University of Southern Queensland

Faculty of Engineering and Surveying

Effect of Irrigation Management On Nitrate Movement Under A Lettuce Crop

A dissertation submitted by

Kimberley Jane Althaus

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Abstract

Irrigation management practices have a significant impact on the leaching of nutrients and salts within a soil profile. Lettuce irrigation is often characterised by high frequency, small volume irrigations to maintain the shallow rootzone in a moist condition.

The introduction of drip irrigation has provided the opportunity to apply soluble nitrogen fertiliser in the irrigation water to maintain high levels of soil nitrogen in the rootzone throughout the season. However, the combination of high soil moisture and nitrogen levels and well drained soils for extended periods of time raises concerns over the potential for nitrate leaching from the rootzone into local groundwater systems. This research involved a field trial to evaluate nitrate movement under a commercial fertigated lettuce crop.

This trial was conducted on a commercial lettuce crop grown on the eastern Darling Downs. Irrigation and fertigation was scheduled and recorded by the grower, based on observation of weather, crop and soil conditions. Soil cores were obtained both pre- and post-season to measure soil moisture, bulk density, nitrate, ammonium and electrical conductivity (EC). Capacitance probes and ceramic soil suction cups were installed in each plot. Soil solution samples were extracted at two or three day intervals throughout the season and the nitrate concentration and EC measured.

The results showed that deep drainage did occur during the season and that nitrate would have been moving out of the root zone. Substantial spatial and temporal variations in soil solution nitrate and EC were observed during the season. Solute movement appears to be related to the pattern of soil-water movement from the irrigation applications. This data suggests that the amount of deep drainage and nitrate leaching is influenced by the irrigation design and management practices. In-season rainfall and soil physical conditions may also play a role.

The key to nitrogen management is minimising the amount of nitrogen and water in the soil, whilst ensuring adequate nitrate and water is available for plant growth. A large amount of water and fertiliser was applied after transplanting, during a period when the plant roots were shallow and plant water requirements were small. Substantial nitrogen was lost to leaching before the plants had reached 20% ground cover.

Approximately one-fifth of the total nitrogen was applied during the last week before harvest. There is some debate over the requirement for nitrogen in the last week before harvest. If nitrate applied during the last week is unused then it would be highly susceptible to leaching during the following fallow period.

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Kimberley Jane Althaus

Student Number: 0050056396

Signature

Date

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Publications Arising From This Research

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Chapter 1 Introduction

Horticulture in general is known for its labour intensiveness. In Australia this is no different, it is a labour intensive, seasonal industry characterised by small scale family farms. These small scale operations are increasingly becoming medium to large operations, with a domestic and international reputation for quality. This quality can be attributed to the high standards in all stages of the supply chain, from farm to consumer (Australian Government Department of Agriculture, Fisheries and Forestry 2008).

The horticulture industry in 2006-07 was the second largest agricultural industry in Australia. Employed within the industry are 81 500 people growing fruit, vegetables and nuts for the domestic and export markets, whilst a further 9 300 are employed in fruit and vegetable processing. The total area under production in Australia is around 250 000 hectares of annual and perennial horticultural crops. It is also now known after surveys that there are 175 000 seasonal positions available each year within the industry (Australian Government Department of Agriculture, Fisheries and Forestry 2008).

The Goulburn Valley of Victoria, the Sunraysia district of Victoria/NSW, the Murrumbidgee Irrigation Area of New South Wales, northern Tasmania, southwest Western Australia, the Riverland region of South Australia, and the coastal strip of both northern New South Wales and Queensland are the major growing areas for horticulture in Australia. The distribution of production is banana, pineapple, mandarin, avocado, mango, fresh tomato, capsicum, zucchini and beetroot production concentrated in Queensland; stonefruit, oranges and grapes in New South Wales, Victoria and South Australia; processing potatoes in Tasmania; fresh pears, canning fruit and processing tomatoes in Victoria; and fresh apples and vegetables in all states (Australian Government Department of Agriculture, Fisheries and Forestry 2008).

Australia has a significant tropical horticultural industry including large irrigation schemes in the Ord River in Western Australia and the Burdekin in Queensland (Australian Government Department of Agriculture, Fisheries and Forestry 2008). Irrigated agriculture in Australia accounts for approximately 70 per cent of total water usage with 13 per cent of this water being utilised in horticulture and viticulture (Australian Government Department of Agriculture, Fisheries and Forestry 2008).

With such a large percentage of water use being attributed to irrigation it is a necessity that best management practices are utilised to accurately and efficiently irrigate crops. Lettuce requires a high irrigation with a lettuce plant consisting of 95% water. Lettuce is harvested in vegetative growth and has a poor root distribution and restricted rooting depth; these factors have an impact on the ability to uptake essential nitrogen and therefore influence the fertilisation strategy. Due to the stage at which a lettuce crop is harvested a high mineral N content is required in the soil until the day of harvest, a shortage of available nitrogen causes growth reduction, yellow leaves and restricted head formation.

It has been identified that the available nitrogen required varies between 150 kg N ha^{-1} in winter to 230 kg N ha^{-1} in the summer. With the rooting depth of lettuce being at an average of 15 cm depth combined with the high levels of nitrogen in the soil after harvest it can be identified that there are significant possibilities for nitrogen losses through leaching both during the cropping stage and after harvest.

Lettuce is the sixth largest vegetable crop within Australia and accounts for 6.5% of the total vegetable production with a gross value of $173.9 million in the 2005/06 year. In 2006 the total production of lettuce in Australia was 179 274 tonnes, with the area planted totalling 7 559 hectares. Queensland alone produces 31% of the national lettuce crop with yields consistently above average at 26.8 tonnes per hectare.

Due to the characteristics of lettuce, irrigation is often characterised by high frequency, small volume irrigations to maintain the shallow root zone in a moist condition. The introduction of drip irrigation has also provided the opportunity to apply soluble nitrogen fertiliser in the irrigation water to maintain high levels of soil nitrogen in the root zone throughout the season. However, the combination of high soil moisture and nitrogen levels and well drained soils for extended periods of time raises concerns over the potential for nitrate leaching from the root zone into local groundwater systems. It also seems likely that the potential for nitrate leaching will be a function of the irrigation application system, fertigation strategy and irrigation management applied. However, there is little reported work on the movement of nitrogen under these conditions.

Nitrogen is an important asset to farmers who, therefore, have an economic incentive to minimise its loss (Webster et al. 1993). More importantly farmland comprises a large proportion of the catchments that feed aquifers and boreholes, which are a source of potable water (Webster et al. 1993) for many farms and town water supplies. This suggests that there is an issue arising from the overuse of nitrogenous fertilisers impacting on surface and groundwater supplies.

The aim of this project is to evaluate the effect of drip irrigation and fertigation management practices on nitrate movement under a commercially grown lettuce crop. The management practices which maximise nutrient use efficiency and minimise losses of nutrients and water to groundwater systems will be identified.

Chapter 2 Literature Review

2.1 Introduction

As water issues become a key topic of debate, today's society are becoming more aware of the condition of the water quality in surface and groundwater supplies. In the agricultural sector it has now become standard practice to apply fertiliser through irrigation water, termed fertigation, to increase yields and the quality of a crop. It is also known that irrigation efficiencies can be very low across all of Australia, with large losses of water occurring to deep percolation. This raises the issue of whether the nutrient's being applied with irrigation water are staying in the root zone and being utilised by the crop, or whether it is being lost through leaching and deep drainage. The main focal point for discussion, due to its many forms and high mobility, is Nitrogen.

Natural nitrate levels in groundwater supplies are typically very low. Some sources of nitrate pollution in groundwater from an agricultural perspective are:

- Cultivation in areas with a relatively thin soil layer;
- Cultivation in areas where the soil has a poor nutrient buffering capacity;
- Over fertilisation of crops, and
- Intensive agriculture.

The main health effect of high concentrations of nitrate levels in the groundwater on humans is methemoglobinemia, better known as blue baby syndrome, which occurs predominantly in infants six months or younger. This can also occur in cattle, horses, sheep, piglets, and chickens. Methemoglobinemia occurs due to the ability of the nitrate to interfere with the bloods ability to transport oxygen, which leads to an oxygen deficiency. Methemoglobinemia is fully treatable if diagnosed in time. This only occurs when drinking water straight from bores that have not been treated to drinking water standards, which occurs with town drinking water supplies. The estimated distribution of nitrate leaching has been identified in the National Land and Water

Resources Audit 1997-2002 and can be seen in Figure 2-1. As can be seen from this, the distributions of high rates of leaching occur in the higher populated areas of Australia.

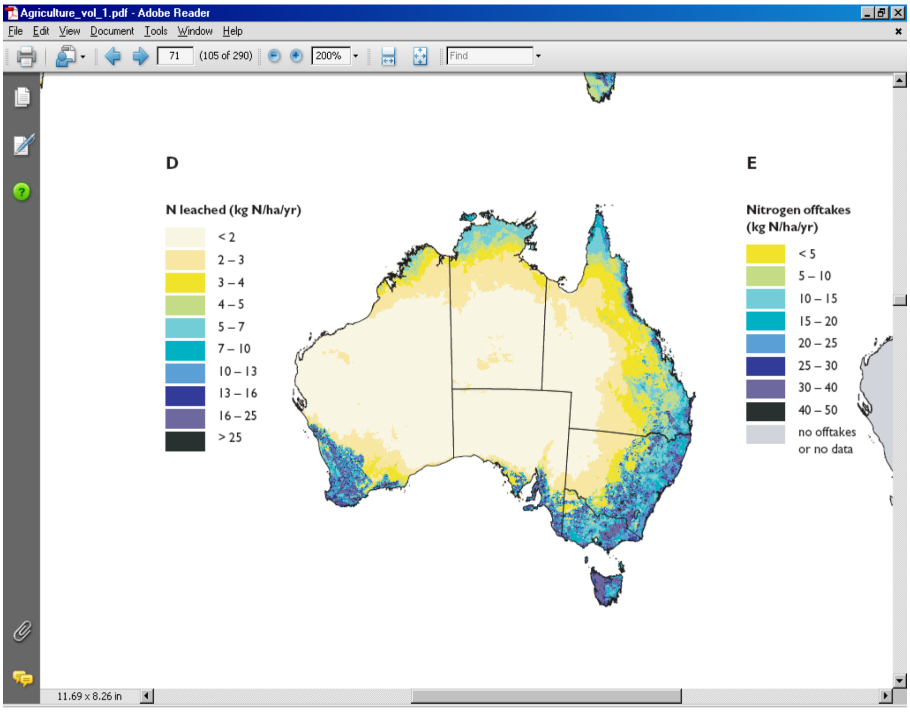


Figure 2-1 Estimated nitrogen loss through leaching (deep drainage). (National Land and Water Resources Audit, 2001)

2.2 Nutrients and Salts within the Soil Continuum

Nutrients, in particular nitrogen, are an important factor in the growth of plants. If there is not an adequate available supply, nutrient deficiency will occur and reduction in yields and growth will be seen. Salt is a natural element in all soils and water with the ability to cause plants to have difficulty in absorbing water and therefore nutrients. Salts within the soil continuum can increase over time from the deposition of dissolved salts in the irrigation water being applied. When the plants utilise the water and nutrients within the soil the salts are left behind to accumulate, which compounds the issue.

