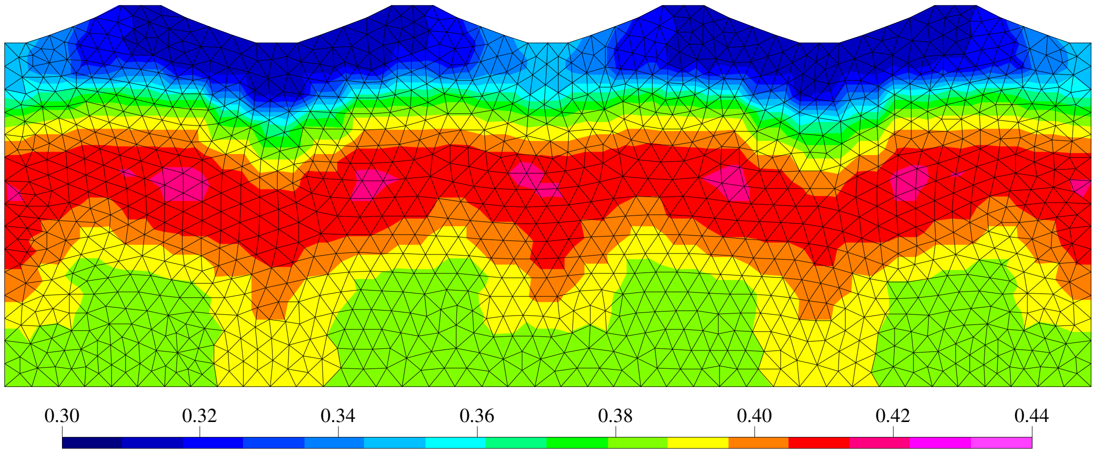


Figure 4.3. The initial soil-moisture profile as interpolated from the field measurements

Following simulation, the soil moisture data was recorded at various depths in four transects (0, 33, 67 and 100 cm away from the wetted furrow) and compared with the volumetric soil moisture data measured in the field. These data points were at depths of 35, 45, 55, 65, 75, 95, 115 and 135 cm below the top of the plant row for the transects located 0 and 100 cm away from the wetted furrow and at depths of 25, 35, 45, 55, 65, 85, 105 and 125 cm below the top of the plant row for the transects located 33 and 67 cm away from the wetted furrow.

4.2.2. Results & Discussion

There are three variables that combine to identify each soil moisture measurement and its corresponding simulated value; namely the day on which it was taken, the distance away from the wetted furrow and its depth below the plant row. The comparisons of the measured (ie the actual value measured in the field) versus modelled (ie the corresponding values simulated by HYDRUS-2D) soil moisture contents are arranged according to each of these variables. Figures 4.4 – 4.9 show each measured value plotted at the point corresponding to its modelled value. These comparisons can also be viewed numerically in Table C.3 in Appendix C.

Figures 4.4 & 4.8 show how the correlation between predicted and measured values tends to decrease with time (ie as the day number increases). A comparison between the simulated and measured values over the entire 63 days only revealed a correlation of 39%. It was noticed that as time progressed, the correlation between the simulated and measured values decreased. A comparison of the simulated soil-water distribution values and the field measurements taken during the first 39 days revealed a correlation of 58%, while the correlation over the first 26 days was up to 64% and over the first 17 days an overall correlation of 69% was obtained. The results with respect to distance away from the wetted furrow and depth below the plant row can be seen for the first 26 days in Appendix D.

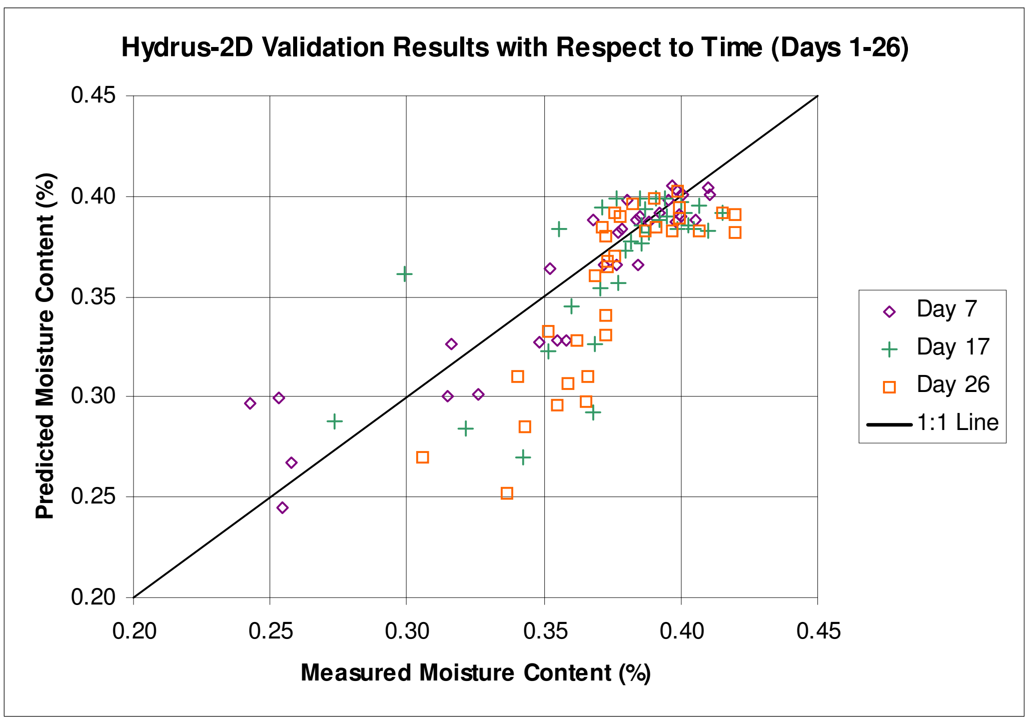


Figure 4.4 HYDRUS-2D validation results with respect to time (for Days 1-26)

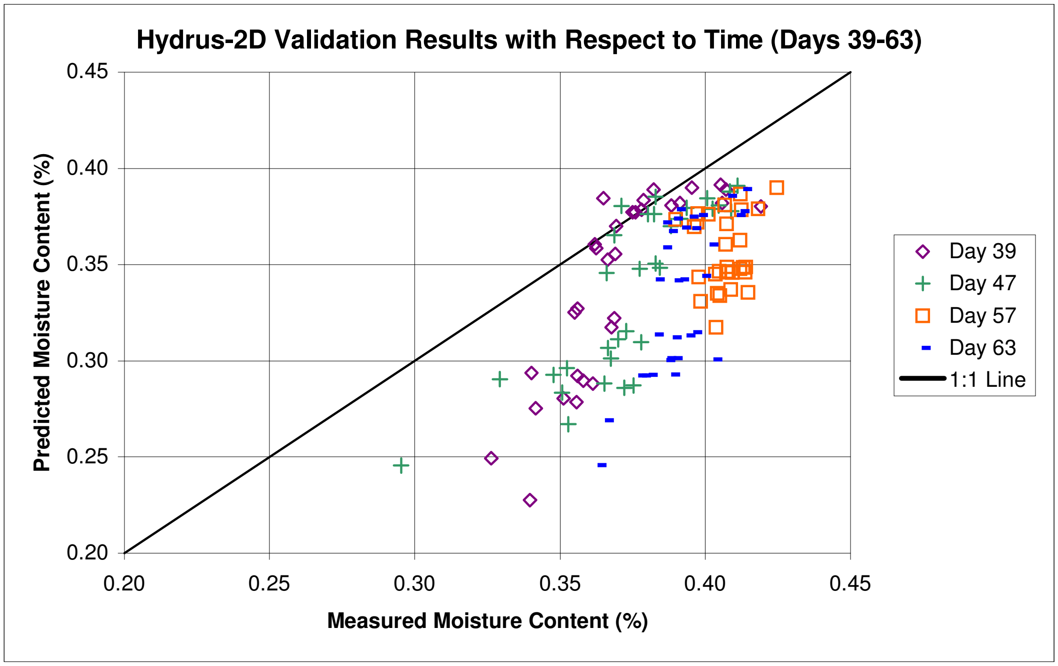


Figure 4.5. HYDRUS-2D validation results with respect to time (for Days 39 – 63)

Figures 4.6 and 4.7 show typical trends between the modelled and the measured output. As previously discussed, the model predicts most accurately at the beginning of the time series. After approximately Day 29, the modelled results become unreliable.

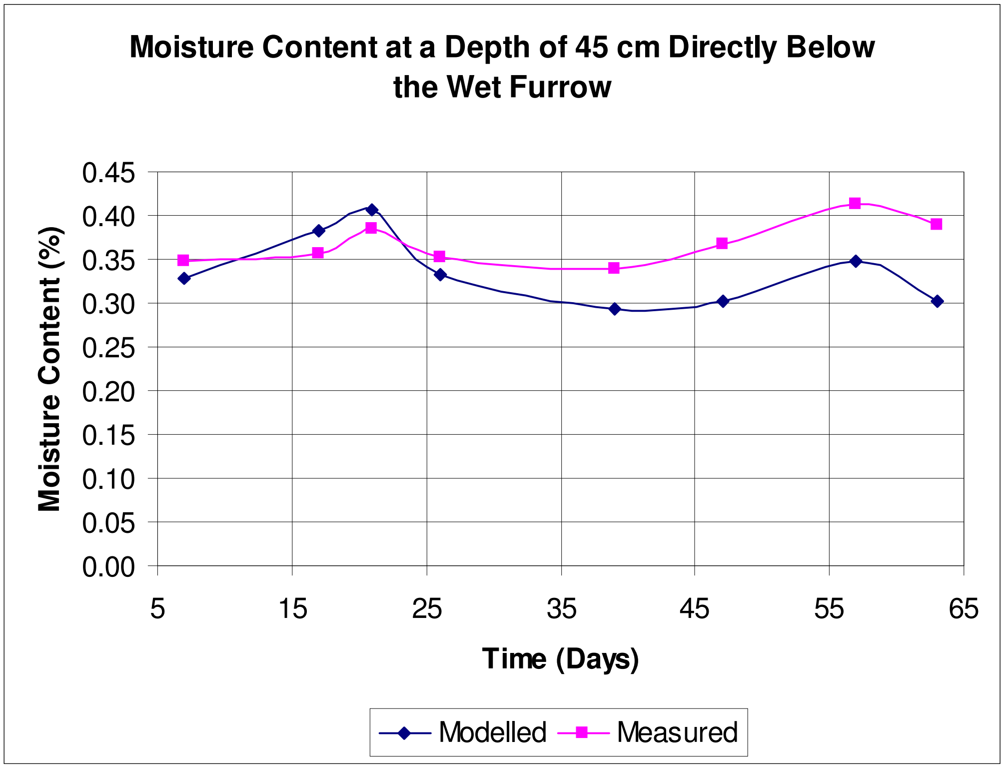


Figure 4.7. HYDRUS-2D validation results at 45 cm below the wetted furrow

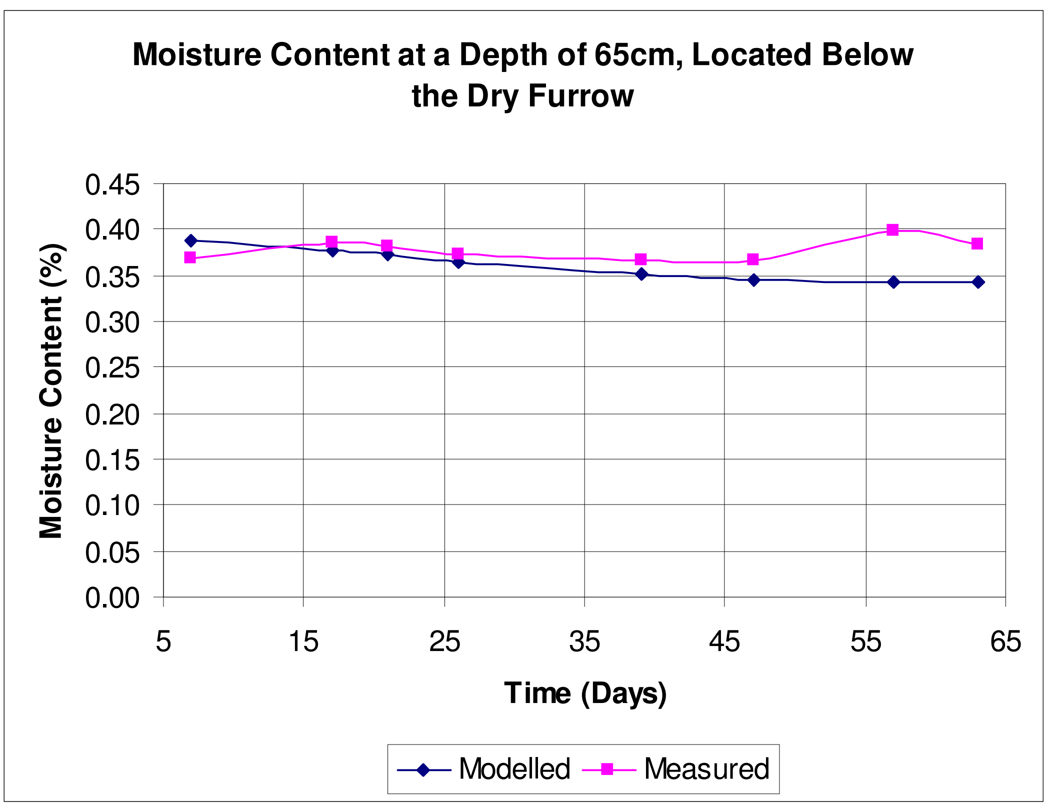


Figure 4.7. HYDRUS-2D validation results at 65 cm below the dry furrow

From Figure 4.8, it can be seen that values predicted for the two points under the plant row (at 0.33 m and 0.67 m away from the wetted furrow) were generally lower than those measured in the field. This is the major region of root water uptake; therefore this phenomenon could be due to excess plant water extraction and other plant properties. Figure 4.8 also indicates that the points in the un-wetted furrow (ie 1.00 m away from the wetted furrow) are also under-predicted. A similar plot showing only up to Day 26 inclusive, indicates that this is not the case for the time-period for which the model is reasonably accurate. This plot can be viewed as Figure D.1 in Appendix D.

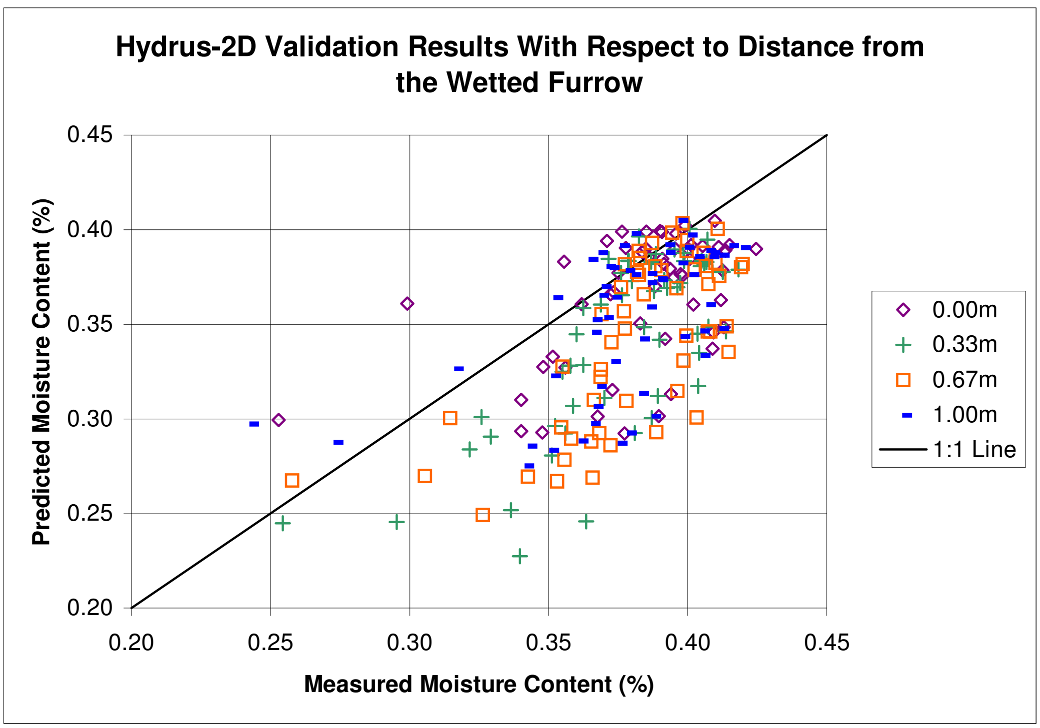


Figure 4.8 HYDRUS-2D validation results with respect to the distance away from the wetted furrow

Under-prediction was also noticeable in the upper and lower layers of the soil; in particular it was noticeable in the soil shallower than 55 cm (Figure 4.9) and deeper than 105 cm (Figure 4.11) inclusive. The under-predictions in the shallower soils are consistent with the theory of excessive plant water extraction. At depths below 75 cm (Figures 4.10 & 4.11), but particularly at depths below 115 cm (Figure 4.11), it was noticed that the predicted values varied very little over time. Combined with under-prediction in this region, it is most likely due to the chosen soil properties. Possible reasons could be that in the model the soil drained too rapidly and to too low a moisture content, or irrigation water was not predicted to reach these soil depths.

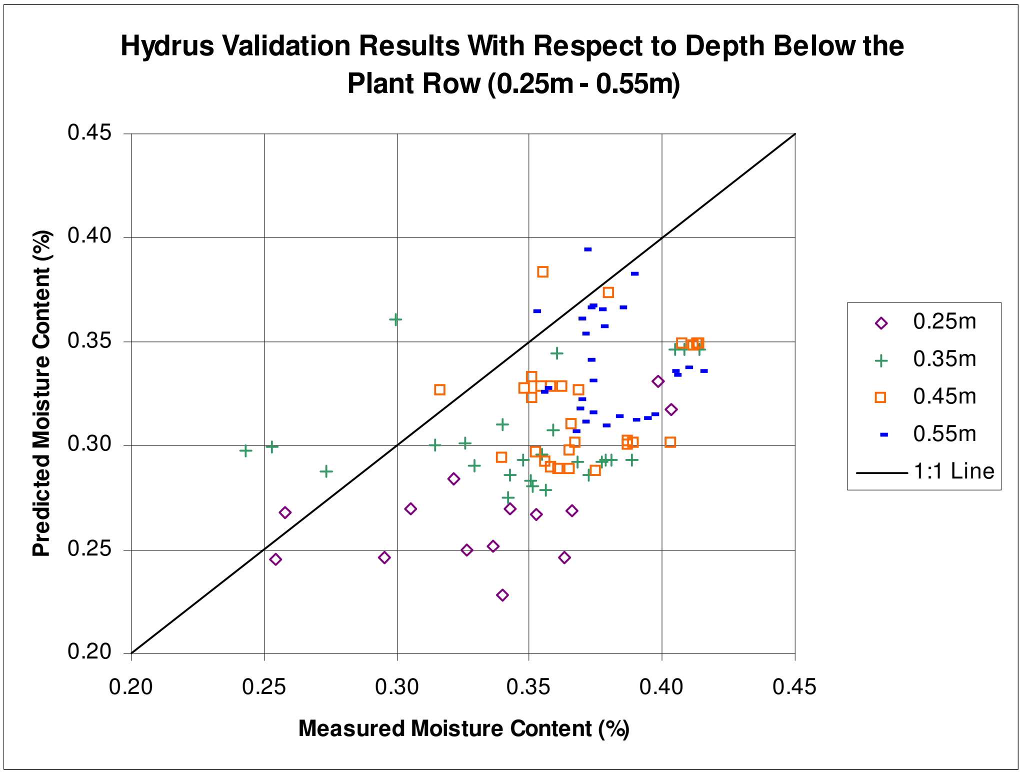


Figure 4.9. HYDRUS-2D validation results with respect to depth below the plant row (for 25 – 55 cm)

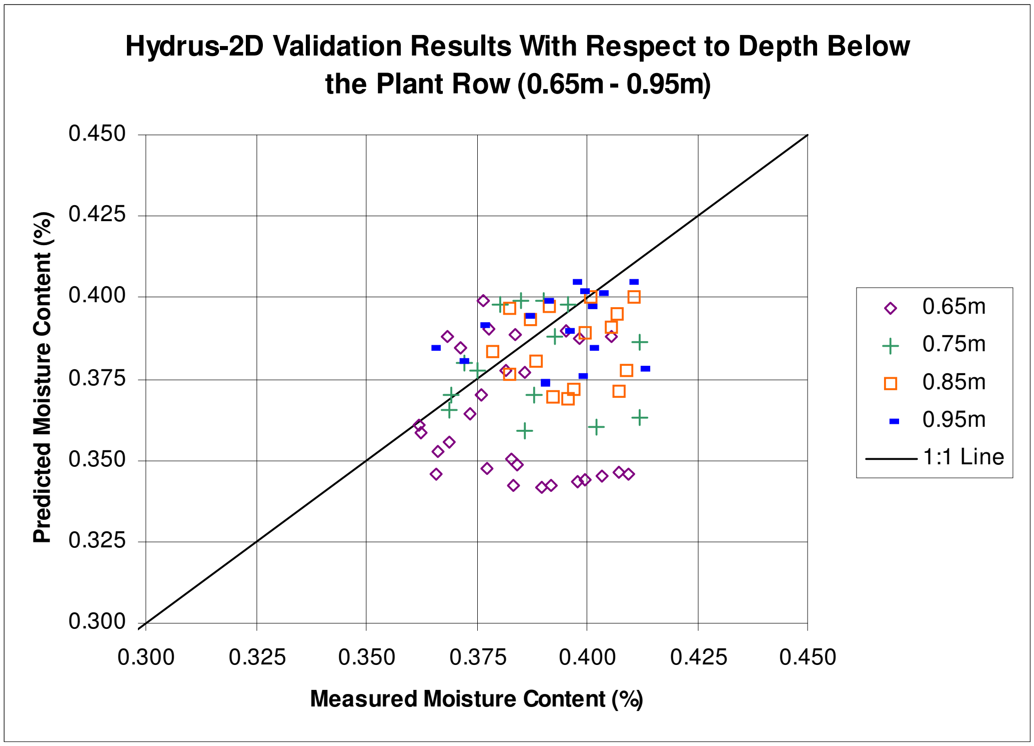


Figure 4.10. HYDRUS-2D validation results with respect to depth below the plant row (for 65 – 95 cm)

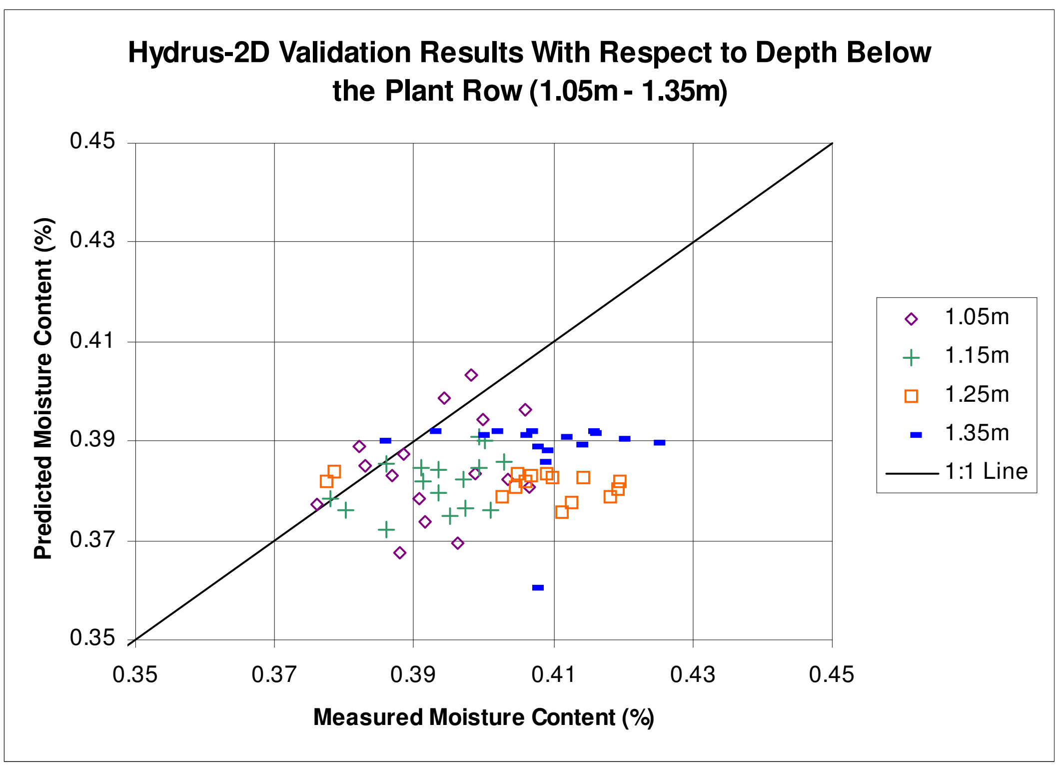


Figure 4.11. HYDRUS-2D validation results with respect to depth below the plant row (for 105 – 135 cm)

Figure 4.11 also shows that predicted values vary very little in the upper soil layers (at depths of 0.25 m and 0.35 m below the plant row). This could be due to the reasonably high value of saturated conductivity in this soil layer or it could represent an equilibrium moisture content caused by plant water uptake. This equilibrium moisture content is the value at which plant water uptake rapidly decreases, therefore over time the moisture content changes very little. Further investigations (ie analysis of the data), revealed that it was an equilibrium caused by plant water uptake.

4.2.3. Conclusion

Real-life conditions were simulated using HYDRUS-2D to validate the program and the parameters entered into it. The simulated soil moisture content values were then compared to in-field measurements. These measurements and simulation points were taken on specific days in four transects across the plant row at numerous depths.

Over short periods of time (ie less than 26 days), reasonably accurate simulations for soil water movement in cracking clay soils were created using HYDRUS-2D. Most errors were associated with under-prediction of soil moisture content values. These were most prevalent in the transects below the plant row, at greater depths in the soil profile (below 1 m) and as time progressed.

4.3. Investigation of PRD Effects

Using the validated soil and plant parameters, a range of commercially suitable irrigation treatments were simulated. All changes to the model parameters and values are detailed in Section 4.3.1, while the methodology of the investigation is outlined in Section 4.3.2. The results in Section 4.3.3 are followed by a discussion in Section 4.3.4 and a conclusion in Section 4.3.5.

4.3.1. Investigation Materials

Most of the simulation parameters are the same as the validation parameters and are therefore detailed in Chapter 3 and Section 4.1, however the atmospheric conditions, plant root distribution and initial conditions are unique to these investigations.

4.3.1.1. Evaporation, Transpiration and Rainfall Quantities

Throughout these simulations, the same values for evaporation and transpiration were used each day. Remaining consistent with the values used in the validation, evaporation was taken to be 1 mm per day. Transpiration values were taken to be the average of the values used for the validation. This meant that the potential transpiration was taken to be 11 mm per day. To ensure the maximum possible opportunity for a substantial pressure head gradient to occur, throughout the simulations it was assumed that there was no rainfall.

4.3.1.2. The Plant Root Parameters

Table 4.3 shows how the root distribution parameters varied with depth from the top of the plant row.

Table 4.3. Root distribution with depth below the plant row

Depth Below the Plant Row (cm)	Root Density
0-10	4
10-20	3
20-30	2
30-40	1
40-60	0.5

It is important to realise that the root intensity and depth of the root zone change as the cotton plant grows. The values (Table 4.3) used in the modelling were arbitrarily chosen to represent the cotton plant root extraction pattern during mid-season. Whilst cotton roots can extend deep into the ground, under irrigated conditions it is believed that most extraction occurs in the top 40 cm of the root zone. Some plant water extraction may also occur at a depth of 40-60 cm, therefore a relatively small density value was placed at this depth.

4.3.1.3. Initial Conditions

The initial conditions for each of the irrigation regimes remained the same. These initial conditions were formed by beginning with a soil profile with a consistent negative pressure head of 10 kPa (field capacity). The soil profile was then acted upon (drained, water extracted from it, etc) until a pressure head of 100 kPa was reached at a depth of 25 cm below the plant row. To the nearest one quarter of a day, this process took 4.25 days. The selection of this initial condition was chosen because this is the nominated refill point for many cotton producers on the Darling Downs.

4.3.2. Investigation Methods

To investigate the ability to impose effective PRD irrigation regimes on cracking clay soils, HYDRUS-2D was used to simulate a series of irrigation techniques (application volumes and frequencies) using the validated parameters. Numerous simulations were computed for each irrigation frequency (every 2, 4, 6 and 8 days). For each irrigation frequency, application amounts of between 10 mm and 80 mm (at increments of 10 mm) were applied for either 20 or 24 days. This time period was selected because it was the time period for which HYDRUS-2D and the parameters entered were found to be valid. Unfortunately, when 10 mm irrigations were applied the internal water balance errors were found to be excessive. For this reason, the 10 mm irrigations do not appear in the results or any further analysis. These large errors may be due to the excessive drying of the soil surface due to evaporation and large plant transpiration values (ie very dry soil profiles), combined with the application of very small amounts of water spread over a large surface area.

The soil moisture gradient across the 1 m plant row was measured at a depth of 30 cm from a point directly below the middle of the wetted furrow to directly below the dry furrow one day after each irrigation and just prior to the next irrigation. At this stage, the stress gradient required to create a PRD effect in cotton is unknown, however it is believed that it would need to be at least 100 kPa. In circumstances where the soil moisture potential on the wetted side of the plant row became drier than 200 kPa it was assumed that the plant would be experiencing deficit irrigation stress and therefore the gradient across the plant would not induce a PRD response. Consequently, the criterion used in this project was that the soil moisture potential on the wetted side of the plant row needed to be maintained at less than 200 kPa and the pressure head gradient across the plant row needed to be greater than 100 kPa to induce a PRD response in cotton.

4.3.3. Results

None of the applied irrigation strategies could create a pressure differential of a least 100 kPa (the minimum thought to be able to create PRD effects in cotton) without causing deficit irrigation (Figures 4.11 – 4.14). Deficit irrigation was assumed to be occurring once the potential directly below the wetted furrow at a depth of 30 cm below the top of the plant row reached 200 kPa. The largest stress gradient that could be created without causing deficit irrigation was approximately 53.2 kPa (Figure 4.9). This gradient dropped to 45.5 kPa just prior to the next irrigation (ie one day later). These gradients were achieved during the ninth cycle of applying 20 mm irrigations every two days. The values found to create Figures 4.11 – 4.14 can be found in Tables E.1 – E.4 in Appendix E.

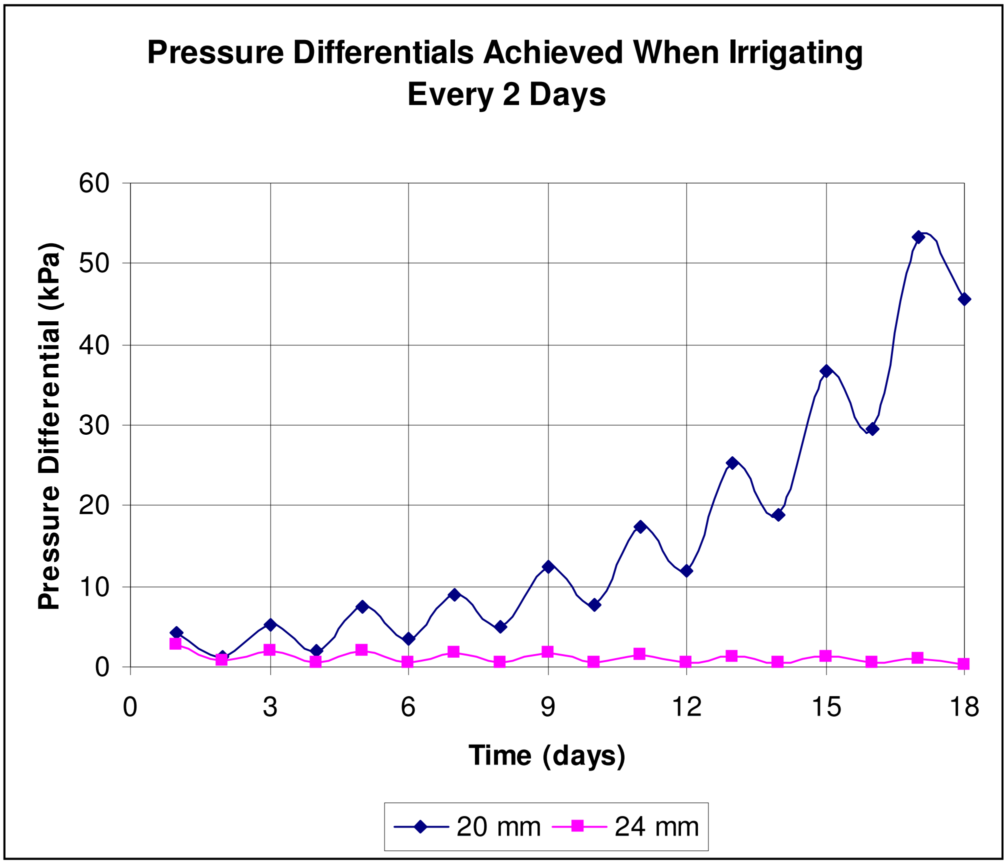


Figure 4.11. Pressure Differentials Achieved When Irrigating Every 2 Days

Note from Figure 4.11 that smaller gradients were achieved using 24 mm irrigations than using 20 mm. For this reason no irrigations of greater volumes were attempted. Note that in Figures 4.12 – 4.14 substantial gradients were obtained, however these irrigations caused deficit irrigation stress.