2.2.1 Nitrogen

2.2.1.1 Overview of Nitrogen

Nitrogen is one of the most limiting nutrients of agricultural plant growth with the main effect of deficiency being the interference with protein synthesis and therefore growth. Within soils nitrogen is mainly found as organic N due to biological and chemical fixation of gaseous N_2 from the atmosphere.

Nitrogen can be found in various forms within soils including gaseous, mineral, non-exchangeable or organic N. Gaseous N consists of N_2, N_2O, NO and NH_3, and is usually ignored from a fertility viewpoint as it itself does not influence fertility. Mineral N is defined as NH_4^+, NO_2^- and NO_3^-. Mineral N are the forms used by plants and represent <2% of the total N. NO_3^- is the main form utilised by plants in well aerated soils however NH_4^+ can also be utilised. Non-exchangeable of ‘fixed’ N is NH_4^+, when ‘fixed’ the NH_4^+ ion is adsorbed onto the negatively charged clay mineral sheets, which for the most part cannot be used by plants. Fixed NH_4^+ accounts 4-8% of the total N in surface soils and 20% in subsoils. Organic N is not readily available for plants to use, it must first be mineralised and account for 80-90% of total soil N.

2.2.1.2 Nitrogen Cycle

The transformations of N in the hydrosphere, lithosphere, atmosphere and biosphere are represented by the Nitrogen Cycle (Figure 2-2). Total soil N levels are affected by the mass balance of gains and losses and therefore vary almost from day to day.

Four main processes can be identified within this cycle, the mineralisation-immobilisation process, the leaching process, the nitrification process and the denitrification process.

Mineralisation-Immobilisation

The mineralisation-immobilisation process can be expressed as organic N$\leftrightarrow$ NH_4^+. Mineralisation is the release of NH_4^+ from organic matter in the soil by microbial breakdown (Raine 2008). This also means that a reverse process accompanies, this being the immobilisation process which represents microbiological uptake of NH_4^+. The mineralisation-immobilisation transformations are made by a range of heterotrophic microorganisms. The net rate of mobilisation-immobilisation is dependent on the amount of carbon and nitrogen present in the decomposing organic material. Net mineralisation occurs when the organic material contains more N than the microorganisms need for cell growth and so excess N is excreted as NH_4^+. Net immobilisation will occur when the organic material contains less N than the microorganisms need for cell growth and so they will then take up NH_4^+ and NO_3^- from the soil.

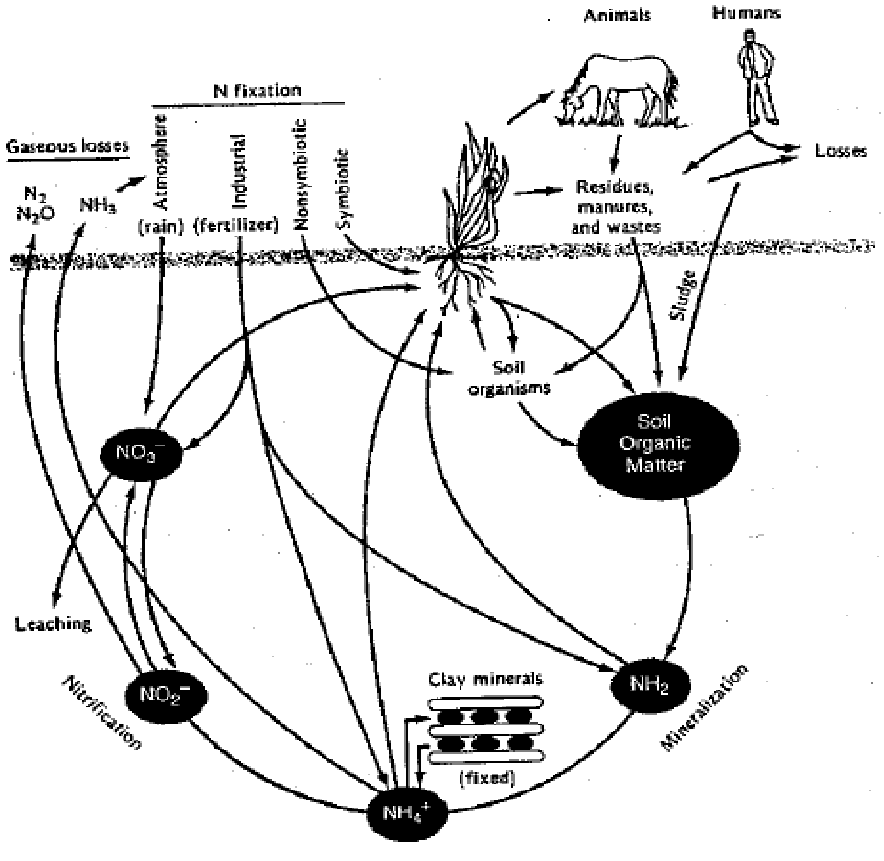


Figure 2-2 The Nitrogen Cycle (Raine 2008, Figure 10.2)

Nitrification ($NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$)

Nitrification usually occurs quite rapidly in well-aerated soils and so if net mineralisation is predominated NH_4^+ and NO_2^- concentrations will be low and NO_3^- accumulation will occur. Nitrification improves the plant availability of mineral N as NO_3^- is more mobile then NH_4^+ and so is therefore more easily leached into the root zone. This ease of mobility can also be detrimental as the availability of mineral N can be significantly decreased by excessive leaching (past the root zone).

Denitrification ($NO_3^- \rightarrow NO_2^- \rightarrow N_2O \rightarrow N_2$)

Denitrification is the microbial reduction of NO_3^- to N_2 or to organic forms of nitrogen. This process is carried out by microorganisms when sufficient oxygen is lacking. There are dissimilative and assimilative pathways for this process with the conversion to N_2 gas being the dissimilative pathway and the conversion to organic forms being assimilative.

Leaching

Leaching and denitrification are the two main NO_3^- reactions. NO_3^- is repelled by negatively charged soil colloids allowing it to move freely in the soil solution. The extent of movement is affected by the amount of rainfall, the soil characteristics, hydraulic conductivity and the agricultural practice in use.

2.2.2 Salinity

2.2.2.1 Overview of Salts

It is known that excessive amounts of salt in a crops root zone can reduce crop quality and yield. Naturally occurring dissolved salts can be found in soils, surface water and groundwater. A build up salts within the soil occurs from different sources, and because of different management practices. The sources of the excess salts can be from irrigation water or from rises in the groundwater table.

All water has a degree of salts within it and so even high quality irrigation water will deposit salts into the soil. Capillary rise and plant roots pull groundwater into the root zone of crops, and with it the salts that are present. High salt concentrations lower the osmotic water potential resulting in water moving into solutions of high solute concentration (Singer & Munns, 2006). As the concentration of solutes within the soil solution increases it becomes difficult for plants to remove water from the soil as water only enters plants roots when the water potential is lower inside the roots than outside (Singer & Munns, 2006). The conclusion drawn from this is that to absorb water from a salty soil solution the plant must increase the concentration of solutes inside it cells (Singer and Munns, 2006)

2.2.3 Interactions between Nitrogen and Salt

As stated earlier the higher the salt content in the soil solution the lower the osmotic water potential and the decreased ability for the roots to absorb water and nutrients. Due to this effect fewer nitrates will be able to be drawn from the soil profile by the roots of the lettuce and hence, a higher concentration of nitrates will be left within the profile. During heavy irrigation or rainfall these nitrates will therefore be more susceptible to leaching.

It is also known that plants in salt stressed conditions can decrease the uptake of water and change the absorption ratio of nutrients (Miceli et al., 2003). A higher content of chlorides in water can reduce the absorption of nitrates as well as the accumulation of nitrates within the leaves of a lettuce (Miceli et al., 2003). Increases in salinity not only result in a decrease in the absorption of nitrates, but also in a reduced marketable yield, average plant fresh weight and leaf number per plant. It has been found that the level of salinity also influences the content and ratio of cations and anions in the plant (Miceli et al., 2003).

2.3 Soil-Water Dynamics

2.3.1 Soil-Water Movement

The flow of water through a soil is governed by potential energies and properties of the soil at that point in time and can be as either saturated, unsaturated or vapour flow. Soil-water movement is therefore influenced by the potential gradient, with the differences in water potential being made up of components of gravitational, pressure, solute, and matric potentials (Singer & Munns 2006). The rate of water movement depends not only on these differences in potential but also on hydraulic conductivity of the soil. The hydraulic conductivity represents the level of ease of movement of water in the soil.

2.3.1.1 Water Potential

The total water potential is the sum of gravity, pressure, matric and solute potential components (Singer & Munns 2006). Unsaturated soil-water movement is dominated by the matric potential differences arising from the differences in water content (Signer & Munns 2006). The solute potential component is the osmotic potential arising from the difference in concentrations of solutes throughout the soil. The water potential of a soil is affected by several different components including water content and time changes. Most soils hold much of their water at high potentials of -0.1 to -1.0 MPa, thus allowing the uptake of water by plants. As time changes and the soil receives irrigation or rain the water content and water potential increase, or become less negative (Singer & Munns 2006). The water content and water potential will rapidly decrease once the wetting fronts start to recede. This is due to the rapid draining of water which is only loosely held in the larger pores, once the larger pores have drained this decline will slow as water is held in smaller and smaller pores.

2.3.2 Soil-Water Retention Curve

Figure 2-3 shows the relationship between the soil-water content and the water potential of the soil. The curve resulting from the plotting of the soil-water potential versus the soil-water content is known as the soil moisture characteristic or the soil-water retention curve. As the name implies, it is a characteristic of the soil properties with the amount of water retained in the soil at any particular suction being dependent on the pore size distribution and pore volumes (Raine 2008). So, the soil moisture characteristic, or soil-water retention curve, will be strongly influenced by the soil textural and structural properties (Raine 2008).

In a saturated soil, all the pores are completely filled with water (Raine 2008). In this state the soil-water may be considered to be at equilibrium with free water at the same elevation and atmospheric pressure and hence, the soil-water potential and suction is zero (Raine 2008). Water will not be extracted from the soil until a critical value of suction (or tension) is applied to the soil-water at which the largest pore/s begins to drain (Raine 2008). This value is small in soils with large pores – coarse textured or well aggregated – it can be seen then, that in soils with small pores a much greater suction is required to initiate pore drainage. From this it can also be seen that at very large suctions only soils with small pores will continue to hold water and it will require very large increases in suction to remove additional soil-water from these pores (Raine 2008).

The soil texture and soil structure have the primary effect on the total porosity and pore size distribution present within the soil (Raine 2008). Sandy soils will generally have a smaller total porosity than clay soils due to the lack of strong aggregation, greater packing and higher bulk densities (Raine 2008). At zero suction the total water content within sandy soils tends to be lower than in clay soils due to the dominance of macropores which result in rapid draining and lack of micropores which result in very low levels of soil-water at high suctions (Raine 2008). The opposite of this is true for clay soils; they generally have higher water contents at zero suction, drain more slowly with increasing suction, and have higher soil-water contents at high levels of suction (Raine 2008).