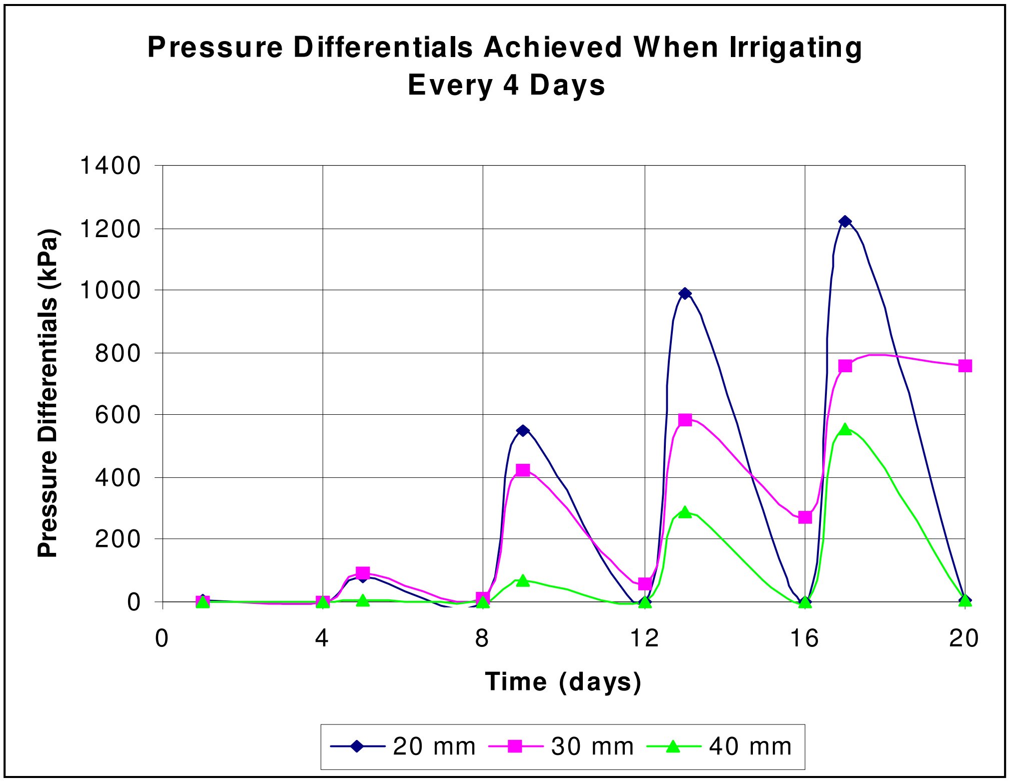


Figure 4.12. Pressure Differentials Achieved When Irrigating Every 4 Days

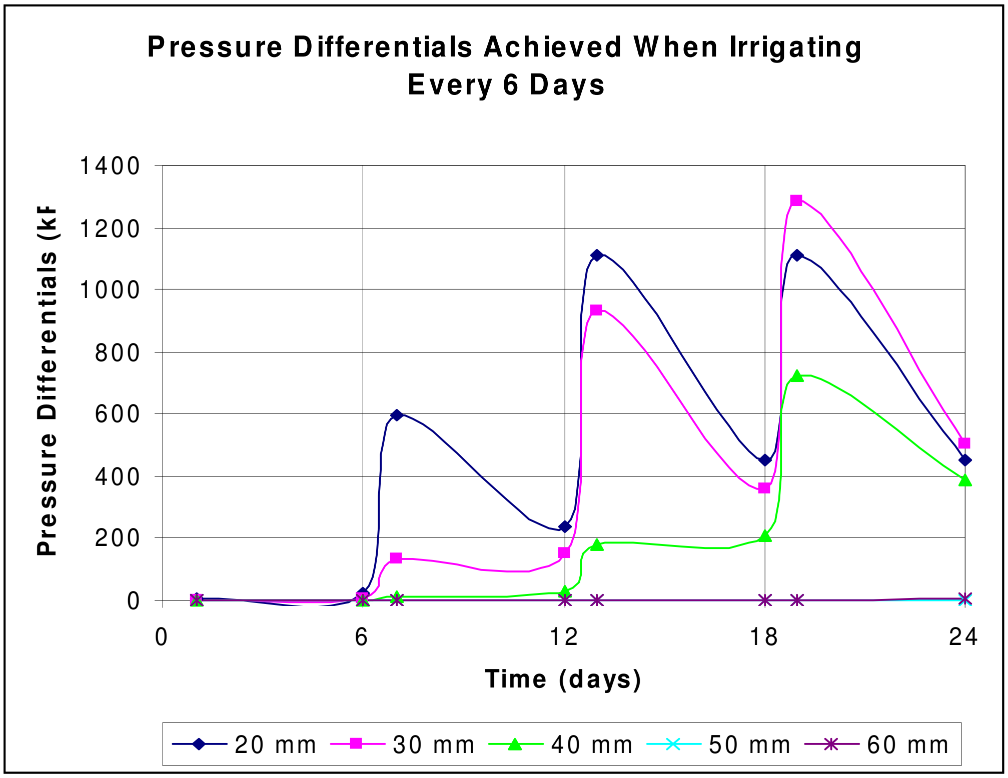


Figure 4.13. Pressure Differentials Achieved When Irrigating Every 6 Days

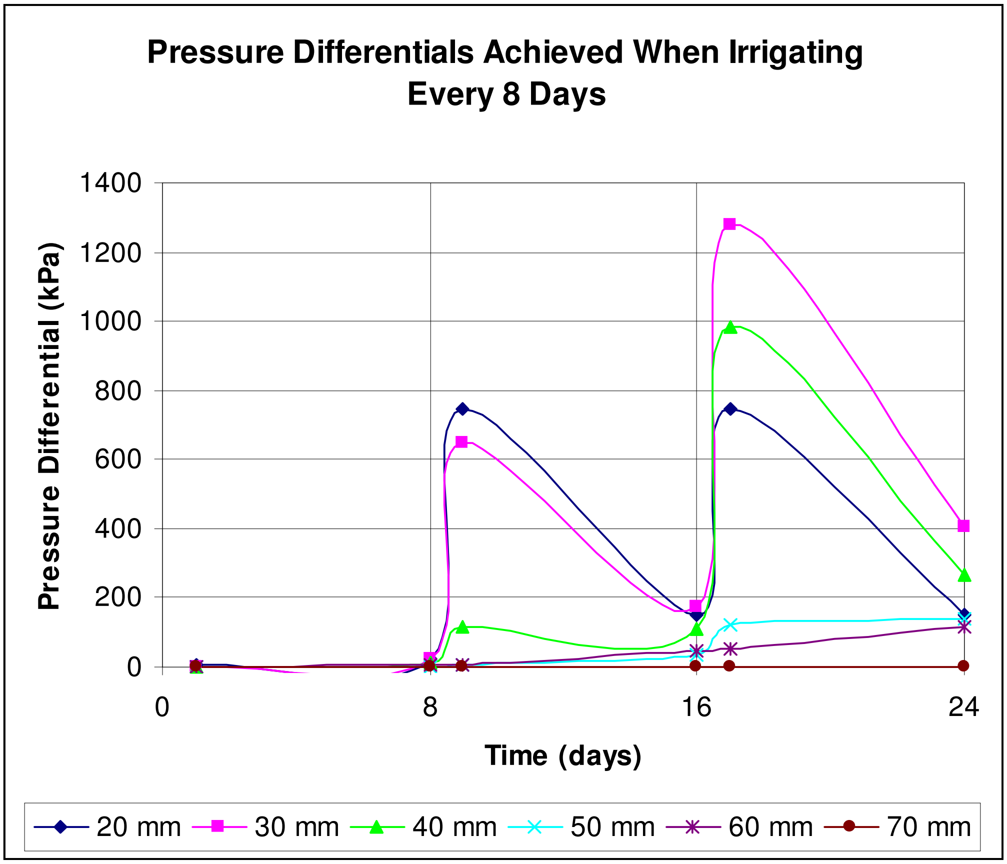


Figure 4.14. Pressure Differentials Achieved When Irrigating Every 8 Days

4.3.4. Discussion

Based on the selected criteria and using the enter parameters, none of the irrigation strategies applied (ie. combinations of irrigation frequency and volume) to this soil produced a soil moisture potential gradient large enough to induce partial root zone drying effects without causing deficit irrigation. The largest gradient that could be created without causing deficit irrigation stress was 53.2 kPa (Figure 4.11). This occurred one day after the ninth 20 mm irrigation applied every two days. This gradient dropped to 45.5 kPa just prior to the next irrigation (ie one day later). For the time periods that the irrigation regimes were simulated for, the only regime that could create pressure head gradients greater than 10 kPa without causing deficit irrigation stress was by applying 20 mm irrigations every two days.

The reasons why significant gradients could not be achieved without causing deficit irrigation stress are unknown, however there are a number of possible explanations. These come under two broad categories, either the creation of PRD effects is not possible for the commercial production of cotton on cracking clay soils, or there are limitations associated with the modelling procedure used.

There are many parameters used in HYDRUS-2D. Whilst these have been parameterised using the best available data, in some circumstances (especially those relating to plant water uptake and root distribution data) there was very little data available. The potential transpiration values also seem very high. To validate the model, values of up to 19.8 mm per day were used (see Table C.1 in Appendix C), created an average potential daily transpiration of approximately 11 mm.

In investigating the application of various alternate furrow irrigation regimes, only one set of initial conditions was used. However, using a different set of initial conditions could have led to different results. The use of different initial conditions for different irrigation amounts (as is done in the field) would also create some differences.

In this project, the stress gradients were only found at one depth (30 cm) below the plant row. By calculating the stress gradient at different depths (particularly at greater depths), larger stress gradients may have been found. It should also be noted that the method of water application may also have resulted in a reduced gradients. Under field conditions where low energy precision application socks are used on centre pivot and lateral move irrigation machines, the water has been observed to partially flow into cracks and not have as large a wetted perimeter as used in the simulations. Under these conditions the water would enter the soil over a much smaller surface area near the centre of the furrow. Of course there also exists the possibility that HYDRUS-2D can not accurately simulate such events and that the validation correlation was a coincidence, rather than an indication of the program's ability to predict field soil moisture conditions.

The creation of PRD effects may not be possible in the commercial production of irrigated cotton on cracking clay soils because of the large gradient required and the soil hydraulic properties. Gradients greater than 100 kPa across the plant row were found only when deficit irrigation strategies were applied and the average soil moisture in the profile exceeded 200 kPa. Whenever the average soil moisture in the profile was less than 200 kPa, then there was sufficient lateral movement of soil moisture, and differences in root extraction between the wetted and dried areas of the root zone, that the gradient remained less than 100 kPa. The use of cracking clay soils appears to be less than ideal for the creation of PRD effects. The upper layers of the soil have a very high hydraulic conductivity and application of irrigation water tends to spread laterally rapidly (ie before the plants can use the water).

4.3.5. Conclusion

Based on the assumed criteria for inducing PRD effects in cotton, none of the irrigation strategies applied (ie. combinations of irrigation frequency and volume) to this soil produced a soil moisture potential gradient large enough to induce partial root zone drying effects without causing deficit irrigation stress. However, further work is required to confirm these results under field conditions.

4.4. Investigation Using 'Macquarie Downs' Soil Conclusion

To investigate the ability to induce PRD effects on commercially grown cotton on cracking clay soils using HYDRUS-2D, appropriate parameters needed to be found for the program. These parameters, mostly relating soil and plant characteristics, were obtained from various sources, however most came from previous studies on the Darling Downs in south-east Queensland. The program HYDRUS-2D and the chosen parameters were then validated by comparison with recent PRD field trial data.

The predictive accuracy of the model simulations were found to progressively increase from 39% to 64% for decreasing simulated growth periods from 63 to 26 days. This led to the conclusion that over short periods of time (ie less than 26 days), reasonably accurate simulations for soil water movement in cracking clay soils were able to be created using HYDRUS-2D and the available soil, plant and climatic data. Most of the errors were associated with under prediction of soil moisture values in the transects below the plant row, at greater depths in the soil profile (below 1 m) and as time progressed.

After validation, the model was used to simulate soil-water movement associated with a range of different irrigation frequencies and quantities. These irrigation regimes covered irrigation frequencies of 2, 4, 6 and 8 days combined with application volumes ranging from 10 to 80 mm and over a period of 20-24 days. The frequent application of 10 mm irrigations caused excessive internal water balance errors and therefore these irrigation regimes were neglected from further analysis. The pressure head gradient across the 1 m plant row was measured at a depth of 30 cm from a point directly below the middle of the wetted furrow to directly below the dry furrow.

To induce a PRD response, the soil moisture potential at 30 cm depth on the wetted side of the plant row needed to be maintained at less than 200 kPa and the gradient across the plant row needed to be greater than 100 kPa. Where the soil moisture potential on the wetted side of the plant row exceeded 200 kPa it was assumed that the plant would be experiencing a significant deficit irrigation stress and the gradient across the plant would not induce a PRD response. Based on these criteria, none of the irrigation strategies applied (ie. combinations of irrigation frequency and volume) to this soil produced a soil moisture potential gradient large enough to induce partial root zone drying effects without causing deficit irrigation. However, further work is required to confirm these results under field conditions.

5. Investigation of PRD on the Jondaryan Soil

The aim of this section was to complete another validation and investigation of cracking clay soils used for commercial cotton production. This time a soil used in a partial root zone drying field trial near Jondaryan was used. In this circumstance the model soil parameters were measured in the field and using laboratory tests. Unfortunately this soil was unable to be validated or used in investigations due to modelling limitations. This chapter therefore covers the attempt to parameterise and validate HYDRUS-2D.

Spatial and temporal soil moisture measurements taken in conjunction with the first double ring infiltrometer test were to be used to validate HYDRUS-2D for the Jondaryn soil. Unfortunately this activity showed no significant temporal changes to the soil moisture content of the surrounding soil and therefore could not be used for validation.

Similarly to the validation of the 'Macquarie Downs" soil, validation of the Jondaryn soil was based on comparison with actual partial root zone drying field trial data at the site. In this trial, the cotton was planted on 29 October 2003 and harvested on 30 March 2004. Due to continual rainfall throughout November, the first soil moisture measurements (made with a neutron moisture meter) were not made until 23 December 2003, just prior to the first irrigation. The final soil moisture measurements made before irrigations returned to full sprinkler emission (rather than LEPA application) were made on 16 February 2004. Consequently the validation simulation period was from 23 December 2003 to 16 February 2004. This is a total of 55 days, containing twelve comparison times (ie times that soil moisture measurements were made), three 30 mm LEPA irrigations and approximately 260 mm of rainfall.

Similarly to the validation data for the 'Macquarie Downs" soil, the measurement data is available for four neutron moisture meter tubes placed across the plant row as a transect. With respect to the middle of a furrow, the tubes are placed 0 cm, 33 cm, 67 cm and 100 cm away from the furrow. Since the plant rows (and therefore furrows) have 1 m centres, this means that the tubes are placed in the middle of the two adjacent furrows and two-thirds of the way up either side of the enclosed plant row. The two middle tubes are offset from the transect to ensure that each reading is unique. The neutron moisture meter determines its value based on a sphere of influence of approximately 15-20 cm. By offsetting the access tubes, none of the spheres of influence should overlap, therefore the effect of a small wet or dry spot is unlikely to effect readings from more than one access tube (distance away from the furrow). This offset is not of concern when comparing measured results with modelled results because HYDRUS-2D assumes that the 2D plane is of infinite width. Since the entire project does not account for lateral variation in soil properties, this is not a problem. In this section of the trial, the irrigated furrows are not alternated, therefore during all of the irrigations the water is applied to the one furrow.

The neutron moisture meter estimated the soil moisture content at depths from 30 cm to 100 cm below the soil surface at increments of 10 cm for each of the tubes. These depths then needed to be adjusted to become depths below the plant row. In doing this it was assumed that the two middle tubes were on the plant row and therefore didn't require adjustment. Since the two outer tubes were in the furrows, these depths were adjusted by subtracting 10 cm (ie a depth of 30 cm below the soil surface became a depth of 40 cm below the plant row). For each comparison time, there are therefore 30 measurement points available for comparison with the simulated values.

5.1. Materials

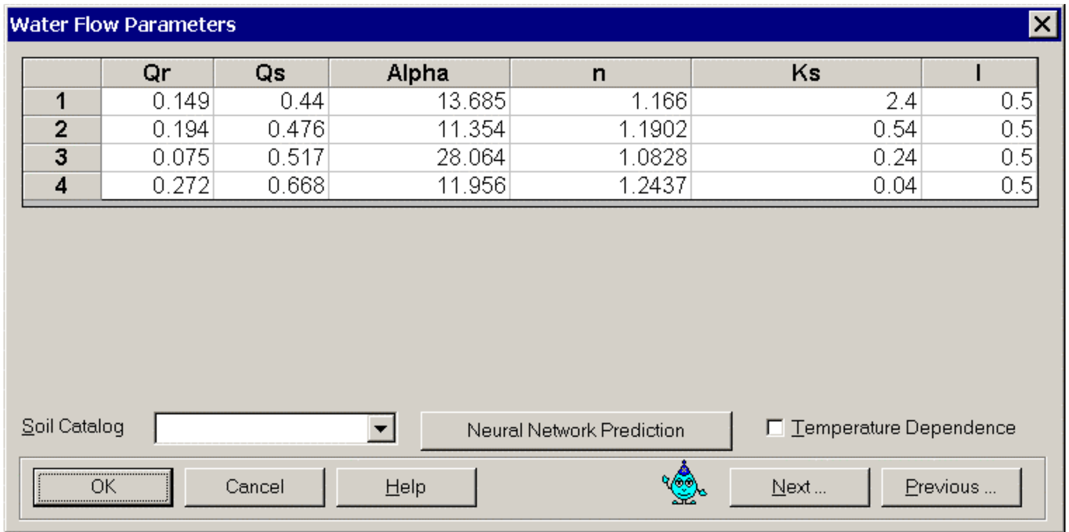
The materials for investigation of PRD on the Jondaryan soil include details about the field trial site, including the soil parameters obtained and the geometry of the soil profile simulated. Other details include atmospheric data, plant root distribution data and the initial soil moisture conditions for the validation. Further parameters and details, ie those common to both the Jondaryan and the 'Macquarie Downs" soil, are available in Chapter 3.

5.1.1. Site

The soil for this investigation was based on that a field trial site located at approximately S27° 22.6' E151° 37.4' (slightly East of Jondaryan on the eastern Darling Downs). The validation, soil and plant data was collected from the partial root zone drying field trial on conventional cotton (Sicot 78) conducted over the 2003-2004 season. The soil could best be described as a brown-grey medium cracking clay. Soil cores taken near the trial revealed layers approximately coinciding with 15 cm, 30 cm and 60 cm below the surface. At around 1 m below the surface some red-yellow mottling was evident. This aspect of the soil was disregarded because the investigation only dealt with the top metre of the soil profile.

5.1.2. Soil parameters

HYDRUS-2D requires parameters to define the hydraulic conductivity curve and the soil water retention curve according to the van Genuchten-Mualem model. The soil water retention curve was determined using the software package, SWRC (Dourado-Neto et al. 2001). This required a number of measured points along the curve, which were found from pressure chambers tests undertaken on soil cores. The saturated hydraulic conductivity values were found from double ring infiltrometer tests. The details of these tests are available in Chapter 6. For layers from 0-15 cm, 15-30 cm, 30-60 cm and 60-100 cm, Figure 5.1 shows the soil parameters found.



	Qr	Qs	Alpha	n	Ks	l
1	0.149	0.44	13.685	1.166	2.4	0.5
2	0.194	0.476	11.354	1.1902	0.54	0.5
3	0.075	0.517	28.064	1.0828	0.24	0.5
4	0.272	0.668	11.956	1.2437	0.04	0.5

Figure 5.1. Soil parameters for the Jondaryan soil

5.1.3. Plant root depths

Estimations of the cotton plant root depths were made using soil water extraction data from an enviroSCAN used during the field trial. The enviroSCAN graph (given as Figure F.1 in Appendix F) shows changes in soil water content over time. These values were recorded every 30 minutes at depths of 20cm, 40cm, 60cm and 80cm below the plant row. When the soil water content at a particular depth began to decrease, it indicated that the plant roots had reached that depth and become activated. This process resulted in the plant root depths during the validation time period shown in Table 5.1 below. The root distribution was merely a linear density change from 4 down to 1 from the surface (0 cm) down to the maximum rooting depth.

Table 5.1. Validation maximum rooting depths

Time Period	Maximum Rooting Depth
23 December – 4 January	60 cm
5 January – 19 January	70 cm
20 January – 3 February	80 cm
4 February – 16 February	90 cm

5.1.4. Evaporation, Transpiration and Rainfall Quantities

The maximum possible evaporation and transpiration values were calculated using WaterSCHED (Harris 2002). This required the provision of weather data obtained by an automatic weather station based at the trial site and various plant parameters (to calculate crop coefficients). The default parameters for a cotton plant were used where further details were unavailable. The basal crop coefficient values were adjusted by Simon White according to leaf-area index data collected during the trial. Note that the maximum potential evaporation and transpiration values were selected from the program, rather than the actual values normally used.

The rainfall quantities and timing were also recorded by the on-site automatic weather station. The rainfall, evaporation and transpiration values for each day of the simulation period are shown in Table F.2 (Appendix F). In HYDRUS-2D rainfall, evaporation and transpiration values are defined as rates, therefore the amounts per day are the average rates in metres per day and are therefore used in the simulations. Note that for part days this rate my not always be very accurate because the actual rate fluctuates throughout the day. For example, if the time period is the final quarter of the day, most of this time will be during darkness, therefore the amount of transpiration and evaporation is likely to me much, much lower than the daily average.

Table F.2 (Appendix F) also gives the effective rainfall. During the simulation there was approximately 260 mm of rainfall, of which some was effective rainfall (ie that which infiltrated into the soil profile) and some was runoff. HYDRUS-2D accounts for this if the rainfall rate is greater than the soil's infiltration rate at any point in time. When this occurs the remainder of the rainfall becomes losses. Unfortunately the timing of the rainfall events is only known to the day, therefore the actual rate of rainfall during each event is unknown.

Nominal effective rainfall values can be computed based on a percent of rainfall being effective and a percent becoming runoff and other losses. Unfortunately this approach is not very precise because the amount of rainfall that enters the soil profile is usually a function of the initial soil moisture conditions and the rainfall rate. For example a storm with a high rainfall rate normally produces a high amount of runoff and contributes very little to the soil moisture stores. Investigation of enviroSCAN curves during these periods and based on industry recommendations, the effective rainfall was estimated to be 45 % of each rainfall event. Obviously this is an extremely rough approximation. How effect rainfall is depends on the current infiltration capacity and characteristic of the soil, the rainfall rate and the initial soil moisture content.

The average of the potential daily evaporation and transpiration over the 55 day simulation period was 1.8 mm per day and 8.7 mm per day respectively. These values seem quite realistic, especially for that time of year.

5.1.5. Initial Soil Moisture Conditions

The initial soil moisture conditions are those obtained using a neutron moisture meter at approximately 2:45 pm on 23 December 2003 at the trial site. Due to this measurement time, the initial time used in HYDRUS-2D is 0.615 days rather than the usual starting time of 0 days. The initial moisture conditions are shown graphically in Figure 5.3 and can be seen in tabular form in Table F.3 in Appendix F.

Each of the values in Table F.3 (Appendix F) took on the area 16.7 cm to the left and 16.7 cm to the right of itself. The initial conditions for the validation of the 'Macquarie Downs" soil interpolated between each of the tube sites (ie mid-way between the 0 cm, 33.3 cm, 66.7 cm and 100.0 cm positions). This step no longer seemed necessary and was therefore ignored. The model results after five days indicate that the large 'steps' that appear in the graphical representation of the initial conditions were removed, mostly due to the actions associated with root water uptake.

The volumetric soil moisture content value for 0.33 m away from the irrigated furrow at a depth of 30 cm was missing. The value below this (ie at a depth of 40 cm, located 0.33 m away from the irrigated furrow) and beside it (ie at a depth of 30 cm in the irrigated furrow) were both 41.1%, therefore the missing number was also assigned that value.

Although no irrigations had occurred yet, the furrow that was to be irrigated had a significantly higher soil moisture content than the unirrigated furrow. A number of reasons were proposed, however none of them appear feasible. Initially it was thought that perhaps the 'wet' access tube was uncharacteristically wet, possibly due to cracking around the tube and water therefore sitting beside tube. This theory was upon realising that the soil moisture content values progressively decreased as the distance from the wet furrow increased. The second theory was that the 'progression' occurred as a result of the counting spheres of the neutron probe access tubes overlapping and therefore registering the same 'wet spot'. Due to the set-up, the spheres of influence of each access tube should not interact. In conclusion this difference appears to be a natural unexplained phenomena.

5.1.6. Model Geometry

The geometry of the Jondaryan soil profile was slightly different to that used in the 'Macquarie Downs" field trial and simulations. The furrow depths at the Jondaryan site were approximately 100 mm below the top of the plant row, rather than the 150 mm at 'Macquarie Downs". Due to the change in soil layers at approximately 1 m below the soil surface, the soil profile for the Jondaryan site was only modelled to 1 m below the plant row. Although root extraction occurs up to 0.9 m below the plant row, this depth should still be great enough to allow all natural plant water uptake to occur. This is especially the case since the plant water uptake at a depth of 0.9 m only has a root density of 1 (see Table 5.1).

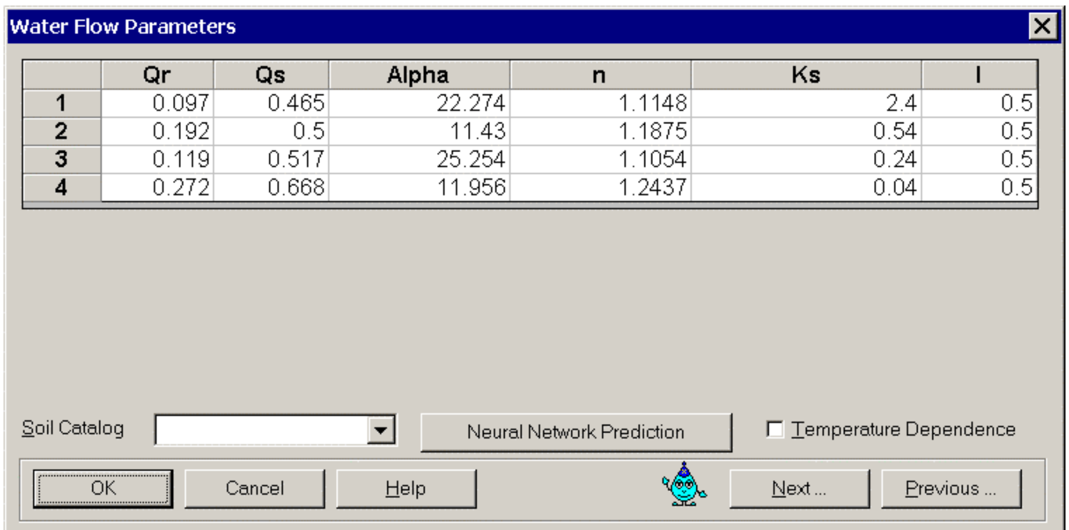
5.2. Method

Using the parameters described, the validation event was modelled using HYDRUS-2D. The first simulation ran from the starting time until the beginning of the irrigation on 1 January 2004. The second simulation then used the output of the first simulation as its initial conditions, changed part of the boundary type and applied the water. This simulation ran until 30 mm of irrigation water had been applied, which took approximately 0.04 days (one hour). After the irrigation event the third simulation began, once again using the output of the previous simulation as the initial values.

Unfortunately the model then crashed. After only a few successful iterations, the model failed to converge. Many parameters were adjusted in an attempt to rectify this problem, however the problem continued. During the most extreme conditions the mesh had a grid size of less than one centimetre and the minimum time step was 8.64 millionths of a second. The initial time step was reduced, the pressure head and water content tolerances were increased, and the tension intervals were adjusted.

The high pressure gradients caused by a saturated zone just near an evaporative surface were thought to be contributing towards the problem, therefore some trials were simulated neglecting evaporation. Investigation of the initial conditions then caused changes to be made in that area. The values provided for the 40 cm, 50 cm and 60 cm depths located in and adjacent to the irrigated furrow were too moist, especially for the upper soil layers. The soil moisture contents given were associated with pressure heads wetter than field capacity. According to the root water uptake parameters at these moisture contents the plants are waterlogged and therefore not extracting water from the profile. Given knowledge of the antecedent weather conditions and the need to incorporate root water extraction (to prevent the profile from becoming saturated during irrigations), all soil moisture values wetter than field capacity were adjusted accordingly.

The soil properties were also adjusted. Instead of using all three samples discussed in Chapter 6 to determine the soil water retention curve only the two similar results were selected. This resulted in a soil with the properties shown in Figure 5.2.



	Qr	Qs	Alpha	n	Ks	l
1	0.097	0.465	22.274	1.1148	2.4	0.5
2	0.192	0.5	11.43	1.1875	0.54	0.5
3	0.119	0.517	25.254	1.1054	0.24	0.5
4	0.272	0.668	11.956	1.2437	0.04	0.5

Figure 5.2. Adjusted soil parameters for Jondaryan soil

Unfortunately the attempted combinations of initial conditions, time step parameters, tension interval parameters, iteration criteria, mesh refinement and soil property adjustment did not result in successfully redistributing the water after the first irrigation. In case the problem was due to some initial condition or validation value, simulations like those in Chapter 4 were attempted. Unfortunately these too failed after applying the first irrigation.

It was noticed that the soil parameter *alpha* for the 'Macquarie Downs' soil was only approximately one-tenth of those used in these investigations. It is likely that this has had a major impact on the soil and HYDRUS-2D's ability to model the imposed conditions.

5.3. Results and Discussion

There are number of error sources involved with determining the values in Table 5.1 (the root extraction pattern). The enviroSCAN loggers were not in the same location as the validation measurement points, therefore the plants at the validation points may have had a different growth rate and root depth exploration rate. This would affect the timing of the actual changes to the root extraction pattern. A similar error is that the depths that the enviroSCAN readings are given at would not be exact. For example when the enviroSCAN readings indicate that soil water has been extracted from 80 cm, it may have been extracted from 78 cm or 82 cm below the plant row. This error would also effect the timing of the actual changes to the root extraction pattern.

Regardless of this potential difference, the timing given for the maximum depth reached is not exact either. The actual date that the roots began extracting at each depth is actually in the middle of each time period. For example, according to the enviroSCAN data, soil water extraction began at 60 cm on 28 December 2004 and soil water extraction began at 80 cm on 27 January 2004. The time period for roots to each depth was made such that the corresponding date was in the middle of the time period. This was because for the week prior the roots would not have reached the corresponding depth, however for the week after this date, the roots would have extended to explore further depths. It was hoped that placing the actual day in the middle would create both over and under-estimation of soil water content values, rather than consistently over or under-predicting.

The enviroSCAN data only gives soil moisture content changes at depths of 20 cm, 40 cm, 60 cm and 80 cm below the profile, therefore the extensions to 70 cm and 90 cm were interpolated. These interpolations were mostly supported by the neutron moisture meter measurements at these depths.

Note also that the enviroSCAN data gives the dates at which soil moisture content initially decreases at each depth, not necessarily the date at which the roots reach this depth. By drying out the surrounding soil, plant roots are able to draw soil water from around them. Fortunately, due to the need to overcome gravity forces, plant roots are usually unable to draw soil water vertically upward from great distances, therefore the assumption that soil water extraction only occurs when plant roots reach that depth is reasonable.

Whilst most of these errors (with the exception of the intensity allocation theory) appear to be very minor, timing errors of a few days could significantly effect the simulated soil moisture contents at certain validation times, especially for those points located close to the change in root depth. The errors associated with soil properties are discussed in Chapter 6, however based on available literature the parameters obtained are realistic.

The values chosen to parameterise the root water uptake characteristic (Feddes model) are also questionable. During the nine days prior to the first irrigation, the simulated soil dried out to field capacity down to at least 40 cm below the top of the plant row whether evaporation was included or not. Different values were tried (for example changing P2H to –8 and P2L to –20, as well as adjusting r2L to 0.001), however they had little impact upon the results. The soil only took marginally longer to dry down to that much.

5.4. Conclusion

Although soil parameters were found and validation data collected, HYDRUS-2D was unable to reproduce the validation circumstances or investigate the potential to impose partial root zone drying on cracking clay soils. This problem could be due to model limitations or parameterisation errors.

6. Jondaryan Soil Properties

The soil properties for the Jondaryan soil were found from appropriate physical tests. The tests were an in-field double ring infiltrometer test to determine the saturated hydraulic conductivities and a laboratory pressure chamber test to determine points on the soil water retention curve.

6.1. Hydraulic Conductivity Curves

The saturated hydraulic conductivity values were required to define the hydraulic conductivity curve for each soil layer. This was determined for each soil layer from two double ring infiltrometer tests.

6.1.1. Materials

The double ring infiltrometer test equipment was borrowed from the Department of Primary Industries and Fisheries, Redland Bay. The tests were conducted on the 21-22 July and 25 July 2004 in close proximity to the field trial area. This area had been fallow since significant rainfall and therefore the soil moisture content at each depth was expected to be reasonably constant across the area of the tests.

A typical double ring infiltrometer test is set up as shown in Figure 6.1 below. The two rings (diameters of 30 cm and 50 cm) hold a constant head of water above the soil surface and the volume of water that infiltrates over time (as determined by the volume of water required to maintain a constant water level) is recorded. Typically a constant head (water level) is achieved using Mariotte bottles. The smaller Mariotte bottle (diameter of 10.4 cm and volume of approximately three litres) is set up to maintain the water level in the inner ring. The water level between the outer and inner rings is held by the larger Mariotte bottle (diameter of 15.5 cm and volume of approximately seven litres).

Figure 6.1. Complete set-up of the double ring infiltrometer test

The Mariotte bottles have an attached clear plastic tube to read their water level (as shown in Figure 6.1) and when in the inverted working position, a plastic tube protruding from the bottom. This tube has a hole in it, known as the air entry hole. The Mariotte bottle is held at a constant height above the water level in the rings (eg rested on a piece of timber) such that the ring water level is in line with the top of the air entry hole. As the ring water level drops, air enters the Mariotte bottle and it releases water until the air entry ceases (ie the ring water level is returned to its original height at the top of the air entry hole).

A double ring infiltrometer is usually used in place of a single ring infiltrometer on soils with high clay content to mitigate the effects of lateral soil movement due to capillary action. The outer ring acts as a 'buffer', allowing for outward soil water movement whilst saturating the soil directly below it. This means that the water from the inner ring should only move vertically because the area adjacent to it is saturated. In practise this not always the case.

According to Hignett (n.d.) the steady state infiltration rate from the inner ring is approximately equal to the saturated hydraulic conductivity. According to (Reynolds et al. 2002), this is a very coarse approximation. For unilateral (ie only vertical) flow, Bouwer (1966, 1986, cited in Reynolds et al. 2002) applied the Green and Ampt (1911, cited in Reynolds et al. 2002) equation to produce the following equation:

$$\frac{q}{K_{fs}} = \frac{H}{L_f} + \frac{1}{\alpha^* L_f} + 1 \qquad (5.1)$$

Where: q = infiltration rate [L.T^{-1}]

K_{fs} = saturated hydraulic conductivity [L.T^{-1}]

H = ring water level [L]

L_f = distance from soil surface to the wetting front [L]

α^* = soil macroscopic capillary length [L^{-1}]

From equation 5.1, it can be seen that the rate of infiltration from the inner ring would approximate the saturated hydraulic conductivity when the distance between the wetting front and the soil surface (ie the infiltration surface) becomes large.