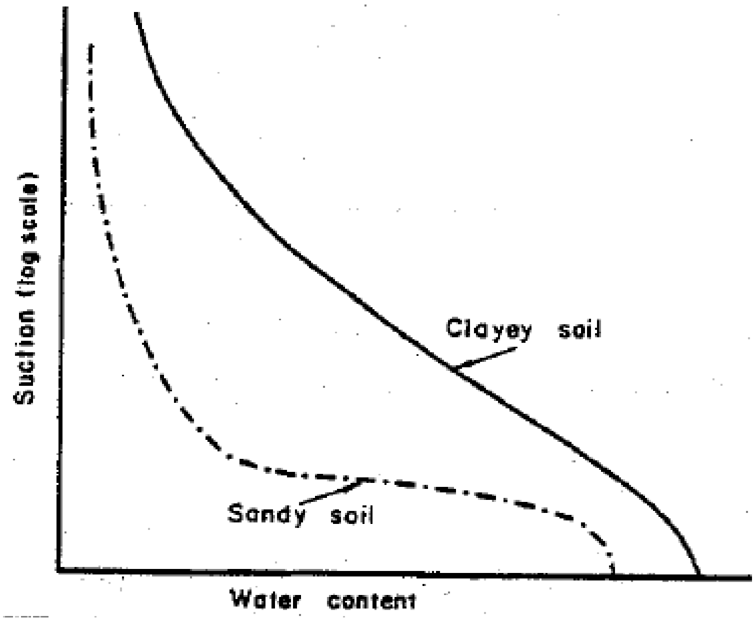


Figure 2-3 Soil Moisture Retention Curves for Different Soils (Hillel 1971, p. 64)

2.3.3 Hydraulic Conductivity

The hydraulic conductivity is a measure of the ease (or difficulty) with which water flows through a soil in response to a given potential gradient (Singer & Munns 2006). In unsaturated soil the water flow is inhibited by the large pores containing air and the water flows through the films of water coating the soil particles and the intermediate sized pores which still contain water (Singer & Munns 2006). As the water content decreases in a soil the water conductivity also decreases due to more inhibiters (pores filled with water, and drag against surfaces from small pores and films and less direct flow paths) to the water flow. From these definitions and Figure 2-4 we can see that the higher the water content the higher the hydraulic conductivity. As the hydraulic conductivity is affected by the soil properties of total porosity, pore size distribution and tortuosity (Raine 2008) we can see that the greater the number of large pores in a soil the larger the hydraulic conductivity is at saturation. This also corresponds with a quicker drainage rate.

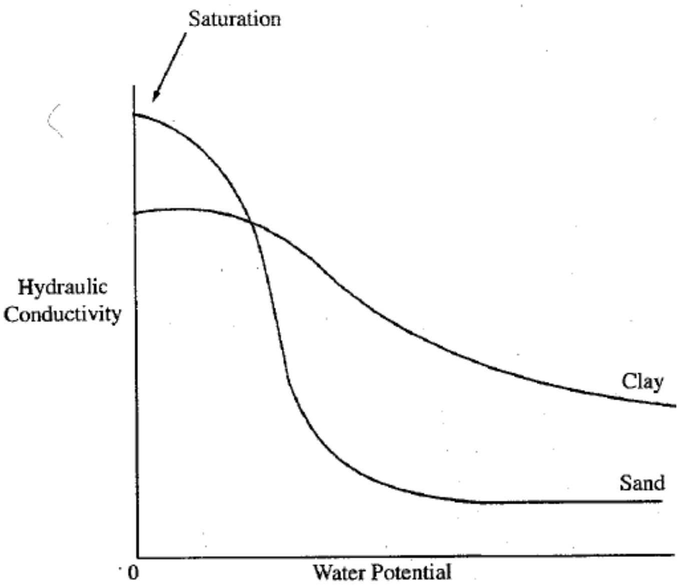


Figure 2-4 Hydraulic Conductivity of Two Types of Soils (Raine 2008, Figure 9.2)

2.4 Irrigation of Lettuce

Lettuce are shallow rooted crops which have a limited capacity to use water storages at depth (Water For Profit Fact Sheet), with lettuce plants extracting up to 85% of their required water from the top 20cm of the soil profile. In order for lettuce to grow effectively and efficiently the soil needs to be kept moist at all times. To eliminate water and nutrient wastage the irrigation system needs to be able to apply water uniformly and frequently, with underwatering leading to tip burn and bolting in warmer climates whilst overwatering will leach nutrients, lower yields and reduce quality (Water For Profit Fact Sheet).

The total crop water requirement for lettuce is highly variable with the season, i.e. summer, but is around approximately 2-3 ML/ha per season. The primary methods of application of irrigation water are sprinkler and drip irrigation. Sprinkler irrigation is primarily used for the initial stages of the cropping season to allow for quick cooling, humidification and minimisation of planting stress for seedlings after transplantation/emergence and until the root systems are established enough to manage these functions. Water is also able to be distributed in a more uniform manner and therefore allows the root systems to establish evenly within the soil profile.

For the optimal growth of lettuce a minimal stress environment is required. Leaf growth and product quality will be disturbed and reduced with any stress. After a certain point of establishment drip irrigation can reduce damage and diseases that are linked with the wetting of leaves. Drip irrigation also allows for successful growth of lettuce with higher water use efficiency than sprinkler irrigation.

2.5 Fertigation of Lettuce

The application of fertiliser through irrigation systems is termed fertigation. Fertigation has become common practice with nitrogen being the most frequent nutrient being applied. Fertigating crops has allowed for a more accurate and controllable application of fertilisers. With applications through trickle irrigation systems the nutrients are being applied directly to the rootzone where required. The amount of fertiliser being applied can also be controlled with a higher precision of meeting crop requirements possible.

Some advantages of using a fertigation system over solid and granular fertilisers include (Burt 2009):

- Savings in fertilisers, fuel, labour and equipment. Various research reports indicate that 25 to 50 per cent less fertiliser may be used with fertigation, compared with the use of solid fertilisers;
- More frequent applications are possible compared with solid top dressings, especially if an automatic system is used;
- Quick absorption of nutrients from fertilisers into plants;
- Less leaching of nutrients below the root zone, when applied little and often.
- Less burning of crops, as the fertiliser is applied in diluted form;
- Fertilisers may be applied in conditions which are too wet for tractor operation;
- Less mechanical damage to the crop, when applied via the irrigation system.

Disadvantages of using a fertigation system over solid and granular fertilisers include (Burt 2009):

- If the irrigation system does not apply water and nutrients uniformly, then fertigation through the irrigation system may result in uneven crop growth;
- Over-watering will result in leaching of nutrients past the rootzone and pollution of the groundwater;
- Fertilisers may settle out and block the irrigation system, especially with trickle irrigation. The irrigation water may also contain high contents of certain salts such as magnesium, calcium and bicarbonate which may react with some nutrients such as phosphates in the fertiliser;
- Bacterial and algal slimes may occur, due to increased levels of nutrients in the water especially with trickle systems. These will block the system, especially if they can develop on suspended particles such as iron;
- Disease problems may be higher when sprinklers are used.

2.6 Nitrogen Leaching As a Result of Irrigation

There have been many studies carried out across the world that have identified that the leaching of nitrogen, as a direct result of irrigation practices, is a major issue that is exceptionally widespread. Through these numerous studies it was identified that the leaching of soil nitrate from the plant root zone to the groundwater was determined by two important factors (Feng et al. 2005). These factors are the amount of nitrate accumulated in the soil exceeding the requirements of the crops, and the drainage volume through the soil. Feng et al. (2005) states that Ottman et al. (2000) and Ritter (1989) both identified that nitrate leaching in irrigated agriculture is assumed to be an inevitable result of the relatively high nitrogen fertiliser rates applied and the need to periodically leach salts from surface soil horizons.

One study conducted in the Hetao Irrigation District of China found that the irrigation practices utilised within the autumn season caused the nitrate-nitrogen concentration within the groundwater to increase 19.87 mg L^{-1}, from 1.73 mg L^{-1} to 21.6 mg L^{-1}; this level exceeds the standards of the World Health Organisation of 11.3 mg L^{-1}. The results of this study suggested that the application of optimised minimum amounts of water and nitrogen to meet realistic yield goals, as well as the timely application of nitrogen fertilisers and the use of slow release fertilisers can be viable measure to minimise nitrate leaching (Feng et al. 2005).

Studies have shown that both the fertiliser method and infiltration process greatly influence the nitrogen distribution in the soil (Mailhol et al. 2001). Nitrogen stored in the upper part of the soil profile that has not been taken up by the plants will leach through the soil profile under heavy rainfall events; this is particularly evident in furrow irrigated systems (Mailhol et al. 2001). After the crop is harvested nitrogen within the top layers, combined with precipitation can contribute to leaching, this is evidently dependent on the level and intensity of precipitation.

2.7 The Use of Suction Cups in Determining Nitrate Leaching

Soil-Water Samplers, also known as suction cups or suction lysimeters (Figure 2-5), are used to collect water samples in the soil profile (ICT International 2008). The samplers can be installed at the depth required for sampling and left in the soil, thus allowing periodic sampling to occur. There have been many studies conducted on the effectiveness of using suction cups to quantify the levels of nutrient and ionic concentrations leaching through the soil profile, with different conclusions being made most times.

A literature review conducted by Litaor in 1988 on soil solution samplers confirms that there have been many reviews conducted on ceramic suction cups, with different findings. It was found that during the 1970s systematic evaluation of soil solution samplers were performed (Litaor 1988). From the studies reviewed it was identified that Cochran et al. (1970) determined that soil heterogeneity affects soil moisture retention and therefore causes non-uniform and irregular solution flow from the soil to the sampler (Litaor 1988). When a constant, and continual, suction is applied to a suction cup, within horizons with different retention and flow properties, it was seen that there was a variation in leachate volumes. Identified by Van der Ploeg and Beese in 1977, was the conclusion that solute content in freely flowing solutions may be significantly different than extracted solutions (Litaor 1988).

Variability in the concentrations of nitrate in soil solutions collected using ceramic porous cups have been explained by sorption, leaching, diffusion, and screening by the cup walls (Litaor 1988). The variability can also be attributed to sampler intake rate, plugging, sampler depth, and the type of the vacuum system applied (Litaor 1988). Therefore it can be seen that each of these elements will affect the rate of sample collection as well as the dependability of the nutrient concentrations extracted.

Silkworth and Grigal (1981) completed a comprehensive study of four different soil solution samplers. The soil solution samplers studied were small (2.2cm outer diameter) and large (4.8cm outer diameter) ceramic cups, fritted glass cups, and hollow cellulose fibres. Their conclusion was that the superior of the cup types was the large ceramic cup sampler, in terms of minimum alteration of soil solution and of low failure rates and adequate volumes of solution (Litaor 1988).

A general outcome that has been identified is that suction cups can be used to quantify leaching losses on unstructured, free draining soils if used correctly (Webster et al. 1993). The use of suction cups gives direct measures of the mineral N concentrations in drainage, but requires an estimate of the drainage volume to give total N leached, this is done through meteorological observations and evapotranspiration equations (Webster et al. 1993).