The average infiltration rate q [L.T^{-1}], between time t_2 [T] and time t_1 [T] can be calculated using equation 5.2 below, as provided by Hignett (n.d.):

$$q = \frac{d_2 - d_1}{t_2 - t_1} \times M \qquad (5.2)$$

Where: d_2 = Mariotte bottle reading at t_2 [L]

d_1 = Mariotte bottle reading at t_1 [L]

M = magnification factor []

Hignett (n.d., p. 7) defines the magnification factor as 'the ratio of the area of the wetted soil to the internal area of the Mariotte bottle'. Conversely, the magnification factor should actually be the inverse of that defined by Hignett (n.d., p. 7). The magnification factor M is therefore:

$$M = \frac{r_{Mariot}{}^2}{r_{ring}{}^2} \qquad (5.3)$$

Where: $r_{Mariotte}$ = internal radius of the Mariotte bottle [L]

r_{ring} = internal radius of the infiltrometer ring [L]

Since the average infiltration rate within each soil layer is required, the depth of the wetting front at each recording is required. This information is also needed to calculate the saturated hydraulic conductivity at each point (see equation 5.1). The total volume of water infiltrated under the inner ring up to each point in time can be determined from the total infiltrated millimetres at each point using equation 5.4 below.

$$V_{infilt} = d \times Area_{Mariotte} \times 1000 \qquad (5.4)$$

Where V_{infilt} is the total volume infiltrated in litres, d is the total depth of water extracted from the inner Mariotte bottle in metres and $Area_{Mariotte}$ is the crosssectional area of the inner Mariotte bottle in metres squared. Multiplying by 1000 converts the result from metres cubed into litres.

The volume of water required to fill each soil profile ($V_{required}$) was the difference between the average saturated volumetric soil moisture content ($\theta_{v\ sat.}$) in each layer and the average initial volumetric soil moisture content ($\theta_{v\ ini.}$) in each soil layer (see equation 5.5).

$$V_{required} = (\theta_{v\ sat.} - \theta_{v\ ini.}) \times V_{layer} \qquad (5.5)$$

V_{layer} is the total volume of the soil layer (ie the layer depth multiplied by the area of the inner infiltrometer ring). The average initial soil moisture contents were found from standard gravimetric oven drying tests. The saturated soil moisture contents were found from pressure chamber tests. The cumulative volume required to fill each soil layer can then be compared to the volume used up to each record point in the infiltrometer tests.

6.1.2. Method

Two tests were undertaken in accordance with directions given in the manual accompanying the double ring infiltrometer equipment (Hignett n.d.). The steps undertaken are reiterated in the following paragraphs. The smaller ring (30 cm diameter) was hammered into the ground. Because of the crumb layer (approximately 10 cm deep) overlying the remainder of the profile, the ring needed to be hammered about 12.5 cm into the ground (ie a few centimetres into the more compact soil. For the second test this crumb layer was removed as shown in Figure 6.2. The larger ring (50 cm diameter) was then hammered into the ground to approximately the same depth.

Figure 6.2. Crumb layer removed

As shown in Figure 6.3(a), inserting the rings caused significant cracks (ie 5 mm wide) to appear beside the ring walls. Higgets (n.d.) recommends using moist bentonite clay to fill these cracks and seal the rings to the soil, however due to resource constraints a mud slurry was used instead. This substitution should have acted in a similar manner to the bentonite because of the high clay content of the soil. Hessian was then placed over the soil surface within the rings, as shown in Figure 6.3(b). This was done to absorb some of the energy and therefore reduce the structural damage caused by instantaneously pouring large amounts of water over a small area.

Figure 6.4. **(a)** **(b)**

(a) Cracks caused by infiltrometer rings

(b) Hessian in rings to minimise water droplet impace

Before starting the test, the Mariotte bottles were set up. This involved determining where the water level should be in the rings and therefore where the holes in the bubbler tubes should be. These holes were then created using a stanley knife. After filling the Mariotte bottles the rings were then filled with water to the pre-determined level. The Mariotte bottles where then placed above the rings (as shown in Figure 6.1) and the trial began.

Accurate readings were not available during the first 10 minutes of the trial because of the time taken to fill the rings, the time required for the Mariotte bottles to stabilise the water level at the correct height and the high initial infiltration rate. This was compounded by the relatively small volume of the Mariotte bottles, therefore they required continual re-filling during this time period. After approximately the first 10 minutes reasonably accurate readings could be taken.

Normally either the time is recorded when the level of water in the Mariotte bottle decreases by a set amount or the level of water is read and recorded at set time intervals. Due to the 'erratic bubbling' (Cook n.d., p. 116) of the Mariotte bottles, the time and water level was recorded upon the completion of each 'bubble'. The surface tension of the water causes these bubbles.

Initially the water level was raised such that no air entered the bubbler tube (ie the water level was in line with the top of the air entry hole). As the water level dropped, the surface tension of the water held the water in the bubbler tube above the air entry hole. Finally the water level dropped low enough to force the surface tension to break and the water level in the bubbler tube fell below the top of the air entry hole. Once this happened the Mariotte bottle ‘bubbled’, releasing enough water to raise water level back up to the top of the air entry hole. These ‘bubbles’ occurred approximately every 30 mm, which equates to approximately 250 ml in the small Mariotte bottle and 570 ml in the large Mariotte bottle.

6.1.3. Results

The infiltration rates and total volume infiltrated to each recording point during the two tests can be seen in Appendix G. As shown in Table G.1 (Appendix G), the volume required to saturate the top one metre (100 cm) of the soil under the inner ring is approximately 8.9 L. During the first test, approximately 5.2 L infiltrated during the first two hours whereas approximately 12.1 L infiltrated during the first two hours of the second test (see Tables G.1 and G.2 in Appendix G). Not only did the total volume infiltrated seem rather high in the second test, water was still infiltrating at 18.8 mm/hr when the wetting front was estimated to have reached 100 cm below the soil surface. Upon visual inspection of soil at this depth, and in comparison to saturated hydraulic conductivities reported at this depth (Connolly et al. 2002; Connolly et al. 2001), this infiltration rate appeared excessive. For these reasons, results from the second test were neglected in further computations.

Table 6.1 below shows the results of applying equations 5.1, 5.2, 5.5 to Trial 1. Note that each of the depths in Table 6.1 are in the middle of each soil layer and can therefore be considered to be representative of their respective layers.

Depth (cm)	Cumulative Volume Required to Fill (L)	Q (mm/hr)	K_{sat} (mm/hr)	K_{sat} (mm/day)
7.5	1.7	310	100	2400
22.5	3.0	40	22.5	540
45.0	4.5	15	10	240
80.0	8.9	5	1.65	40

Table 6.1. Saturated hydraulic conductivities

6.1.4. Discussion

The are many potential errors associated with the hydraulic conductivity tests. Many of these relate to the physical ability to accurately measure quantities, however some of it is to do with the fulfilment of assumptions that the equations are based on.

The ability to read times and Mariotte bottle levels are small random errors that are further reduced by the magnification factor. The height that the Mariotte bottles are refilled to is a much larger source of error, however the readings effected by this do not appear to be too out of place.

During the tests there are many physical sources of error. If the water levels in the inner and outer ring are not the same then the water from the inner ring will not be representative of the water flow through the soil section beneath this ring. If the outer ring level is higher, then this water should move through the profile faster, partially wetting the area under the inner ring before the water from the inner ring can reach each depth. If the outer ring level is lower, then the water from the inner ring will move through the profile faster, therefore lateral soil water movement will occur into the surrounding unsaturated region. Fortunately the margin for error would be reasonably large (ie at least 5-10 mm). This is because the non-uniformity of soil and soil structure means that there will be differences in soil water travel speed whether the water levels are the same or not. Factors such as tortuosity and the presence of cracks would have a substantial impact on the movement of the water through the soil.

Sealing the rings to the surrounding soil was very difficult, especially when cracks as large as those in the second test (ie approximately 5 mm wide) appeared. If these are not sealed adequately, the rings will 'leak'. This will cause very high infiltration rates to be calculated in the upper soil layers. The presence of substantial natural cracks does this anyway, however these additional cracks add to the high infiltration rates. Since cracking within a soil is a function of the soil moisture content and the wetting and drying history of the soil, the amount of cracking present within the soil is highly variable with time anyway. This means that the infiltration rate is also highly variable.

The calculations to determine the depth that the water has infiltrated to are dependent on a number of assumptions. Firstly it assumes that each depth becomes totally saturated before gravity and soil moisture gradients move the water vertically through the soil. Secondly it assumes that the there is no lateral flow from the inner ring (ie all water from the inner ring remains beneath this ring). It also relies on accurate soil parameters, including the initial volumetric soil moisture contents obtained and the saturated volumetric soil moisture content values. The initial soil moisture contents should be reasonably accurate because they were created using gravimetric oven drying tests from eight soil cores located within 1.5 m of the infiltrometer rings. Recall that the site had been fallowed for six months and there had been no plant root water extraction, therefore the lateral changes in soil moisture content were minimal. Similar to the calculation of infiltration rates, the volume of water applied up to each time period must also be reasonably accurate.

6.2. Soil Water Retention Curve

The parameters for the soil water retention curve were estimated using the software, SWRC (Dourado-Neto et al. 2001). This required at least three points on the curve and then fitted the curve to the points based on the Newton-Raphson iterative method to minimise the sum of squares error. Three 46 mm diameter soil cores (ie two inch outer steel core diameter) were taken at the site of the double ring infiltrometer tests using the hydraulic soil-coring rig provided by the NCEA. A 20 mm sample was taken from each layer within each core. It was attempted to obtain a sample from approximately the top, middle and bottom of each layer. The top layer (0-15 cm) was an exception to this where all samples were taken from near the bottom of the layer because approximately the top 10cm of this layer was a crumb layer and therefore unsuitable for use in the pressure chamber.

These samples were saturated and placed in the pressure chamber provided by the Faculty of Engineering and Surveying at the University of Southern Queensland's Toowoomba campus where they were subjected to pressures of 460 kPa, 200 kPa, 100 kPa, 33 kPa and 0 kPa. At each of these pressures the samples were allowed to equilibrate (ie they remained at that pressure until the flow of water out of the samples ceased or reduced to an inconsequential rate). They were then weighed and the pressure was increased to the next recording value. After the weight of each sample had been determined for each of the pressures, the samples were oven dried at 100 ^{o}C to determine the mass of dry soil. Given the mass of the weight samples at each pressure, the gravimetric soil moisture content (θ_g) could then be determined for each sample at each pressure using equation 5.6.

$$\theta_g = \frac{m_{wet} - m_{dry}}{m_{dry}} \tag{5.6}$$

Where: m_{wet} = mass of wet soil [M]

m_{dry} = mass of dry soil [M]

The gravimetric soil moisture content values (θ_g) were then converted to volumetric soil moisture content values (θ_v) using equation 5.7.

$$\theta_v = \rho_b \times \theta_g \tag{5.7}$$

Where ρ_g is the average bulk density of the soil in that layer. The result in Table 6.2 show the average bulk density for each for each soil layer, together with the average volumetric soil moisture content for each layer and pressure combination.

Depth (cm)	ρ_g **(g/cm^3)**	θ_v **at 460 kPa**	θ_v **at 200 kPa**	θ_v **at 100 kPa**	θ_v **at 33 kPa**	θ_v **at 0 kPa (saturation)**
0-15	1.27	24.9%	26.1%	28.0%	30.3%	44.0%
15-30	1.41	28.0%	29.2%	31.1%	33.5%	47.6%
30-60	1.40	31.9%	33.4%	35.4%	37.8%	51.7%
60-100	1.44	35.7%	37.4%	39.7%	43.3%	66.8%

Table 6.2. Average pressure chamber results for each soil layer

For each layer, the volumetric soil moisture content at each pressure was input into SWRC. SWRC can calculate the parameters for a number of soil water retention curve equations, however the van Genuchten Model was selected in this case because that is what is selected for use in HYDRUS-2D. After looking at the parameters used in the 'Macquarie Downs' soil investigation, initial values of 0.5 and 1.2 were chosen for *alpha* and *n* respectively. In accordance with the calculation methods used by HYDRUS-2D, the parameter *m* was set to be dependent on the value of *n* in accordance with Mualem's recommendations. To use the values shown in Table 6.2, the soil moisture content values were converted to decimals with units of cm^3/cm^3 and the pressure values were given with the units of kPa.

Although a saturated soil water content value had been obtained, it was decided to extrapolate the saturated soil water content based on methods proposed by Jong-van-Lier and Dourado-Neto. The same option was chosen to compute the residual soil water content. The only limitations imposed were for the residual soil water content to be positive and for the saturated soil water content to be less than or equal to one. The van Genuchten parameters produced by SWRC are summarised in Table 6.3 below.

Depth (cm)	*Alpha* (kPa^{-1})	*n*	Residual Soil Moisture (*Qr*)	Saturated Soil Moisture (*Qs*)
0-15	1.3685	1.1660	0.149	0.440
15-30	1.1354	1.1902	0.194	0.476
30-60	2.8064	1.0828	0.075	0.517
60-100	1.1956	1.2437	0.272	0.668

Table 6.3. SWRC's van Genuchten parameters

Although the parameters *alpha*, *n* and *Qr* calculated for the 30-60 cm layer did not seem to fit in, because of the lack of other information these parameters were used for the validation and investigation of the Jondaryan soil.

6.2.1. Discussion

Although a curve was successfully fitted to the data points, there were many potential sources of error. Most of the potential error sources involved in calculating the soil water retention curve parameters are related to the spatial variability of soils and physical measurement limitations. This variation is especially great in this circumstance because the soil data collection site was approximately 250 metres away from where the validation soil moisture content data was collected.

Physical measurement limitations include the ability to accurately weigh the soil samples and determine their volume. These random errors are not expected to be of concern because the errors are small and multiple sampling usually reduces random error due to the cancelling effect of positive and negative errors. The random spatial variability of the soil properties also means that even if these measurements were perfect, the results would still not be the exact properties of the validation soil. In fact, the properties of the soil would vary over the 0.5 m^2 area enclosing the validation measurement points (ie the neutron moisture meter access tubes).

Physical measurement limitations also include the non-random errors of the ability to apply the pressures and reach equilibrium in the pressure plate analyses. The ability to apply exact pressures is limited by the accuracy of and the ability to read the pressure dial. These errors are only expected to be within a few kilopascals and are therefore insignificant. Whilst this may appear to be a random error, it is not because all of the samples are subjected to the pressure at the same time and are therefore each pressure reading for all of them is either under or over read.

In some circumstances, the water had not totally ceased to flow from the soil samples because of the pressure. In these circumstances the measured soil moisture content (ignoring other measurement errors) would be greater than that obtained if equilibrium had been reached (ie water had stopped flowing out of the soil sample). In these circumstances the flow of water had become so small that it would have made very little difference to the soil moisture content anyway.

Of greater concern is a non-random error associated with the wet masses of the soil samples. These samples were weighed on the wet filter paper that they sat on in the pressure chamber. In contrast, in the oven dried masses the filter paper would also have been dried. Consequently the soil moisture contents (both gravimetric and volumetric) would have been slightly over estimated because some of the measured moisture would have been in the filter paper, rather than in the equilibrated soil sample. This error could be approximately eradicated by placing a wet filter paper on the pressure plate with the samples and weighing it each time the samples equilibrate (ie have one sample with no soil on it).

In contrast, the ability of oven drying to remove all of the soil water and leave only soil is not perfect. This process will always leave some tightly held water in the soil. Consequently the gravimetric and volumetric soil moisture contents would have been slightly under-predicted. The amount of this under-prediction is unlikely to cause differences within the first three significant figures of the values calculated.

7. Final Conclusions

The results of this project indicate that partial root zone drying is not possible on cracking clay soils under commercial cotton production, however further work is needed to confirm these findings. The difficulty in appropriately parameterising the soil water movement model indicates that there are many potential areas of improvement in this investigation. The conflicting literature regarding saturated hydraulic conductivities for cracking clay soils is one area that requires more study before such models can be accurately parameterised.

Continuation of this project could come in the form of determining the gradient at different depths. To fine-tune the parameterisation of the model, a sensitivity analysis should be undertaken to determine where efforts should be concentrated.

Before further research is undertaken in this field, whether or not cotton will respond to PRD should be firstly ascertained. If cotton does respond to PRD (for example in glass house trials and/or split pot experiments) then how to create this response (ie what pressure gradient is required) needs to be determined.

Results from this project lead to the recommendation that the cotton industry should not adopt partial root zone drying without considerable research and trials.

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Appendix A.
Project Specification

University of Southern Queensland
Faculty of Engineering and Surveying

ENG 4111/4112 Research Project
PROJECT SPECIFICATION

FOR:	**Loretta McKEERING**
TOPIC:	Evaluating the Potential for Partial Root Zone Drying (PRD) on Clay Soils in Commercial Cotton Production Systems
SUPERVISOR:	A/Prof Steven Raine (NCEA)
SPONSORSHIP:	National Centre for Engineering in Agriculture (NCEA) Cooperative Research Centre for Irrigation Futures (CRCIF)
PROJECT AIM:	The aim of this project is to investigate the potential to impose partial root zone drying conditions on cracking clay soils used for commercial cotton production.

PROGRAMME: **Issue A, 07 June 2004**

1. Undertake a review of literature regarding PRD and soil water movement.
2. Gain familiarity with the use of the Hydrus-2D soil water simulation model.
3. Obtain appropriate soil water parameters for a cracking clay soil.
4. Validate model operation and parameterisation by comparison with measured field data from a commercial cotton production system.
5. Impose a range of irrigation strategies to evaluate the effect of timing, and volume applied on soil water movement.
6. Determine potential to impose soil water gradients across the crop root zone.
7. Develop recommendations regarding the ability to impose PRD on cracking clay soils under cotton production.

As time permits:

8. Undertake an additional evaluation of field measured PRD data and compare with simulated results for the specific site.
9. Apply and analyse further PRD treatments for the specific site above.

AGREED: ____________________ (Student) ____________________
(Supervisor)

Dated: ___ / ___ / ____ ___ / ___ / ____

Appendix B.
Comparison of Pedotransfer Soil Water Retention Curve With Manually Adjusted Curve

Soil 1

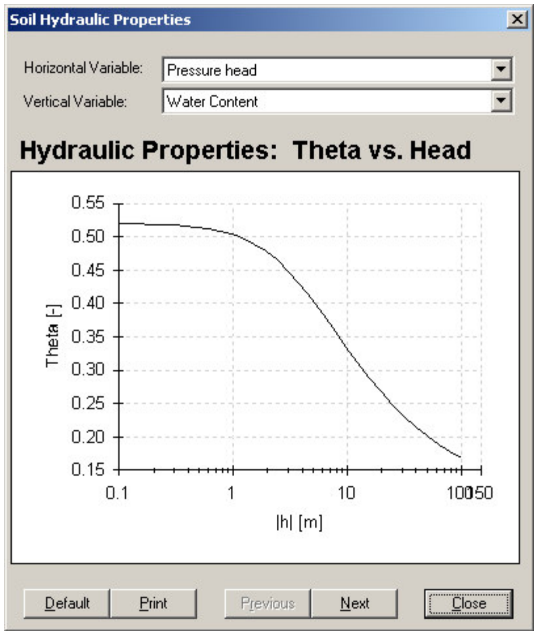


Figure B.1.
Rosetta soil (n=1.5323, A=0.26)

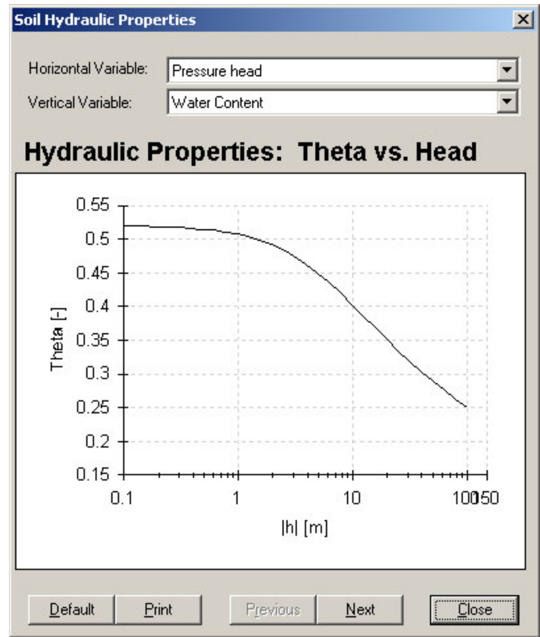


Figure B.2.
Altered soil (n=1.32, A=0.22)

Soil 2

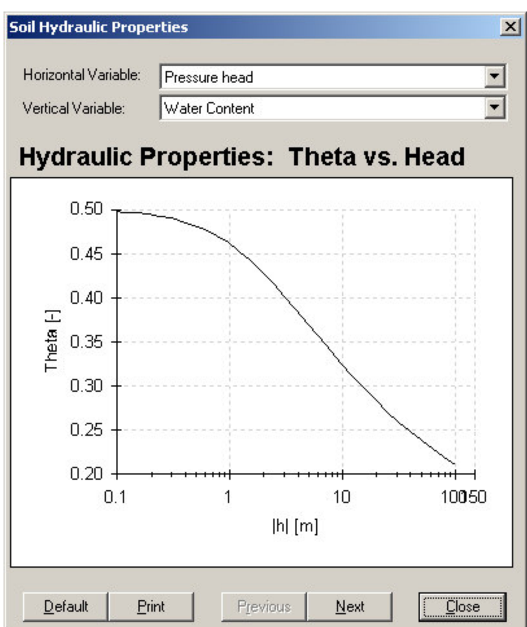


Figure B.3.
Rosetta soil (n=1.2858, A=0.65)

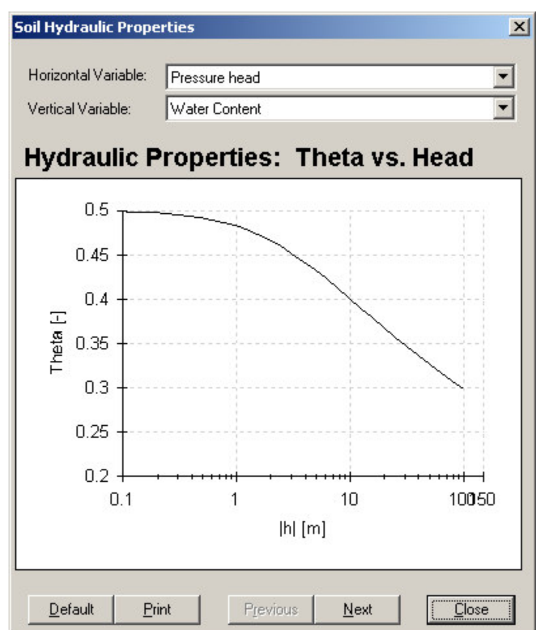
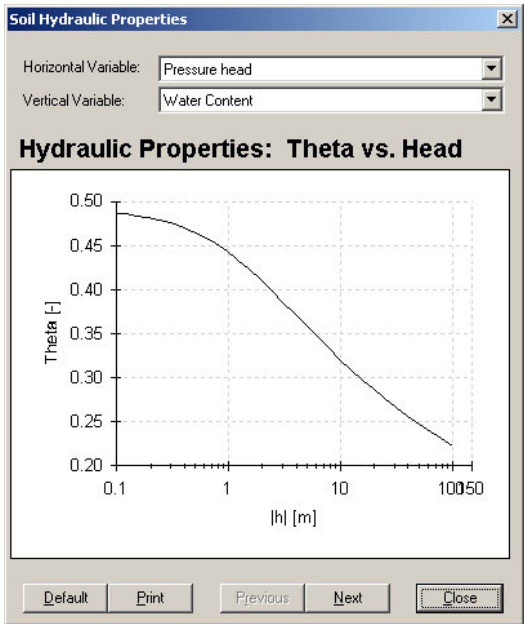


Figure B.4.
Altered soil (n=1.18, A=0.4)

Soil 3



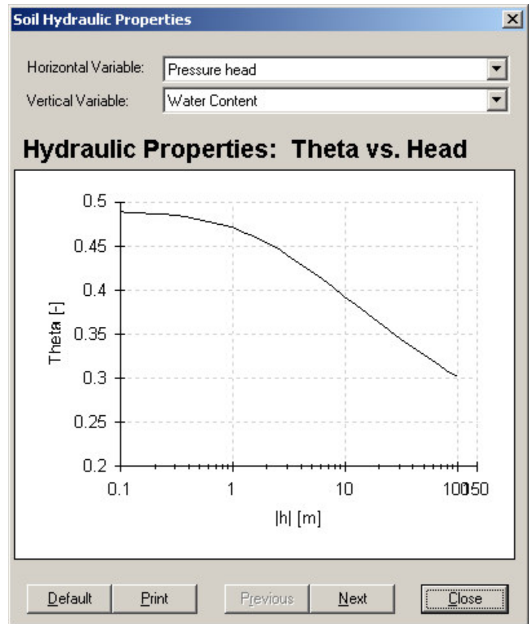
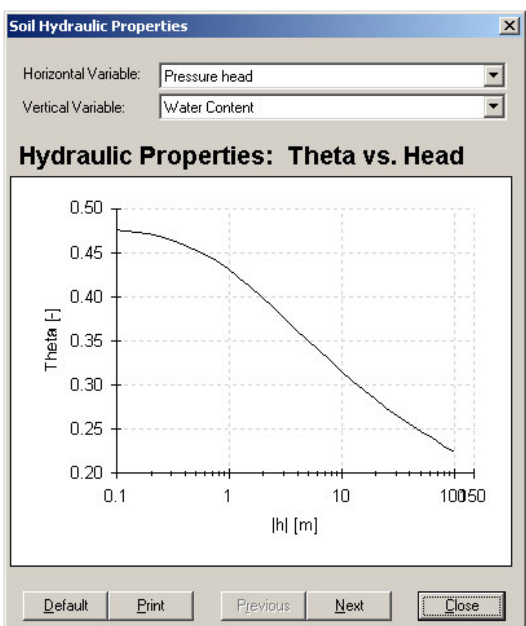


Figure B.5.
Rosetta soil (n=1.2361, A=0.96)

Figure B.6.
Altered soil (n=1.16, A=0.5)

Soil 4



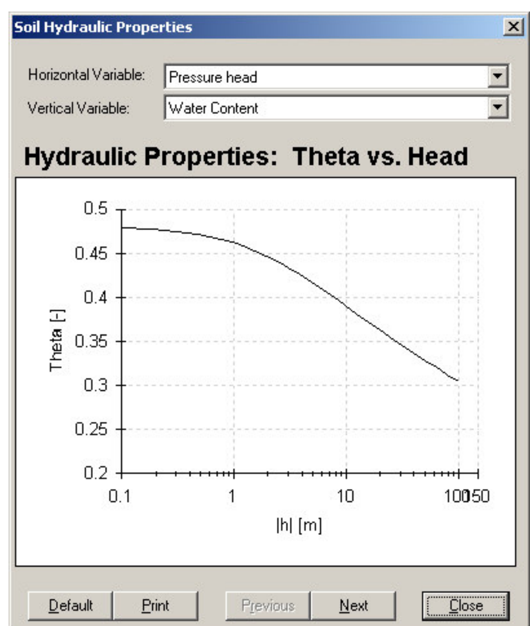
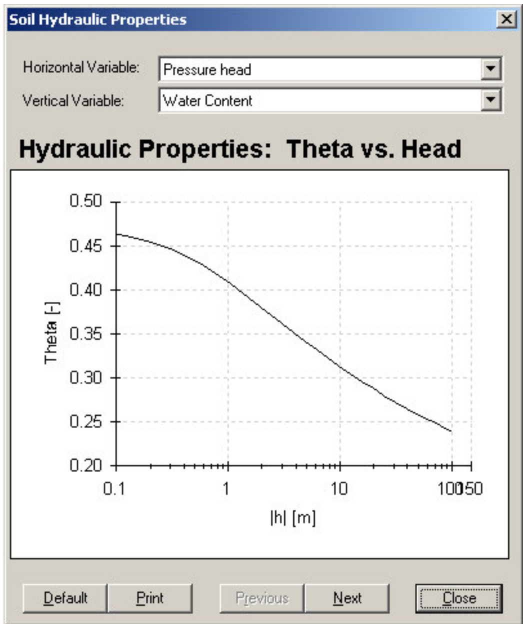


Figure B.7.
Rosetta soil (n=1.2211, A=1.11)

Figure B.8.
Altered soil (n=1.15, A=0.5)

Soil 5



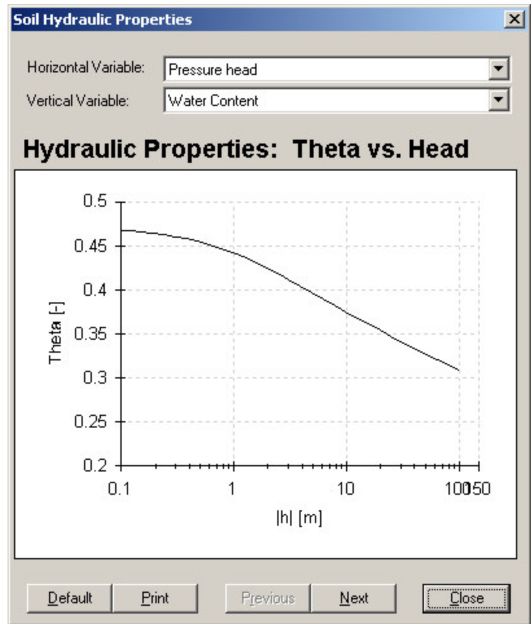
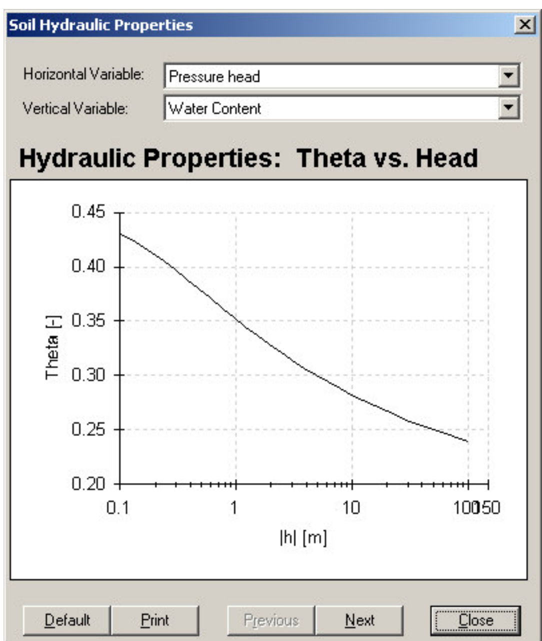


Figure B.9.
Rosetta soil (n=1.1808, A=2.03)

Figure B.10.
Altered soil (n=1.12, A=1.1)

Soil 6



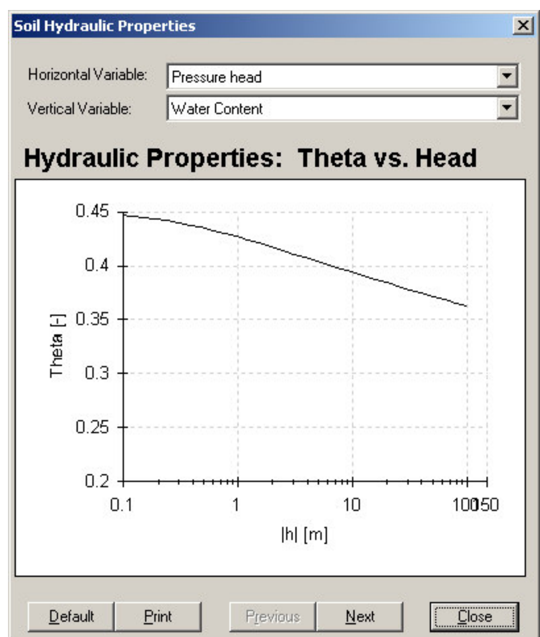


Figure B.11.
Rosetta soil (n=1.2394, A=6.76)

Figure B.12.
Altered soil (n=1.07, A=3.0)

Appendix C.
Validation of the "Macquarie Downs" Soil

Table C.1. Daily atmospheric validation data for the 'Macquarie Downs' Soil

Day No.	Date	Evaporation (mm)	Transpiration (mm)	Rainfall (mm)	Irrigation (mm)
1	2/01/03	1.0	12.2	1.8	
2	3/01/03	1.0	9.7		
3	4/01/03	1.0	11.0		
4	5/01/03	1.0	13.7		
5	6/01/03	1.0	13.0		
6	7/01/03	1.0	13.4		
7	8/01/03	1.0	13.5		
8	9/01/03	1.0	13.6		
9	10/01/03	1.0	19.8		
10	11/01/03	1.0	13.5		
11	12/01/03	1.0	12.7		
12	13/01/03	1.0	11.7		56
13	14/01/03	1.0	12.2		
14	15/01/03	1.0	14.6		
15	16/01/03	1.0	14.4		
16	17/01/03	1.0	13.2		
17	18/01/03	1.0	13.2		
18	19/01/03	1.0	11.4		56
19	20/01/03	1.0	17.9	3	
20	21/01/03	1.0	11.3	0.2	
21	22/01/03	1.0	14.6		61
22	23/01/03	1.0	17.3	3.2	
23	24/01/03	1.0	12.3		
24	25/01/03	1.0	11.3		
25	26/01/03	1.0	12.6		
26	27/01/03	1.0	11.7		
27	28/01/03	1.0	15.0		
28	29/01/03	1.0	14.1		
29	30/01/03	1.0	13.8		
30	31/01/03	1.0	14.1		
31	1/02/03	1.0	16.1		
32	2/02/03	1.0	9.3		
33	3/02/03	1.0	12.2		
34	4/02/03	1.0	9.9	3.8	
35	5/02/03	1.0	3.0	0.8	
36	6/02/03	1.0	7.4		
37	7/02/03	1.0	9.0		
38	8/02/03	1.0	8.7		
39	9/02/03	1.0	9.4		
40	10/02/03	1.0	4.3		37
41	11/02/03	1.0	7.3		
42	12/02/03	1.0	6.5	13.2	
43	13/02/03	1.0	10.7		

Table C.1. Daily atmospheric validation data for the 'Macquarie Downs" Soil cont…

Day No.	Date	Evaporation (mm)	Transpiration (mm)	Rainfall (mm)	Irrigation (mm)
44	14/02/03	1.0	16.0		
45	15/02/03	1.0	13.7		
46	16/02/03	1.0	11.8		
47	17/02/03	1.0	9.3		
48	18/02/03	1.0	11.9		
49	19/02/03	1.0	10.6	4.2	
50	20/02/03	1.0	9.2	1.4	
51	21/02/03	1.0	6.8		
52	22/02/03	1.0	5.0	27	
53	23/02/03	1.0	3.0	42.4	
54	24/02/03	1.0	7.7		
55	25/02/03	1.0	7.5		
56	26/02/03	1.0	7.0	0.2	
57	27/02/03	1.0	9.0		
58	28/02/03	1.0	7.6		
59	1/03/03	1.0	6.6		
60	2/03/03	1.0	10.1		
61	3/03/03	1.0	9.9		
62	4/03/03	1.0	9.6		
63	5/03/03	1.0	9.0		
	6/03/03				

Table C.2. Initial conditions of the validation of the 'Macquarie Downs" soil

The numbers in *italics* represent those that have been linearly interpreted from those around them.