In soils subject to cracking ceramic cups are widely regarded as being a flawed method as water can by-pass the ceramic cups (Webster et al. 1993). In soils that do not contain macropores the use of ceramic cups has also been questioned, in particular, to what extent and in which conditions do cups preferentially sample from large seepage pores (Webster et al. 1993). Despite these facts ceramic cups are widely used to measure leaching losses. The ease of installation and the relatively cheap method of sampling make ceramic cups an ideal method for monitoring leaching (Weaver et al. 2002).

From a study conducted by the Australian Cotton Co-operative Research Centre (NSW) and the School of Environmental Sciences, Griffith University, Nathan (QLD), it was concluded that ceramic cup samplers were able to estimate the quantities of nutrients and salts that moved beyond the root zone of irrigated crops (Weaver et al. 2002).

Further, in a study conducted five years previous Hatch et al. (1997) concluded that suction cups were inappropriate for determination of the overall leaching losses in a particular soil type, more precisely heavy clay's. Despite this Hatch et al. concluded that suction cups did provide useful data on changes in ionic concentrations which occurred in different soil horizons.

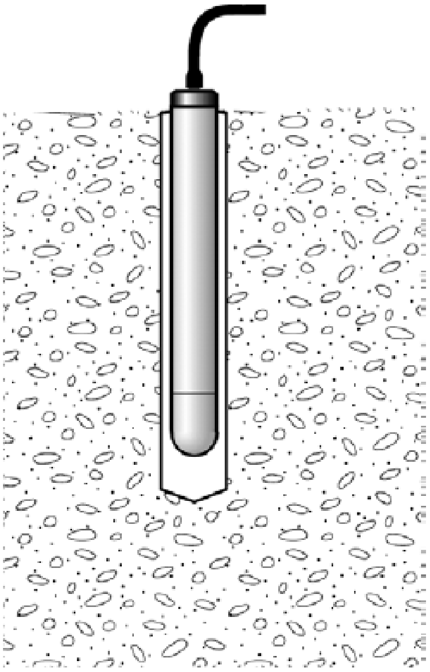


Figure 2-5 Installed Suction Cup (ICT International 2008)

Some of the errors that have been identified as being associated with the use of suction cups for soil solution sampling are:

- Intake rates of cups change if they are left in the field for several months or years;

- Unequal intake rates of suction cups, this possibly being due to faults in the suction cups with regards to them maintaining the same suction as other replicates in the trial;
- CEC of new and old ceramic suction cups differ, this difference can be overcome by having suction cups of the same age and usage, being used in the replicates of the trial; and
- If cups have been leached with dilute acid and distilled water, the first few samples from the field will be inaccurate and need to be disposed of. This inaccuracy is due to the CEC taking up selected cations and underestimating concentrations of soil solution.

The overall conclusion that can be drawn about ceramic suction cup solution samplers is that they are a cheap and effective manner for taking soil solutions for analysis. Considerations must be taken when deciding to use the ceramic suction cup samplers with the most important being what the specific problem being studied is. This will then provide a guide to what the cost of set up should be. Overall there are several important factors that combine to determine the concentration of ions collected by a ceramic suction cup sampler and from many studies it has been proven that they are a viable instrument to use.

2.8 Soil-Water and Nutrient Modelling

Soil-water movement models show changes in soil-water potential and can therefore map the soil-water movement. From this it can be seen how they can be applied to analyse and predict if water is remaining within the surface layers of the soil or if it is moving through to groundwater supplies. The basis for predicting what is occurring is the application of a water balance. The complexities of these water balances vary with the model (McKeering 2004), so far in the development process of models, there are many different options for accounting for the losses and gains to the soil-water system and can therefore be seen to be reasonably accurate.

Many researchers have identified that the modelling software HYDRUS is a quite practical and useful modelling system to use when modelling soil-water and solute movements within a soil profile. HYDRUS-2D is a Microsoft Windows based modelling environment for analysis of water flow and solute transport in variably saturated porous media (Simunek 2004). HYDRUS-2D has been used to simulate unsaturated flow and solute transport in past analyses and was identified as being very appropriate when solving the Richard's equation (1931) for saturated-unsaturated flow and the convection-dispersion equations for solute transport. The Richard's equation (1931) is represented by:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_t}\left[K\left(K\frac{A}{ij}\frac{\partial h}{\partial x_j} + K\frac{A}{iz}\right)\right] - S \qquad [1]$$

whilst the convection-dispersion equation [2] is represented by:

$$\frac{\partial \theta c}{\partial t} + \frac{\partial \rho s}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial c}{\partial x_j}\right) - \frac{\partial q_i c}{\partial x_i} + \mu_w \theta c + \mu_s \rho s + \gamma_w \theta + \gamma_s \rho - S c_s \qquad [2]$$

For equations [1] and [2] the following holds (Coquet et al. 2005, Simunek et al. 2000):

- θ is the volumetric water content [L^3L^{-3}];
- h equals the pressure head [L];
- x_i are the spatial coordinates [L];
- z is the vertical coordinate positive upward [L];
- t is time [T];
- $K\frac{A}{ij}$ are components of a dimensionless anisotropy tensor ($K\frac{A}{}$) in the two main spatial directions;
- K is the unsaturated hydraulic conductivity [LT^{-1}];
- S is root water uptake [T^{-1}];
- c is the solution concentration;

- s is the adsorbed concentration;
- μ_w & μ_s are the first-order rate constants for the liquid and solid phases;
- γ_w & γ_s are the zero-order rate constants for the liquid and solid phases;
- ρ is the soil bulk density;
- S is the sink term in the water flow equation;
- c_s is the concentration of the sink term;
- q_i is the i^{th} component of the volumetric flux density; and
- D_{ij} are the components of the dispersion coefficient tensor for the liquid phase.

The Richard's equation (1931) is a non-linear partial differential equation which is a combination of Darcy's Law and the continuity equation. The Richard's equation (1931) is the foundation of all mechanistic models used to simulate the dynamics of water (or other liquid) in permeable materials, including soils, rocks, aquifers, or industrial materials (Buchan 2008). Because of the generalness of the Richard's equation (1931) it can be used in many models. In unsaturated soils the processes that can be represented by the Richard's equation (1931) include the infiltration of water into the soil, its redistribution once inside the soil, water uptake by root fibres and the drying by evaporation (Buchan 2008).

Within HYDRUS-2D there are several assumptions made by the Richard's equation (1931). Simunek et al. (2000) identify some of these assumptions to be that the effect of the air phase is neglected and Darcy's equation is valid at both very low and very high flow velocities, this can present problems in very clayey soils as the flux is not proportional to the driving forces with low velocities. As well as these the osmotic and electrochemical gradients in the soil-water potential are negligible, the fluid density is independent of the solute concentration and the matrix and fluid compressibility's are relatively small.

It must be noted, that although the Richard's equation (1931) can be used in many models and is quite robust, the analysis of it also neglects hysteresis and anisotropy

(Buchan 2008). Complications from the Richard's equation (1931) include the extreme non-linearity of the hydraulic properties, inconsistencies between the scale at which the hydraulic and solute transport parameters are measured and the scale at which the models are being applied and the lack of accurate and cheap methods for measuring the unsaturated hydraulic properties (Simunek et al. 2000).

When analysing solute movement and transport within a soil profile a dispersion coefficient it required. Bear (1972) derived an equation for finding the dispersion coefficient and found it be represented by

$$\theta D_{ij} = D_T |q| \delta_{ij} + (D_L - D_T)\left(\frac{q_j q_i}{|q|}\right) + \theta\ D_d\ \tau\ \delta_{ij} \qquad [3]$$

The terms in this equation represent (Simunek et al. 2000):

- D_d is the ionic or molecular diffusion coefficient in free water [L^2T^{-1}];
- τ is the tortuosity factor [dimensionless];
- γ_{ij} is the Kronecker delta function ($\gamma_{ij} = 1$ if $i = j$, and $\gamma_{ij} = 0\ otherwise$); and
- D_L & D_T are longitudinal and transverse dispersivities [L].

In order to solve the convection-dispersion equation for solute transport initial boundary conditions must be set, as with all partial differential equations. The three types are First-type (Dirichlet type), Second-type (Neumann type) and Third-type (Cauchy type). The Dirichlet type (first-type) boundary conditions prescribe the concentration along a boundary segment, and are therefore ideal for use when modelling a constant concentration. The Neumann type (second-type) boundary conditions are used when a boundary segment is an impermeable boundary or when water flow is directed out of the region (Simunek & van Genuchten, 1994). The Cauchy type (third-type) boundary conditions are you to describe a concentration flux along a boundary segment (Simunek & van Genuchten, 1994). It has been identified that yet another boundary condition is required for volatile solutes when they are present in both liquid and gaseous phases.

This boundary condition has an additional term to account for gas diffusion through a stagnant boundary layer (Simunek & van Genuchten, 1994).

Several different models are used within HYDRUS-2D to represent the soil-water retention curves and hydraulic conductivity functions. These models are the van Genuchten model, the van Genuchten-Mualem model, the modified van Genuchten model (Vogel and Cislerova), and the Brooks and Corey model. The van Genuchten model, modified van Genuchten (Vogel and Cislerova) model and the Brooks and Corey model apply to the soil-water retention curve, whilst the van Genuchten-Mualem model, the modified van Genuchten model (Vogel and Cislerova), and the Brooks and Corey model apply to the hydraulic conductivity functions.

In 1980 van Genuchten proposed a mathematical representation of the soil-water retention curve (SWRC) (Rassam et al. 2004). It is given by

$$S_e = (1 + |\alpha\psi|^n)^{-m} \qquad [4]$$

where α, m, and n are fitting parameters (usually $m = 1 - \frac{1}{n}$), and S_e is the normalised volumetric water content given by (Rassam et al. 2004)

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad [5]$$

here, θ is the volumetric water content at any pressure head, and θ_s and θ_r are the saturated and residual water contents respectively (Rassam et al. 2004). Because of the absence of an air entry value the van Genuchten model only gives a reasonable result (Ippisch 2005). It has therefore been established that an air entry value needs to be accounted for to provide accurate results.

In 1988 Vogel and Cislerova modified the van Genuchten model by incorporating a non-zero air entry value (AEV) into the model (Rassam et al. 2004). The modification is implemented by introducing a fictitious water content θ_m that is higher than θ_s and replaces θ_s in the van Genuchten model (Rassam et al. 2004). There are limitations to this, in that the fictitious water content is used only when the water potential is less than the AEV, above this the water content is equal to θ_s.

Brooks and Corey (1964, 1966) concluded from comparisons of a large number of experimental data that the SWRC could be described by the following formula (Rassam et al. 2004)

$$S_e = \left(\frac{AEV}{h}\right)^n \qquad [6]$$

where n is the pore size distribution index. Brooks-Corey models have the advantages of mathematical simplicity, reasonable accuracy (Russo 1988; Rossi & Nimmo 1994; Kosugi 1994), and a physical basis in fractal descriptions of soil pore space (Tyler and Wheatcraft 1992).