Depth	Distance from Wetted Furrow						
	0.000	0.167	0.333	0.500	0.667	0.833	1.000
1.35							
1.25		*33.93*	32.43	*31.91*	31.39	*31.246*	
1.15	35.42	*36.48*	37.53	*37.03*	36.54	*33.83*	31.11
1.05	38.58	*38.91*	39.24	*39.29*	39.34	*37.66*	35.98
0.95	40.06	*40.40*	40.74	*40.62*	40.50	*39.21*	37.92
0.85	41.52	*41.51*	41.51	*41.67*	41.83	*40.82*	39.81
0.75	41.61	*41.16*				*41.34*	41.07
0.65		*40.67*	39.94	*40.66*	41.38	*41.19*	
0.55	41.20	*40.22*				*40.58*	40.93
0.45		*39.56*	38.54	*38.80*	39.06	*39.82*	
0.35	39.95	*39.29*				*39.42*	40.22
0.25		*38.92*	38.74	*38.47*	38.20	*38.94*	
0.15	38.25	*38.49*				*38.663*	39.12

Table C.3. Validation Results

	Distance (m) From the Wetted Furrow							
	0.00		0.33		0.67		1.00	
	Actual	Model	Actual	Model	Actual	Model	Actual	Model
Day 7	0.2529	0.2995	0.2544	0.2448	0.2578	0.2675	0.2427	0.2972
	0.3481	0.3275	0.3259	0.3009	0.3146	0.3005	0.3165	0.3264
	0.3722	0.3657	0.3579	0.3283	0.3549	0.3277	0.3522	0.3641
	0.3836	0.3884	0.3764	0.3653	0.3841	0.3658	0.3683	0.3879
	0.3958	0.3981	0.3984	0.3877	0.4057	0.3880	0.3803	0.3979
	0.4097	0.4047	0.4007	0.4004	0.4108	0.4005	0.3971	0.4050
	0.4001	0.3899	0.3884	0.3872	0.3982	0.4035	0.3993	0.3909
	0.3851	0.3902	0.3786	0.3837	0.3773	0.3818	0.3923	0.3920
Day 17	0.2992	0.3610	0.3216	0.2840	0.3425	0.2695	0.2732	0.2876
	0.3555	0.3833	0.3600	0.3447	0.3682	0.2925	0.3513	0.3228
	0.3711	0.3941	0.3799	0.3729	0.3687	0.3262	0.3704	0.3538
	0.3765	0.3990	0.3883	0.3820	0.3771	0.3569	0.3859	0.3769
	0.3851	0.3991	0.3952	0.3896	0.3818	0.3777	0.3925	0.3882
	0.3907	0.3989	0.4070	0.3949	0.3872	0.3931	0.4005	0.3973
	0.3859	0.3855	0.3986	0.3833	0.3944	0.3985	0.4030	0.3858
	0.4012	0.3919	0.4049	0.3836	0.4099	0.3827	0.4152	0.3915

Table C.3. Validation Results cont…

	Distance (m) From the Wetted Furrow							
	0.00		0.33		0.67		1.00	
	Actual	Model	Actual	Model	Actual	Model	Actual	Model
Day 26	0.3401	0.3102	0.3365	0.2516	0.3055	0.2697	0.3429	0.2856
	0.3514	0.3328	0.3586	0.3070	0.3545	0.2956	0.3656	0.2975
	0.3733	0.3671	0.3623	0.3286	0.3662	0.3102	0.3729	0.3305
	0.3778	0.3904	0.3687	0.3605	0.3725	0.3407	0.3733	0.3645
	0.3901	0.3992	0.3715	0.3845	0.3760	0.3699	0.3724	0.3799
	0.3989	0.4022	0.3825	0.3965	0.3996	0.3889	0.3761	0.3915
	0.3909	0.3846	0.3868	0.3832	0.3998	0.3945	0.3971	0.3825
	0.4150	0.3918	0.4067	0.3830	0.4196	0.3820	0.4196	0.3906
Day 39			0.3397	0.2276	0.3264	0.2493	0.3416	0.2753
	0.3401	0.2936	0.3511	0.2806	0.3557	0.2785	0.3612	0.2883
	0.3560	0.3272	0.3559	0.2923	0.3581	0.2896	0.3677	0.3173
	0.3620	0.3606	0.3550	0.3251	0.3686	0.3222	0.3663	0.3525
	0.3750	0.3773	0.3625	0.3586	0.3690	0.3555	0.3694	0.3700
	0.3954	0.3900	0.3788	0.3835	0.3884	0.3806	0.3648	0.3844
	0.3914	0.3820	0.3760	0.3773	0.3823	0.3888	0.3780	0.3784
	0.4053	0.3914	0.4058	0.3820	0.4192	0.3803	0.4071	0.3890
Day 47	0.3478	0.2927	0.2953	0.2457	0.3529	0.2671	0.3507	0.2834
	0.3676	0.3012	0.3293	0.2905	0.3722	0.2861	0.3752	0.2872
	0.3729	0.3154	0.3524	0.2962	0.3653	0.2881	0.3666	0.3067
	0.3830	0.3506	0.3700	0.3110	0.3779	0.3096	0.3660	0.3457
	0.3882	0.3700	0.3844	0.3484	0.3775	0.3478	0.3686	0.3653
	0.4006	0.3844	0.4090	0.3778	0.3825	0.3762	0.3712	0.3806
	0.3936	0.3795	0.3915	0.3736	0.3829	0.3851	0.3803	0.3762
	0.4111	0.3909	0.4047	0.3808	0.4025	0.3789	0.4085	0.3879
Day 57			0.4036	0.3173	0.3984	0.3309	0.4049	0.3465
	0.4130	0.3486	0.4138	0.3462	0.4080	0.3463	0.4118	0.3479
	0.4088	0.3370	0.4075	0.3488	0.4139	0.3489	0.4050	0.3338
	0.4093	0.3457	0.4041	0.3350	0.4147	0.3355	0.3977	0.3436
	0.4120	0.3629	0.4035	0.3449	0.4073	0.3462	0.4070	0.3605
	0.4124	0.3785	0.3972	0.3719	0.4073	0.3712	0.4010	0.3762
	0.3974	0.3765	0.3963	0.3696	0.4066	0.3809	0.3899	0.3736
	0.4246	0.3898	0.4181	0.3789			0.4120	0.3866
Day 63	0.3772	0.2924	0.3633	0.2459	0.3658	0.2690	0.3786	0.2925
	0.3895	0.3014	0.3809	0.2927	0.3887	0.2930	0.3874	0.3015
	0.3939	0.3132	0.3869	0.3005	0.4032	0.3007	0.3830	0.3136
	0.3918	0.3422	0.3892	0.3122	0.3962	0.3149	0.3833	0.3424
	0.4019	0.3604	0.3898	0.3419	0.3994	0.3441	0.3859	0.3591
	0.3982	0.3757	0.3925	0.3693	0.3959	0.3691	0.3897	0.3740
	0.3950	0.3749	0.3878	0.3676	0.3906	0.3786	0.3859	0.3721
	0.4134	0.3891	0.4125	0.3777	0.4112	0.3758	0.4082	0.3857

Appendix D.
Validation Results of the "Macquarie Downs" Soil for 26 Days

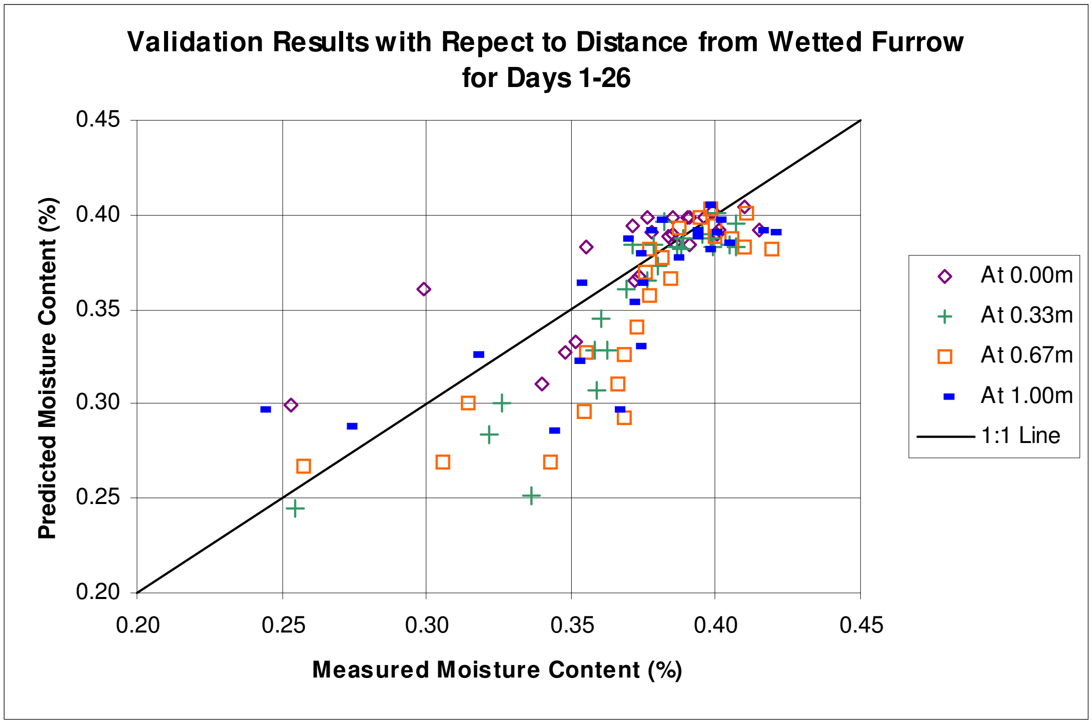


Figure D.1. Hydrus-2D validation results until Day 26, shown with respect to the distance away from the wetted furrow

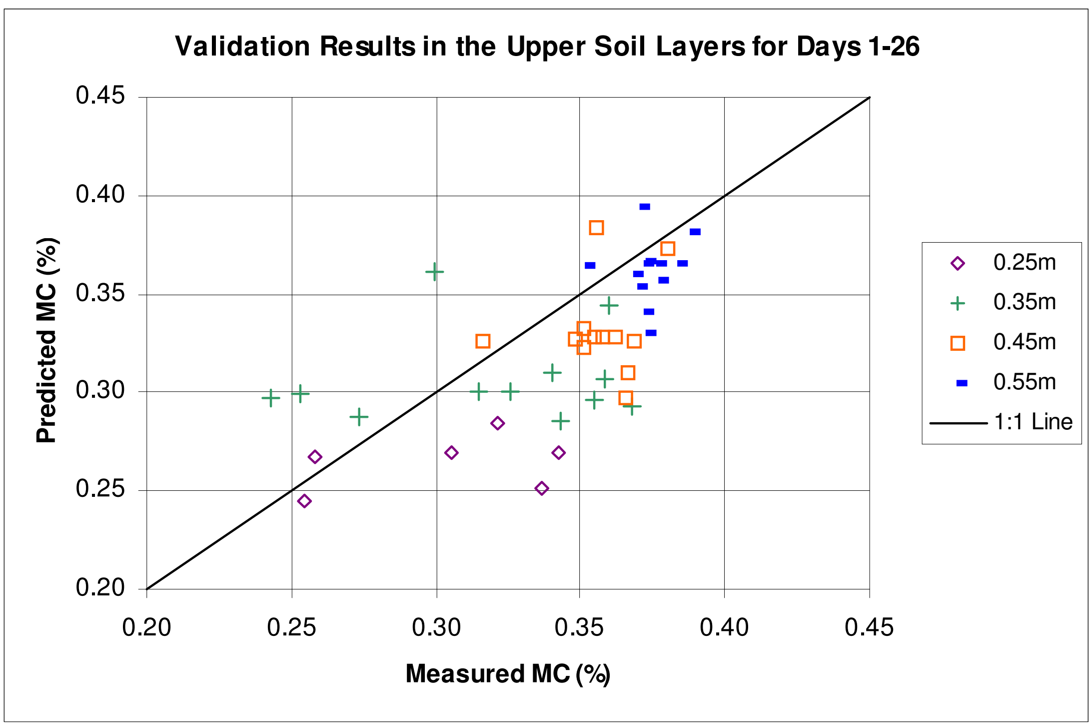


Figure D.2. Hydrus-2D validation results until Day 26, shown with respect to depth below the plant row (for 25-55cm)

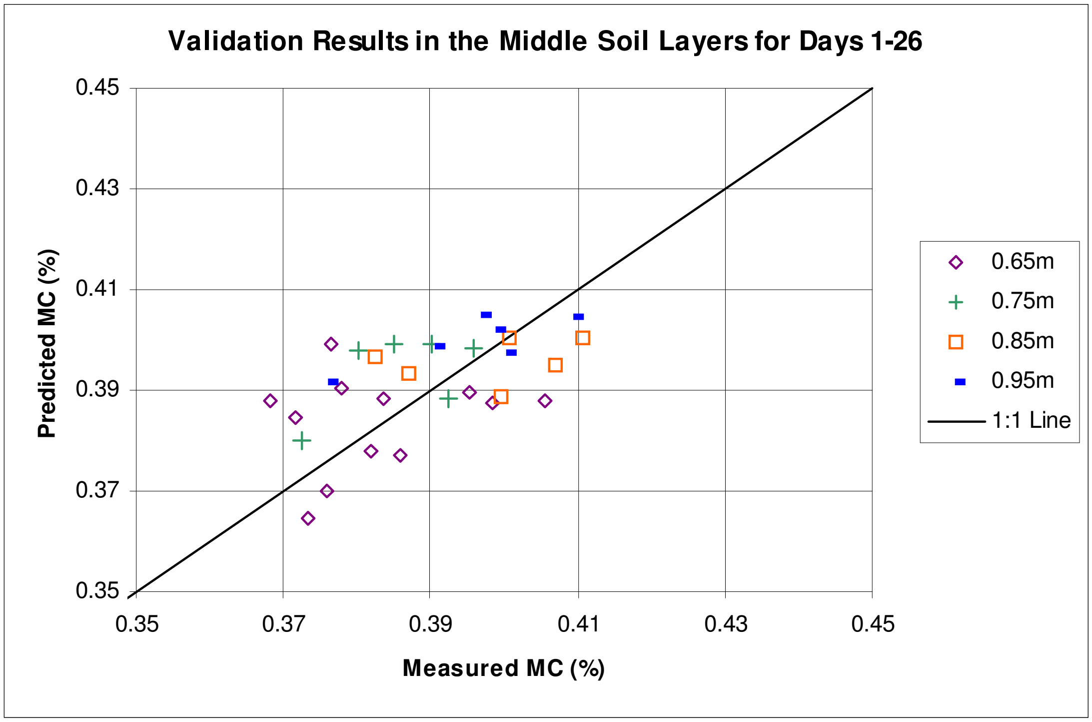


Figure D.3. Hydrus-2D validation results until Day 26, shown with respect to depth below the plant row (for 65-95cm)

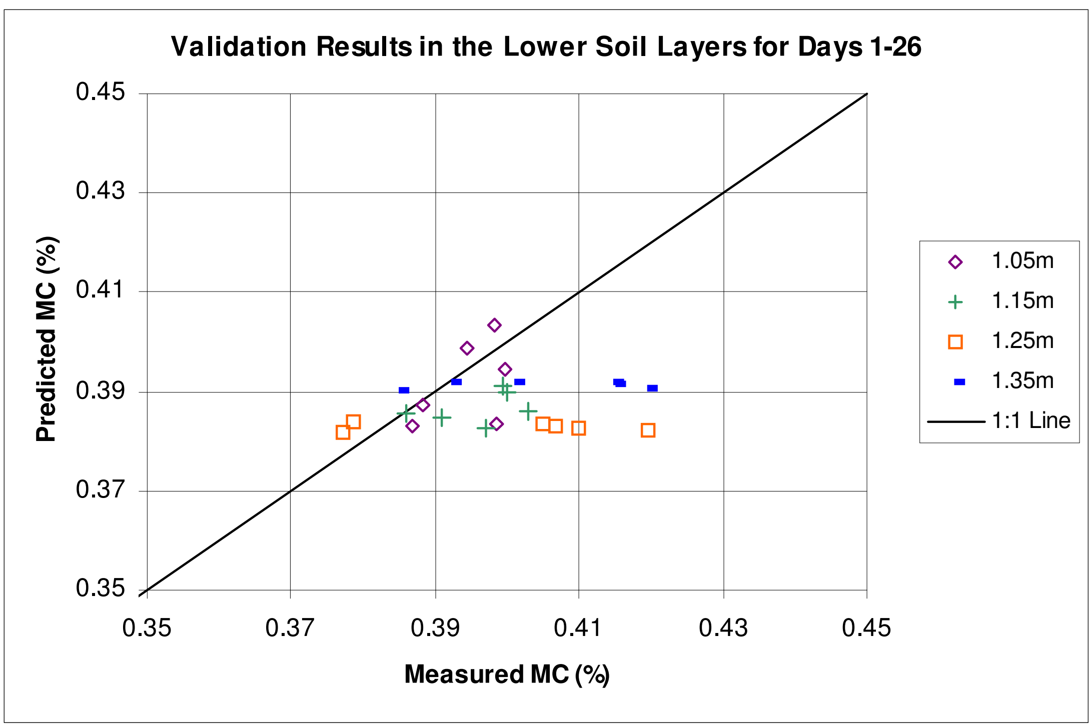


Figure D.4. Hydrus-2D validation results until Day 26, shown with respect to depth below the plant row (for 105-135cm)

Appendix E.
Investigation Results Using the "Macquarie Downs" Soil

Table E.1. Pressure head gradients when irrigating every 2 days (kPa)

Cycle No.	One Day After the Irrigation		Just Prior to the Next Irrigation	
	20 mm *	24 mm *	20 mm *	24 mm *
1	4.1	2.8	1.2	0.7
2	5.3	2.1	2.1	0.6
3	7.5	2.1	3.5	0.6
4	9.0	1.7	4.9	0.5
5	12.4	1.7	7.6	0.5
6	17.3	1.5	11.8	0.5
7	25.3	1.3	18.8	0.4
8	36.7	1.2	29.5	0.4
9	53.2	1.1	45.5	0.3

Red italics – the potential on the wetted side of the plant row is in excess of 200 kPa
Pink italics – the potential on the wetted side of the plant row exceeds 200 kPa by the end of the cycle
* – irrigation amount applied

Table 4.5. Pressure head gradients when irrigating every 4 days (kPa)

Cycle No.	One Day After the Irrigation			Just Prior to the Next Irrigation		
	20 mm *	30 mm *	40 mm *	40 mm *	30 mm *	40 mm *
1	4.1	1.4	0.3	0.5	1.5	0.6
2	*81.9*	*92.0*	*8.2*	*0.3*	*10.2*	*0.7*
3	*550.1*	*420.4*	*70.1*	*0.1*	*56.7*	*1.1*
4	*990.5*	*583.0*	*286.7*	*1.0*	*272.8*	*2.0*
5	*1222.0*	*758.9*	*556.2*	*3.4*	*759.3*	*4.3*

Red italics – the potential on the wetted side of the plant row is in excess of 200 kPa
Pink italics – the potential on the wetted side of the plant row exceeds 200 kPa by the end of the cycle
* – irrigation amount applied

Table 4.6. Pressure head gradients one day after each irrigation when irrigating every 6 days (kPa)

Cycle No.	One Day After the Irrigation				
	20 mm *	30 mm *	40 mm *	50 mm *	60 mm *
1	*8.4*	*1.5*	*0.6*	0.1	0.5
2	*596.9*	*133.5*	*11.5*	0.2	0.5
3	*1112.4*	*929.5*	*177.8*	0.3	*0.9*
4	*1112.9*	*1285.0*	*723.2*	*1.0*	*1.8*

Cycle No.	Just Prior to the Next Irrigation				
	20 mm *	30 mm *	40 mm *	50 mm *	60 mm *
1	*23.2*	*5.6*	*0.2*	1.0	0.5
2	*235.3*	*147.8*	*31.4*	1.0	0.2
3	*449.3*	*357.4*	*206.6*	0.9	*2.1*
4	*449.7*	*505.9*	*385.3*	*2.6*	*7.7*

Red italics – the potential on the wetted side of the plant row is in excess of 200 kPa
Pink italics – the potential on the wetted side of the plant row exceeds 200 kPa by the end of the cycle
* – irrigation amount applied

Table 4.7 Pressure head gradients one day after each irrigation when irrigating every 8 days (kPa)

Cycle No.	One Day After the Irrigation					
	20 mm *	30 mm *	40 mm *	50 mm *	60 mm *	70 mm *
1	*4.1*	*1.5*	*0.6*	*0.1*	*0.5*	*0.1*
2	*745.3*	*645.7*	*117.4*	*3.8*	*7.7*	*0.2*
3	*745.4*	*1278.4*	*982.3*	*121.4*	*51.5*	0.3

Cycle No.	Just Prior to the Next Irrigation					
	20 mm *	30 mm *	40 mm *	50 mm *	60 mm *	70 mm*
1	*26.0*	*22.1*	*12.2*	*0.7*	*7.3*	*0.8*
2	*149.1*	*173.7*	*111.9*	*32.6*	*47.8*	*0.7*
3	*149.0*	*405.7*	*267.1*	*137.9*	*114.7*	2.1

Red italics – the potential on the wetted side of the plant row is in excess of 200 kPa
Pink italics – the potential on the wetted side of the plant row exceeds 200 kPa by the end of the cycle
* – irrigation amount applied

Appendix F.
Validation of the "Macquarie Downs" Soil

Figure F.1. EnviroSCAN graphs for the validation period

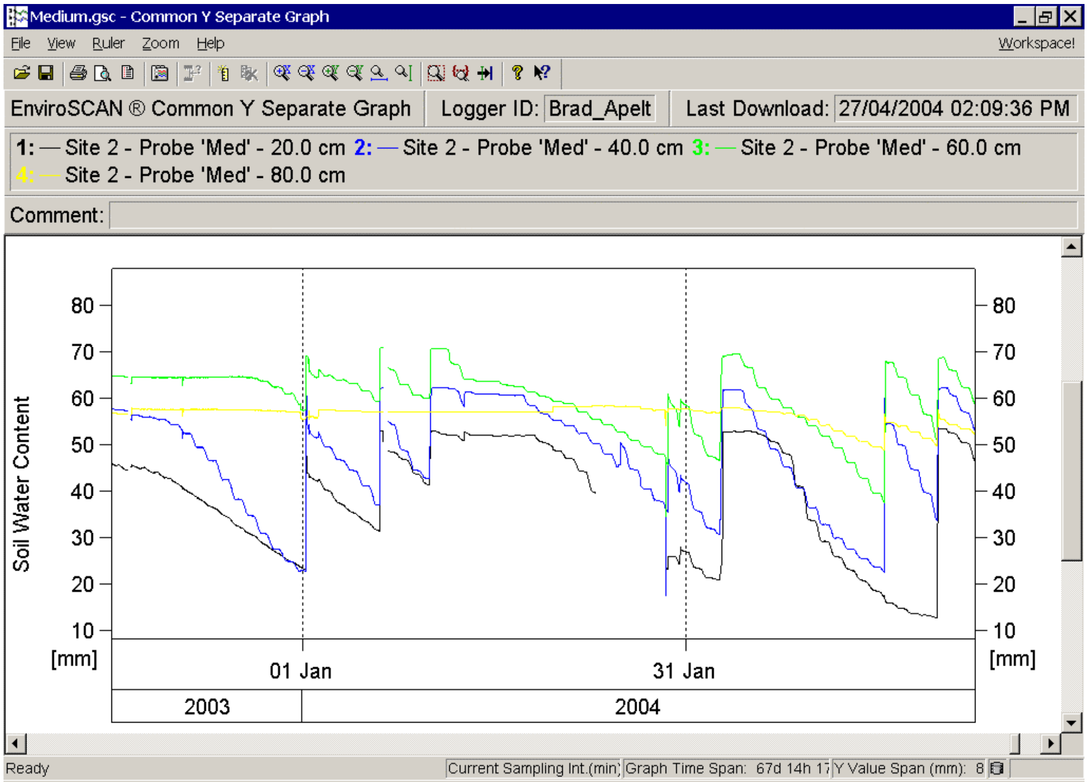


Table F.1. Atmospheric data for the validation of the Jondaryan soil

Note that all irrigations are 30 mm

Day	Date	Rainfall (mm)	Effective Rainfall (mm)	Evaporation (mm)	Transpiration (mm)	Irrigation Time
0	23/12/03			4.4	11.3	
1	24/12/03			4.6	11.6	
2	25/12/03			2.9	8.2	
3	26/12/03			3.4	9.7	
4	27/12/03			4.2	10.7	
5	28/12/03			2.8	7.2	
6	29/12/03			2.2	9.3	
7	30/12/03			2.3	9.3	
8	31/12/03			2.3	9.3	
9	1/01/04			2.5	10.2	0:01
10	2/01/04			2.6	10.7	
11	3/01/04			2.3	9.5	
12	4/01/04			2.4	9.7	
13	5/01/04			1.8	8.1	
14	6/01/04			2.1	9.7	

Table F.1. Atmospheric data for the validation of the Jondaryan soil cont…

Note that all irrigations are 30 mm

Day	Date	Rainfall (mm)	Effective Rainfall (mm)	Evaporation (mm)	Transpiration (mm)	Irrigation Time
15	7/01/04			2.7	12.4	0:01
16	8/01/04	5.6	2.5	3.4	14.2	
17	9/01/04			2.7	12.0	
18	10/01/04			2.2	10.0	
19	11/01/04	31.8	14.3	1.2	6.0	
20	12/01/04	18.8	8.5	0.5	3.7	
21	13/01/04	1.0	0.5	1.6	8.2	
22	14/01/04	17.6	7.9	1.8	8.5	
23	15/01/04	8.0	3.6	0.8	5.1	
24	16/01/04	55.2	24.8	0.5	3.1	
25	17/01/04	4.0	1.8	1.7	7.9	
26	18/01/04	6.2	2.8	1.3	6.5	
27	19/01/04	1.6	0.7	2.2	11.2	
28	20/01/04			1.2	6.3	
29	21/01/04			1.1	6.3	
30	22/01/04			1.3	7.6	
31	23/01/04			1.5	8.7	
32	24/01/04			1.4	8.1	
33	25/01/04	1.6	0.7	2.3	11.4	
34	26/01/04	11.6	5.2	1.5	9.2	
35	27/01/04			1.9	11.2	
36	28/01/04			1.3	8.1	
37	29/01/04	0.8	0.4	2.8	14.1	
38	30/01/04	13.4	6.0	1.5	9.0	
39	31/01/04	4.6	2.1	1.3	7.5	
40	1/02/04			2.0	11.4	
41	2/02/04			1.6	10.5	
42	3/02/04	60.2	27.1	0.5	3.8	
43	4/02/04	2.8	1.3	0.4	3.1	
44	5/02/04			1.1	7.3	
45	6/02/04			1.0	7.1	
46	7/02/04			1.0	7.1	
47	8/02/04			1.1	7.4	
48	9/02/04			0.9	7.6	
49	10/02/04			0.9	7.8	
50	11/02/04			1.0	8.5	
51	12/02/04			1.0	8.2	
52	13/02/04			1.0	8.4	
53	14/02/04			1.1	8.8	
54	15/02/04			1.0	7.8	11:50
55	16/02/04			1.2	9.9	

Table F.2. Initial conditions for the validation of the Jondaryn Soil

Depth (cm)	Tube 1	Tube 2	Tube 3	Tube 4
100	41.1%	39.4%	38.9%	41.3%
90	41.1%	41.9%	39.6%	43.0%
80	40.9%	41.1%	41.6%	44.8%
70	40.1%	40.8%	43.1%	44.4%
60	38.3%	41.1%	45.0%	44.2%
50	37.6%	42.8%	44.7%	43.7%
40	33.7%	38.7%	41.9%	41.9%
30		33.7%		
20				
10				

Table F.3. Adjusted initial conditions for the validation of the Jondaryn Soil

Depth (cm)	Tube 1	Tube 2	Tube 3	Tube 4
100	41.28%	39.4%	38.9%	41.3%
90	43.00%	41.9%	39.6%	43.0%
80	44.85%	41.1%	41.6%	44.8%
70	44.36%	40.8%	43.1%	44.4%
60	44.25%	41.1%	45.0%	44.2%
50	43.68%	42.8%	44.7%	43.7%
40	41.91%	38.7%	41.9%	41.9%
30				
20				
10				

Appendix G.
Double Ring Infiltrometer Test Results

Table 6.1. Recordings from the first double ring infiltrometer test

Time (hr:min:sec)	Flow Rate (mm/hr)	Percentage Difference	Total Water Used (L)	Depth (cm)
0:00:00			0.000	
0:10:04	312.1		2.428	15 cm
0:18:23	43.3	86.1	2.853	*22.5 cm*
0:25:12	39.1	9.7	3.167	30 cm
0:31:27	34.6	11.6	3.421	
0:38:15	33.9	2.0	3.693	
0:46:23	27.5	19.0	3.956	
0:57:22	20.3	25.9	4.220	*45 cm*
1:10:41	15.2	25.5	4.457	
1:26:41	13.1	13.8	4.703	
1:44:15	13.5	-3.6	4.984	
2:08:14	9.3	31.2	5.247	60 cm

Table 6.1. Recordings from the second double ring infiltrometer test

Time (hr:min:sec)	Flow Rate (mm/hr)	Percentage Difference	Total Water Used (L)	Depth (cm)
0:02:14			2.319	
0:03:01	524.7		2.803	
0:05:48	*722.4*	*-37.7*	*5.172*	
0:06:46	596.7	17.4	5.852	
0:11:24	262.8	56.0	7.286	
0:12:46	263.8	-0.4	7.711	
0:14:18	235.1	10.9	8.136	
0:16:17	170.9	27.3	8.535	
0:18:37	148.3	13.2	8.943	
0:22:53	89.6	39.6	9.393	
0:26:12	97.8	-9.2	9.775	
0:31:07	55.7	43.0	10.098	
0:36:50	53.0	4.9	10.455	
0:45:13	33.5	36.7	10.786	
0:57:00	26.3	21.6	11.151	
1:12:22	18.8	28.7	11.491	100
1:42:48	10.0	47.0	11.848	
2:09:17	9.0	9.7	12.128	
2:42:12	8.5	4.9	12.460	
3:21:50	5.6	34.0	12.723	
4:10:50	5.2	8.7	13.020	

Appendix H.
Literary Source

New irrigation method could halve agricultural water consumption, **2002, news article, environmental data interactive exchange (edie), viewed 15 May 2004, <http://www.edie.net/news/Archive/5925.cfm>**

A new irrigation system invented by plant scientists could halve agricultural water use while supplying us with tastier fruit and vegetables. Partial root drying is gaining popularity across Europe and has already been commercialised on grapes in Australia. The UK scientists behind the scheme have now set up a European consortium to test root drying on vegetables, fruit, cotton and even garden shrubs.

Agricultural development in Southern Australia has long been limited by the capacity of the Murray-Darling river, the main water supplier for the region's vineyards. Five years ago, scientists from the Australian research organisation CSIRO experimented on vines, splitting their roots between wet and dry soil in an attempt to restrict water consumption and leaf formation. The results were exceptional. With only half the roots irrigated at any one time, with no reduction in yield, water use efficiency doubled and the grapes improved in flavour and colour. Further tests in the field, where vines were irrigated on alternate sides over a three-week cycle, proved equally promising.

The idea behind partial root drying (PRD) stemmed from earlier work on apple trees carried out at Lancaster University. Bill Davies, a plant scientist from the Biology Department, experimented with root splitting to explore chemical signalling between roots and shoots. Roots were divided between two containers, one of which was dried out while the other remained well watered. Roots experiencing the dry soil were found to release abscisic acid, a stress hormone that signals the plant to inhibit leaf growth. As a result, the plant's stomata remained partially closed, new leaves were suppressed, and sugars were redirected to the fruit.

The success with both apples and grapes spurred Prof Davies and a colleague, Mark Bacon, to form the consortium IRRISPLIT, funded by the European Commission. The consortium, made up of scientists from Cyprus, Turkey, Portugal and the UK, is now testing the irrigation system on olives, citrus fruits, tomatoes, aubergines, raspberries and cotton. So far, tomato plants have been found to respond similarly to grapes, with a reduction in vegetation and tastier fruit. Raspberries have also been successfully grown at half the normal watering rate. Turkish cotton trials have furnished yet more encouraging results.

Turkish scientists from Cukurova University, Adana, developed two methods of irrigation to match the needs of wealthy and poor farmers alike. Cotton crops were irrigated with either a system of alternating pumps or the traditional practice of furrows and ridges, with alternate furrows being filled with water between crops grown on ridges. Preliminary results have shown PRD to generate a doubling in water efficiency for similar yields. Scientists were also delighted to find a shortened ripening time for the cotton bolls. For conventionally grown Turkish crops it is a battle to collect the cotton before the rainy season begins. The PRD irrigated crops generated less foliage, hence less shading and the bolls ripened faster under the hot sun. Thus the harvest was ready three weeks before the rain.

Unlike regulated deficit irrigation, which is used widely to reduce agricultural water use and tends to stress the plant to the point of reduced quality and yield, PRD continues to meet the plant's needs, allowing it to regulate its own water status. Professor Davies is optimistic about the long-term impacts of the research. "PRD is a low-tech way of manipulating crop yield and can be applied to many systems. In an ecological context, given that 70% of water goes to agriculture, PRD has significant social consequences."

Dr Bacon uses PRD on his home-grown tomatoes. "You can see the difference between conventionally grown and PRD grown tomatoes. As for shrubs, you can control the shape of the plant quite effectively. Several national nurseries are already experimenting with PRD on hardy ornamentals."