2.9 Objectives

The efficiency of nutrient use by horticultural crops can be improved by the implementation of fertigation and irrigation management practices appropriate to the soil and crop constraints. From studies conducted by past researchers it has been identified that depending on the soil properties and irrigation, fertigation and crop management practices there is potential for highly mobile nutrients (e.g. plant available nitrogen (nitrate)) to be moved below the rootzone by drainage. This suggests that by changing management practices optimum nutrient and water use efficiencies can be achieved. It is therefore a necessity to identify if losses are occurring.

Objectives of this project are to:

1. Collect measurements on irrigation water and fertiliser application and movement under commercial field conditions.

2. Evaluate field data to identify recommendations for fertiliser and irrigation management practices to reduce nitrate movement.

3. Investigate the potential to use HYDRUS-2D to model soil-water and nitrate movement under different environmental conditions.

This project will use field trials and nutrient modelling to investigate the movement of nitrogen in soil under a drip irrigated commercial horticultural production system. Recommendations on strategies to improve the irrigation and fertigation management to improve fertiliser use efficiency and minimise drainage losses will be developed.

Chapter 3 Evaluation of Soil-Water and Nitrate Movement under Commercial Field Conditions

3.1 Introduction

Lettuce has traditionally been irrigated with solid set sprinkler irrigation systems (Barraclough and Co 1999) but with recent water shortages there has been an increased adoption of drip irrigation systems. To evaluate the effect of irrigation management on soil-water and nitrate movement (Chapter 2.4), a trial was conducted on a commercial lettuce production farm on the eastern Darling Downs, Queensland. The site where the trial was located had been used to grow lettuce for a period in excess of 10 years with cover crops of wheat being grown between seasons.

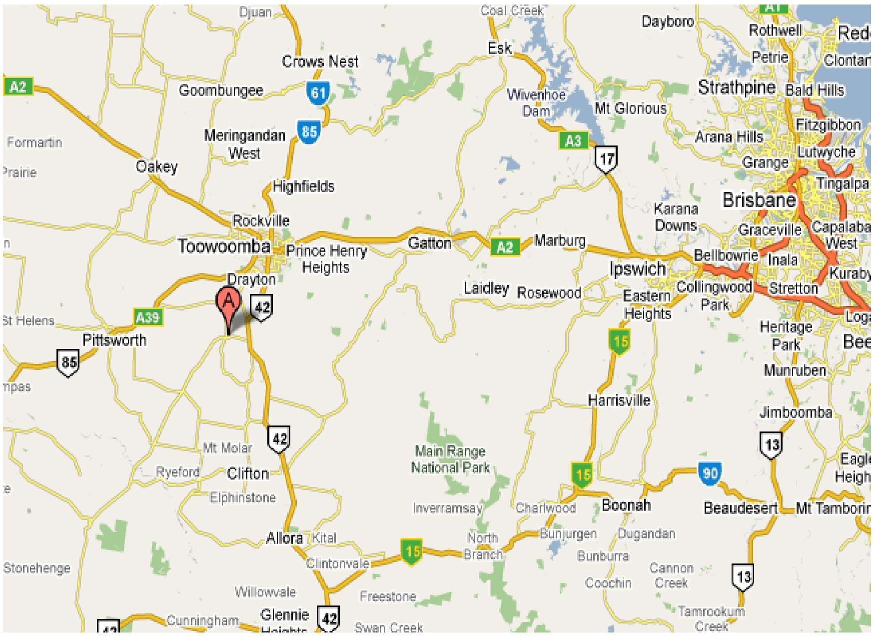


Figure 3-1 Locality of field trial

The trial collected data for both sprinkler and drip irrigation events and conditions within the soil profile. The data collection systems were replicated twice for two different set-up methodologies resulting in four collection plots.

3.2 *Materials and Methods*

3.2.1 Site Selection and Characterisation

The field trial was conducted on a commercial lettuce production farm located at Cambooya on the eastern Darling Downs. This site was chosen due to its close proximity to the research base and suitability for investigation. Due to the long period of commercial operation the chosen farm had extensive systems and practices in place. This allowed for the normal practices that have been proven to work for the grower to be evaluated.

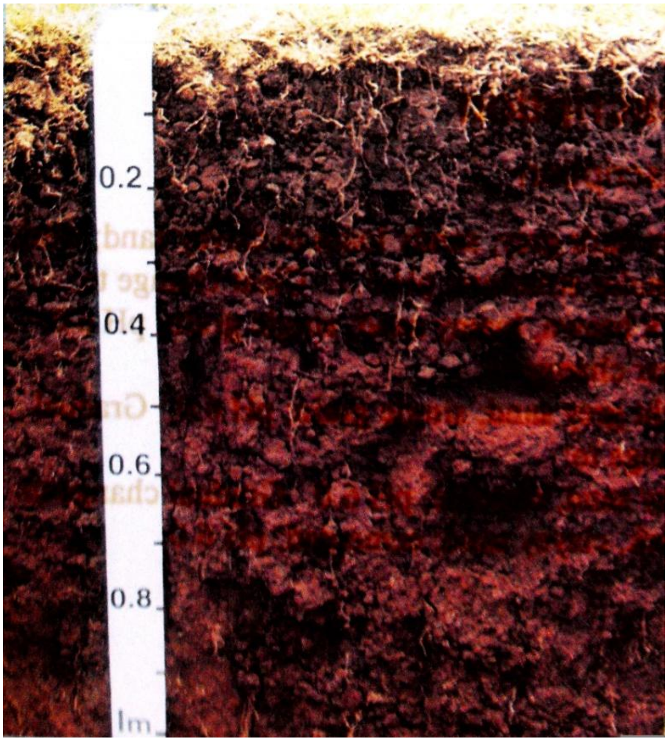


Figure 3-2 Example characteristic soil profile (Harms 1996)

The specific location of the trial site on the farm was chosen based on its horizontal uniformity down the slope of the hill on which all possible sites were located. Two plots were also located on either side of the chosen plot which allowed for the potential higher irrigation volumes due to sprinkler irrigation overlaps to be accounted for.

The first step required in starting the field trial was to determine a section of soil which was comparatively uniform within the trial plot. To do this an electromagnetic survey of the field was conducted using an EM38 (Geonics Ltd., Ontario, Canada) to select four monitoring plots with consistent soil properties (Figure 3-4).

An EM38 instrument measures the apparent soil conductivity, which was recorded and analysed. When an electric current is passed through a transmitter coil in the EM38 a magnetic field is generated. This primary field in turn induces a relatively weak secondary magnetic field in the soil profile with the strength of this secondary magnetic field being representative of the conductivity of the soil profile. As the conductivity of a soil comprises of soil moisture content, soil temperature, soil porosity, amount and composition of colloids and soil salt concentration, it was possible to determine where in the field the most appropriate section of soil was to locate replicate positions of sampling.

Figure 3-3 Soil core rig attached to utility

The soil at the site is a Red Ferrosol (Isbell, 1996). It is characterised by gradual horizon boundaries and a gradual increase in clay content (Figure 3-2). The soil surface structure breaks down under cultivation and a plough pan can develop (Harms 1996). This soil is freely drained and is suitable for most types of irrigation and crops. On sites suitable for cropping, this soil would generally be assessed as good quality agricultural land (Harms 1996). Being highly erodible on cultivated slopes greater than 3% it is recommended that a maximum surface cover is maintained to preserve the soil structure and reduce erosion. To further reduce erosion, and minimise leaching of water to groundwater supplies, low volume irrigation systems such as trickle are recommended.

3.2.2 Site Layout and Agronomy

The field trial plots used were cultivated into beds 1.2 m wide separated by 0.4 m furrows. Four rows of five week old lettuce seedlings were transplanted onto each bed on the 28th of January 2009. The site was irrigated until the 20th of February 2009 using a solid set sprinkler irrigation system consisting of ISS Rainsprays sprinklers on 0.4 m risers. The sprinklers were arranged in a rectangular pattern with 9 m spacing's along the laterals and an 8 m lateral spacing. Irrigations after the 20th of February 2009 were applied using a drip irrigation system. Two rows of drip tube with 0.4 m emitter spacing (2.3 L/hr/emitter) were installed 80 cm apart on the surface of the beds (Figure 3-5).

Figure 3-4 Conducting an EM38 scan of a potential field trial plot on the eastern Darling Downs

Irrigation water was supplied from a local bore that sources the groundwater from directly beneath the cropping fields. Urea and potassium nitrate with N:P:K ratios of 46:0:0 and 13:0:46, respectively, were dissolved in the irrigation water and applied during both the sprinkler and drip irrigation events.

Irrigation and fertigation was scheduled and recorded by the grower. Timings of both irrigation and fertigation were based on observation of weather, crop and soil conditions undertaken by the grower. These observations were completed using the usual methods used which included a small weather station to record temperature and rainfall and visual observation of the crop and soil conditions. No further instrumentation was used by the grower.

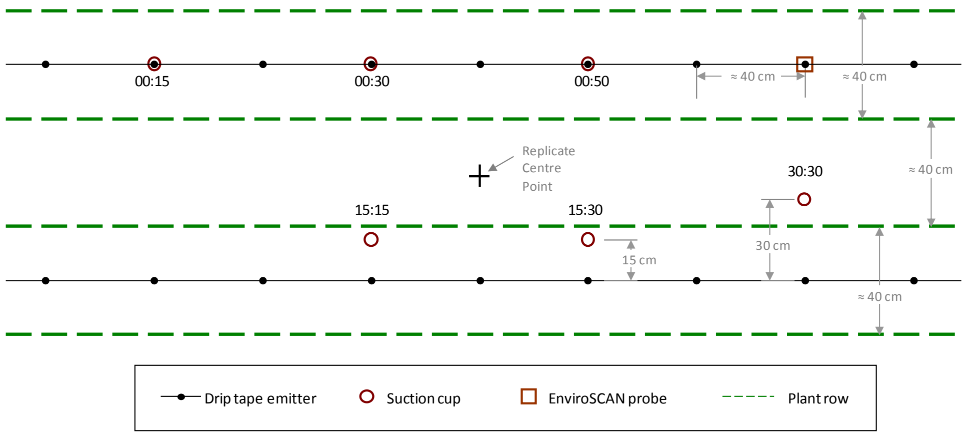


Figure 3-5 Plan view of the plot layout showing location of drip tape and sensors

Meteorological data was collected by a weather station (Figure 3-6) situated in close proximity to the trial site. Daily evapotranspiration for a reference crop (ET_0) was calculated using the FAO Penman-Monteith equation (Allen et al. 1998, eq. 6). The weather station consisted of a tipping bucket rain gauge, temperature, and wind speed and wind direction instruments. An inbuilt logger powered by a solar panel periodically recorded all of the data. In the event that any components on the weather station failed the growers meteorological data as well as SILO and Bureau of Meteorology data was obtained.

3.2.3 Plot Layout

The trial plot layout (Figure 3-5) was decided on to allow the collection of data from several points that would allow adequate representation of the entire soil profile below the crop. Ceramic soil solution samplers were positioned, in a range of combinations, at depths of 15 cm, 30 cm, and 50 cm down the soil profile, and distances of 0 cm, 15 cm, and 30 cm away from the drip tape. An EnviroSCAN probe was also located in each replicate with recordings be taken at 10 cm, 20 cm, 30 cm, 40 cm, and 50 cm.

Figure 3-6 Weather station located near the trial site

3.2.4 Soil Moisture Monitoring

The pre-plant and post-harvest soil core samples were used to obtain the soil moisture, bulk density, nitrate, ammonium and electrical conductivity (EC) of the soil at the trial site (see Section 4.2.2.1).

EnviroSCAN (Sentek, Adelaide) capacitance probes were located in each plot adjacent to a drip emitter and measured soil moisture changes with the soil profile at 10 cm increments up to a depth of 50 cm. From the data obtained from the EnviroSCAN we are able to confirm when water is applied through either rainfall or irrigation events. The data recorded at a depth of 40 cm to 50 cm gives an indication of whether there is leaching below the rootzone arising from current management practices. This is so as there is no evidence of the crop at this depth.

Logging tensiometers were installed to measure the soil-water potential. This data was to be used to verify whether readings recorded from both the EnviroSCAN and suction cups were reasonable, however became ineffectual when the data was erroneous. The data combined would have been able to be used to assist in the identification and confirmation of whether or not there was excess water in the soil profile which could have moved below the root zone and into groundwater supplies.

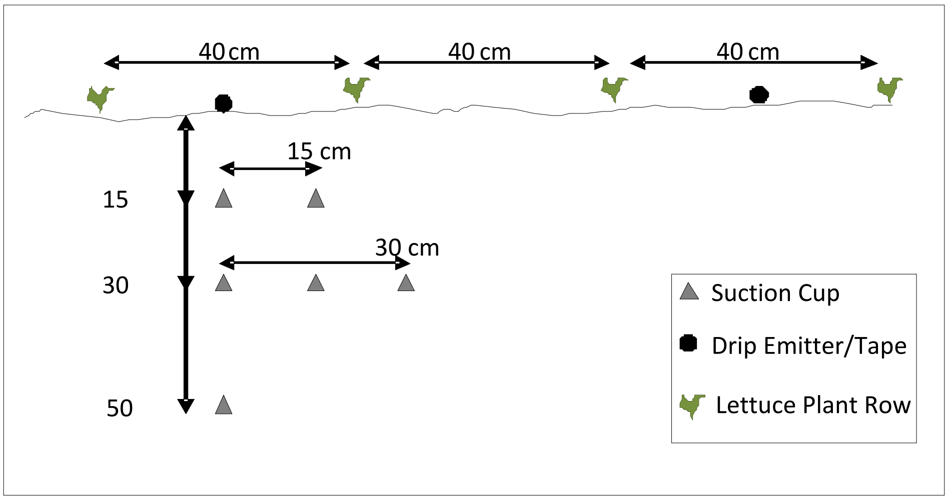


Figure 3-7 Diagrammatic representation of soil profile through beds showing the position of drip emitters and the soil suction cup samplers

3.2.5 Soil Nutrient Monitoring

Once an appropriate site was selected from the results obtained through the EM38 scan, soil core samples were taken where each replicate would be situated, both before and after harvesting. These were used to determine the bulk density, initial and final moisture content, initial and final nitrate and ammonium concentration, the electrical conductivity (EC), particle size distribution and soil moisture characteristic curves (see section 4.2.2).

Soil core samples were taken using a hydraulically driven soil core rig attached to a utility (Figure 3-3). A total sampling depth of 50 cm was decided upon to record what is occurring below the rootzone of the lettuce plants. Each soil core sample was cut into four segments that represented 0-10 cm, 10-20 cm, 20-30 cm and 30-50 cm.

The depths were chosen based on the characteristics of the rooting systems of lettuce crops. The 0-10 cm depth sample gave a beneficial representation of the area of the soil profile that contains most of the roots of the lettuce plants. The sample at a depth of 10-20 cm gave a good representation of the area that surrounds the lower extent of the rootzone. The sample taken at 20-30 cm shows the initial area below the rootzone that should have little to no roots and will be the first section of the soil profile that will indicate possibilities of leaching of nutrients and water. The sample at a depth of 30-50 cm should have very little change in its water and nutrient content due to the crop having no influence on the soil characteristics at this depth.

Ceramic soil suction cup samplers were used to extract soil solutions at various combinations of depths (ranging from 15 to 50 cm) and distances (0 to 30 cm) from the drip emitters (Figure 3-7). Two types of samplers were used, the SoluSAMPLER™ (Sentek, Adelaide) and Model 1900 Soil-Water Sampler (ICT International, Armidale). Both suction cups were installed at similar locations relative to the drip emitters and the same suction (~20 kPa) was applied for the same period (typically 24 hours) with each cup. The Model 1900 is a large volume sampler with a capacity of >1000 mL. The Sentek (Adelaide) SoluSAMPLER is a low volume sampler with a capacity of 70-75 mL. Two of the monitoring plots were installed with the SoluSAMPLER and the other two plots had the Model 1900 samplers installed.

Initial sampling of soil solutions took place daily with a total of 28 samples being analysed throughout the course of the trial. Daily initial sampling was conducted to allow for equilibrium between the soil slurry used to install the suction cups and the soil profile to occur at a faster rate. Daily sampling was preferred as concentrations and volumes could be more easily linked to irrigation and rainfall events and linked relatively between the two varieties of suction cups. Time between sampling was ideally left for no longer than 48 hours; however environmental conditions at the trial site could influence this. Each sample extracted had the nitrate concentration and electrical conductivity tested and recorded.

3.3 Results

3.3.1 Water and Fertiliser Applications

The potential evapotranspiration for the crop season was 232 mm and the total volume of water applied during this period was 294 mm. A total of 101 mm of irrigation water was applied through sprinkler irrigation and a further 134 mm of water was applied through the drip irrigation. During the trial it rained a total of nine days, applying an average of 6.5 mm on each occasion (Figure 3-8a). There was slightly higher depths of irrigation water applied by the individual drip irrigation events compared to the sprinkler irrigation events (Figure 3-8a).

A total of 93 kg/ha of nitrogen was applied through fertiliser applications during the trial. A further 21 kg/ha of nitrogen was applied due to the concentration of nitrogen (30 mg/L) present in the bore water supply, creating a total of 114 kg/ha of nitrogen applied throughout the season. The fertiliser application rates were substantially higher on a wetted area basis for the drip irrigation events (Figure 3-8b). It is interesting to note that approximately one-sixth of the total nitrogen was applied in the last week before harvest. There is some debate (Huett and Dettman 1992; Doerge, *et al.* 1991) as to the effectiveness and level of uptake at this late stage. If this nitrogen is not taken up by the plants it will remain in the soil, susceptible to leaching until it is utilised by the next crop.

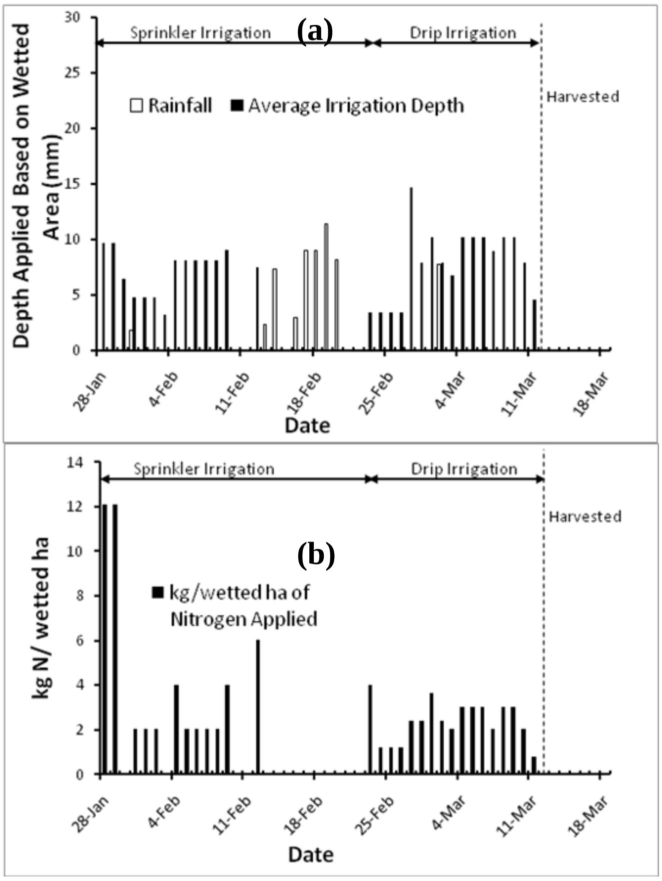


Figure 3-8 (a) Rainfall and irrigation application and (b) fertigation application for the trial lettuce crop on the eastern Darling Downs, Queensland.

3.3.2 Water Movement within the Soil Profile

The EnviroSCAN data (Figure 3-9) shows that soil moisture throughout the soil profile was high for the majority of the season. Extraction occurs primarily within the surface layer (0-10cm) of the soil profile and increases as the season progresses. Later in the season some minor extraction occurred from the 20 cm and 30 cm depths. Anecdotal observations of rooting depths of lettuce plants suggest that roots typically only extend to a maximum of 15 cm. Hence, some of the water extraction in the 20 cm to 30 cm depths may be attributed to water extraction in the surface layer creating a soil matric gradient which moves water up through the profile. Continuous high moisture observations at 40 cm and 50 cm depth and spiking associated with irrigation and rainfall events at these depths suggests that there is deep drainage occurring due to both rainfall and irrigation events throughout the season.

3.3.3 Effect of Soil Solution Sampling Methodology on Nitrate Measurement

Considerable differences between the different suction cups were observed in both the volume of soil solution extracted and the measured nitrate concentrations (Table 3-1). Generally, smaller volumes were measured using the SoluSAMPLER. The largest volumes extracted using the Model 1900 was 174 mL while the largest using the SoluSAMPLER was only 25 mL. However, the difference between the average nitrate concentrations measured with the different cups varied according to sampling location in the profile.

At 15 cm depth, the Model 1900 cups measured substantially lower average seasonal nitrate nitrogen levels (i.e. 252 – 313 mg/L) than the SoluSAMPLER (455 – 548 mg/L) (Table 3-1). However, at 50 cm depth, the average seasonal nitrate nitrogen level for the SoluSAMPLER was approximately 100 mg/L less than that measured using the Model 1900, however this was not regarded as substantial. Differences at 30 cm depth were also negligible, however the substantial differences found at a depth of 15 cm appear to occur during early growth stages and diminished after the beginning of substantial plant growth and the change to trickle irrigation.

Good soil contact around the SEC solute samplers is hard to maintain compared to the Sentek solute samplers, especially under shallow installations, due to wind vibration and handling during solute sampling. Therefore it is possible that gaps between the SEC solute samplers and the surrounding soil allowed preferential flow of irrigation (sprinkler) and precipitation down toward the SEC ceramic cups, resulting in a difference in soil solute concentration. Preferential flow may only be part of the reason for the apparent differences as it is also likely to be function of the relative pore size from which the soil solution is being extracted, but this is not corroborated at other depths. However, the implications of this finding in relation to bypass pathways within the root zone and the impact on the potential for using soil suction cups for measuring plant available nitrate and deep drainage require further investigation.

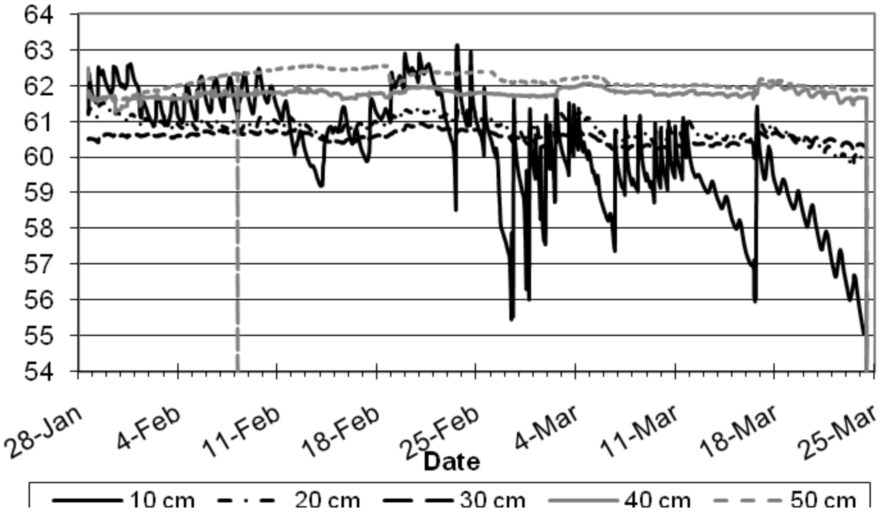


Figure 3-9 Relative soil moisture change for a sprinkler and drip irrigated lettuce crop on the eastern Darling Downs, Queensland.

3.3.4 Nitrate Movement within the Soil Profile

Pre-plant nitrate nitrogen was 13 mg/kg in the surface layer and 23 mg/kg at 30-50 cm. However, during the season the surface nitrate nitrogen increased to 27 mg/kg while the nitrate nitrogen in the 30-50 cm horizon decreased to 13 mg/kg (Table 3-2). The nitrate nitrogen concentration in the top 30 cm of the soil profile and directly under the drip emitter was initially 400 to 550 mg/L (Figure 3-10). At a distance of 15 cm from the drip emitter the concentration was only slightly lower with a concentration range of 300 to 500 mg/L (Figure 3-10). As the season progressed these values were observed to decrease significantly and most notably at a greater rate after the switch from sprinkler to drip irrigation. The reduction was observed to follow a period of rainfall and no fertiliser application (Figure 3-8). The soil solution data (Figure 3-10) and soil moisture data (Figure 3-9) showing movement of water at depth suggests that the presence of in-season rainfall was a significant cause of nitrate movement through the profile. However, it should be noted that at depths and distances away from the drip emitter wetted zone, the nitrate concentrations remained persistently high. This suggests that this area may have been drier prior to the rainfall events and likely suffered less drainage and nitrate loss. This confirms that the nitrate movement within the soil profile is highly dependent on water movement.

Table 3-1 Average nitrate concentrations extracted from the Model 1900 Soil-Water Sampler and the SoluSAMPLER in a field trial lettuce crop on the eastern Darling Downs, Queensland.

		Distance From Emitter (cm) : Depth (cm)					
Type of Suction Cup		0:15	0:30	0:50	15:15	15:30	30:30
Model 1900	Volume (mL)	50	30	50	37	38	24
	Nitrate (mg/L)	313	330	312	252	351	427
SoluSAMPLER	Volume (mL)	17	13	9	16	14	11
	Nitrate (mg/L)	548	308	223	455	299	435

Table 3-2 Soil chemical analysis for soil growing a lettuce crop on the eastern Darling Downs, Queensland.

		Depth			
		0-10cm	10-20cm	20-30cm	30-50cm
Ammonium Nitrogen (mg/kg)	Pre-Plant	0.99	0.97	0.9	0.6
	Post-Harvest	1.13	0.51	0.78	0.57
Nitrate Nitrogen (mg/kg)	Pre-Plant	13	19	21	23
	Post-Harvest	27	15	18	13
Electrical Conductivity (dS/m)	Pre-Plant	0.13	0.16	0.19	0.23
	Post-Harvest	0.25	0.23	0.19	0.15

3.3.5 Changes in Electrical Conductivity within the Soil Profile

The soil solution EC patterns throughout the season appeared to mirror the change in soil solution nitrate (Figure 3-11). At the start of the field trial the electrical conductivity within the soil profile ranged from 0.13 dS/m in the top 10 cm to 0.23 dS/m in the 30-50 cm depth (Table 3-2). Throughout the trial reasonably high values of EC were observed within the soil solutions extracted (Figure 3-11). The EC in the surface layer is lower than at depth confirming the accumulation of salts with depth due to crop water extraction and salt movement as irrigation and rainfall moves within the profile. There is greater variation directly under the emitter than at 30cm away from the emitter suggesting that the wetter soil moisture conditions in this area contribute to the salt movement, particularly during periods of rainfall. During the trial the EC was lower, with average root zone soil-water EC below 2 dS/m at a distance of 15 cm from

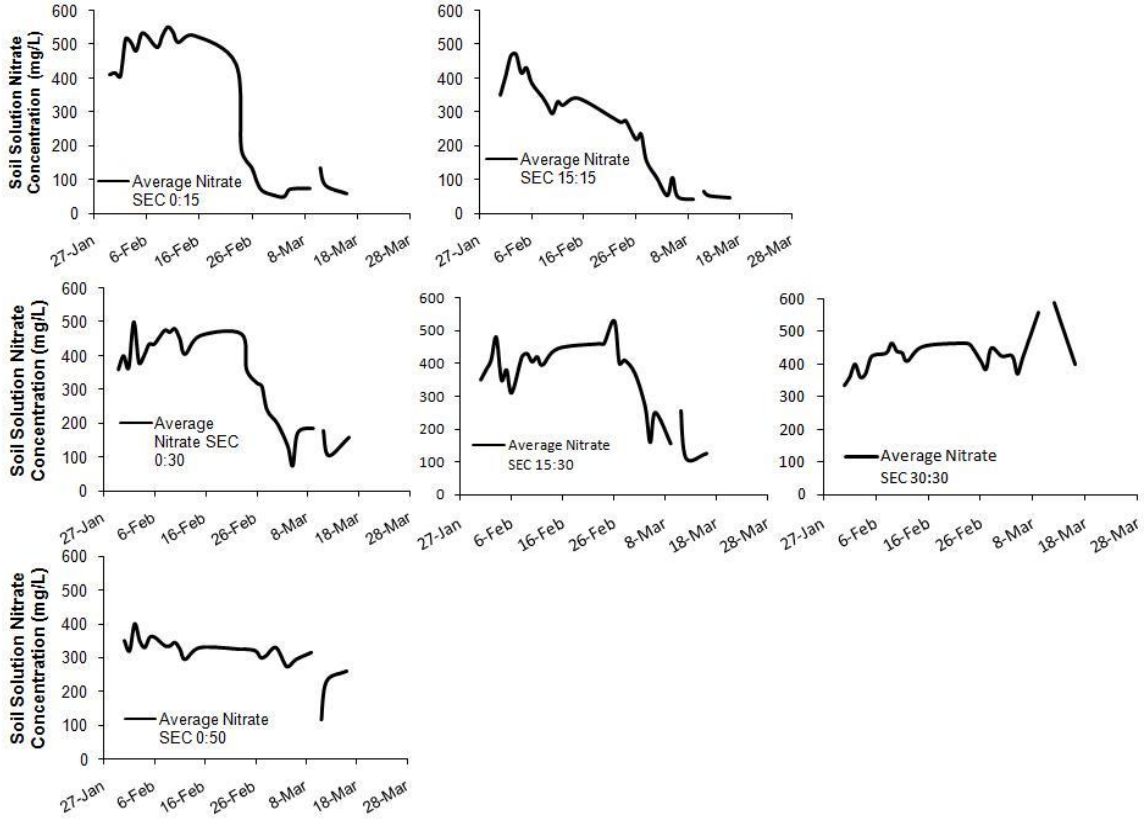


Figure 3-10 Nitrate concentrations collected from the soil profile using Model 1900 soil solution extractor during a lettuce crop on the eastern Darling Downs, Queensland. (Labels are horizontal distance in cm:depth in cm).

the closest emitter (Figure 3-11). At the emitters, the average root zone EC in the soil-water was below 2.8 dS/m throughout the trial, with average EC at 15 cm depth remaining below 2.6 dS/m (Figure 3-11). Based on the work of Maas and Hoffmann (1977), this would have resulted in only a very small (if any) yield loss due to salinity, because the soil solution extract threshold EC for lettuce under steady state conditions is commonly reported to be 1.3 dS/m with a 25% yield loss occurring at 3.2 dS/m. However, this data shows substantial variation in soil EC within the root zone with this variation occurring both spatially at any point in time and temporally as a consequence of irrigation, fertigation and rainfall inputs. The impact of this variation on crop production is not known and requires further investigation.

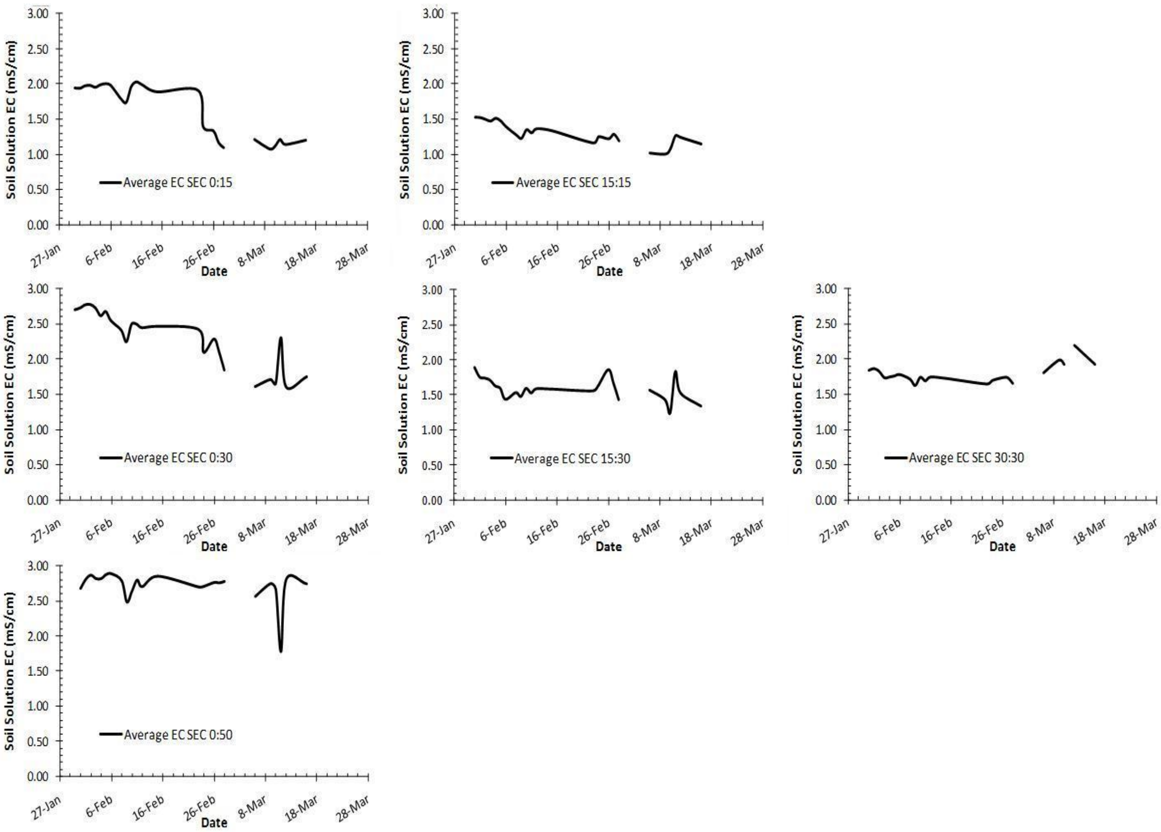


Figure 3-11 Electrical conductivity of soil solutions collected using a Model 1900 soil solution extractor during a lettuce crop on the eastern Darling Downs, Queensland. (Labels are horizontal distance in cm:depth in cm).

3.4 Discussion

It has been identified that the irrigation and fertigation application management practices are not adequate to prevent leaching of nutrients and water below the crop rootzone. There is however several variables which if altered may change this outcome. If the seasonal rainfall pattern was different and there was very little rainfall, the management practices utilised may have been appropriate with the possibility that very little leaching might occur. If the crop type was one that had a deeper rootzone with a larger volume then once again the management practices utilised may have been suitable.

Two variables alterable by the grower include the fertigation and irrigation application volumes. Smaller more frequent applications of irrigation water could have the same growth results as the larger less frequent applications. There is potential that they could be more effective with the rootzone having a more appropriate water to air ratio so as to attain optimum growth and yields. This principle also holds for the fertigation applications as fewer nutrients may lead to higher growth rates and yields which otherwise may be inhibited by an oversupply of nutrients. Although crops need an adequate supply of water and nutrients an oversupply will have an adverse effect crop growth and yields.

3.5 Conclusions

A field trial has been conducted on a commercial sprinkler and drip irrigated lettuce crop. This work has shown that deep drainage did occur during the season and that nitrate would have been moving out of the root zone. Substantial spatial and temporal variations in nitrate and EC in the soil solution were observed which appear to be related to the pattern of water movement associated with the irrigation applications. Hence, it would seem reasonable to suggest that the level of deep drainage and nitrate leaching would be influenced by the irrigation design and management practices as well as the in-season rainfall and soil physical conditions. The key to nitrogen management is minimising the amount of nitrogen and water in the soil, whilst ensuring adequate nitrate and water is available for plant growth. Currently a large amount of water and fertiliser is applied after transplanting, during a time when the plant roots are very shallow and plant requirements are small. Measurements suggest substantial nitrogen was lost to leaching before the plants had reached 20% ground cover.

The uptake of nitrogen by lettuce during the week prior to harvest requires further investigation. Available research is conflicting as to whether nitrogen uptake during the week prior to harvest is negligible. During these trials, approximately one-fifth of the total nitrogen was applied during this period, if unused it is highly susceptible to leaching during the fallow period. However, further work is required to identify appropriate design and management practices under a range of conditions. Substantial differences were also observed between the soil solution nitrate and EC measurements obtained using difference soil solution extractors installed at shallow depths. The implications of these differences in terms of either the utility of the measurements obtained with either instrument and/or nitrate and EC movement requires further investigation.

Chapter 4 Evaluating the Potential of HYDRUS-2D to Model Soil-Water and Solute Movement under Irrigation

4.1 Introduction

The modelling of soil-water and nutrient movement using mathematically based computer models has large potential for the identification of best irrigation and fertigation management practices for lettuce production systems. Through appropriate calibration and validation using collected field data an ideal model can potentially be developed. Following development of a suitable model various management practices can be evaluated under differing in-season environmental conditions.

4.2 Materials and Method

4.2.1 Model Selection and Operation

HYDRUS-2D is a finite element model for simulating the movement of water, heat, and multiple solutes in variably saturated media (PC Progress, 2008). HYDRUS-2D has numerous functions built into its extensive programming and therefore only those relevant to this project will be discussed. The model requires the user to input soil and soil-water parameters, root water uptake patterns and root distribution, solute parameters, time variable conditions and decide on the method of flow throughout the soil profile. The mesh is manually generated and manipulated to allow for optimum results generation. Boundary conditions relating to moisture content, solute concentration and root distribution are also entered into the model. Further data which HYDRUS-2D defaults to, such as iteration criteria, can be manipulated to best suit the output capabilities of the model. The details on model operation and parameterisation, including assumptions are provided in Appendix E.

4.2.2 Characterising the Soil Parameters

4.2.2.1 Laboratory Analysis of Soil Parameters

Following the collection of the soil core samples several parameters were calculated using laboratory analysis. The moisture content, bulk density, particle size distribution and soil-water retention curve were all found after completing separate laboratory analyses.

Moisture content and bulk density

The gravimetric moisture content and bulk density of the soil profile was found using intact soil core samples taken at depths of 0-10 cm, 10-20 cm, 20-30 cm and 30-50 cm. Once each sample had been carefully retrieved they were placed in ovenproof cylinders. Each sample was weighed after removal from the field and oven dried at 105℃ for 48 hours. Following oven drying, the final weight of the sample was determined.

The gravimetric moisture content was found using the following equation:

$$\theta_g = \frac{Mass\ of\ wet\ soil - Mass\ of\ oven\ dry\ soil}{Mass\ of\ oven\ dry\ soil} \qquad [7]$$

Whilst the bulk density was calculated by:

$$\rho_b = \frac{Mass\ of\ oven\ dry\ soil}{Volume\ of\ soil\ sample} \qquad [8]$$

Following the determination of these two parameters the volumetric water content was then calculated using the following equation:

$$\theta_v = \rho_b \times \theta_g \qquad [9]$$

These values were determined for two replicate soil core samples and the median value calculated. Results from this laboratory analysis for pre-plant and post-harvest can be seen in Table 4-1.

Table 4-1 Initial and final median gravimetric moisture content, bulk density and volumetric moisture content for a trial plot on the eastern Darling Downs

Sample Depth (cm)	Gravimetric Moisture Content (cm^3/cm^3)	Bulk Density (g/cm^3)	Volumetric Moisture Content (g/cm^3)
Pre-season Values			
0-10	0.4134	1.0457	0.4357
10-20	0.3766	0.9208	0.3492
20-30	0.4919	1.1851	0.5849
30-50	0.4677	1.1253	0.5306
Post-season Values			
0-10	0.2215	0.6743	0.1523
10-20	0.3714	0.9147	0.3400
20-30	0.4724	1.1210	0.5299
30-50	0.5091	1.2125	0.6174

Particle size distribution

The particle size analysis was conducted on samples from 0-10 cm, 10-20 cm and 30-50 cm depths which had been air dried and sieved to 2mm in size. The particle size distribution was determined using an ultrasonic probe to mix a 25 g sample of soil with approximately 100 mL of deionised water. These samples were then increased in size by the addition of deionised water to create a full sample of 500 mL. After the addition of extra water the solution was mixed with a specially designed plunger to create a uniform solution. Samples were then taken with a particle size distribution pipette at appropriate depths and sampling times. The first sample taken at 2 cm depth was comprised of silt and clay particles whilst the final sample at 10 cm depth contained solely clay particles. The samples were placed in individual containers and oven dried at 105°C for forty-eight hours. The final weight of the sample was then determined.

Due to the HYDRUS-2D being based on American soils the particle size analysis had to be conducted to the particles sizes recognised as the American standard. A comparison of differences in particle sizes between Australia and America can be seen in Table 4-2.

Table 4-2 Comparison of particle sizes recognised in Australia and America

	Particle Size (mm)	
	Australia	America
Sand	2 – 0.02	2 – 0.05
Silt	0.02 – 0.002	0.05 – 0.002
Clay	<0.002	<0.002

To conduct the particle size distribution analysis the standard timings used to conduct the test had to be recalculated. It was determined that the sampling times would be 35 seconds at 2 cm depth, in place of 4 minutes and 48 seconds, and 1 hour and 35 minutes at 10 cm depth, which is the same used for the Australian sampling method. The final sampling time remained the same due to the recognition that clay particles being extracted are the same size in both Australian and American standards.

To calculate the fractions of each particle the following equations were used:

$$m_{od} = \frac{m_{ad}}{105} \times 100 \qquad [10]$$

$$Particle\ Fraction = \frac{m_{od}}{10mL} \times \frac{500mL}{m_{od}} \times 100 \qquad [11]$$

Using these two equations the particle size distributions seen in Table 4-3 were found.

Table 4-3 Particle size distribution for the trial site located on the Eastern Darling Downs

	% Sand	% Silt	% Clay
0-10	10.1200	26.0400	63.8400
10-20	11.5935	26.2490	62.1575
20-30	10.1200	30.0300	59.8500
30-50	7.7578	26.1616	66.0806

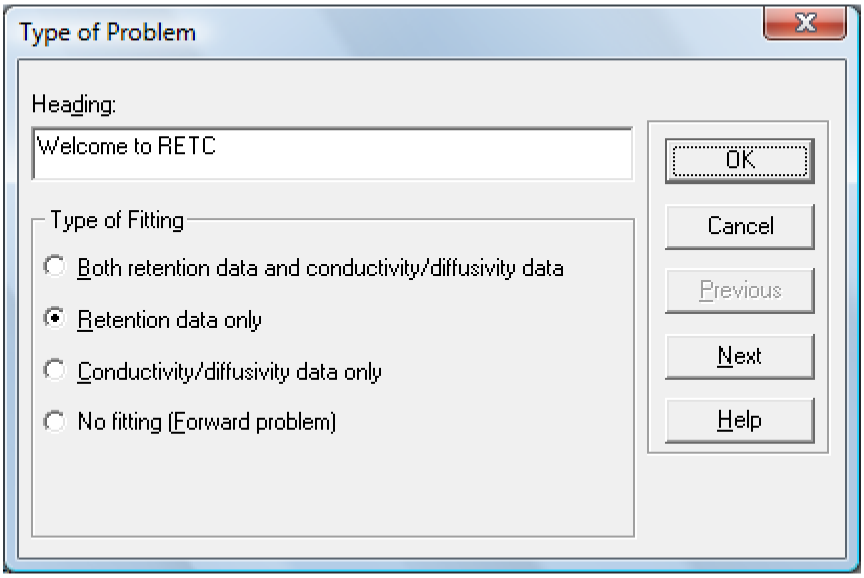
The particle size analysis data was used in initial HYDRUS-2D modelling until the soil-water retention curve could be calculated. It was also used to start the calculation of the soil-water retention curve to ensure that the program RETC was in close proximity to the correct soil parameters.

Soil-Water Retention Curve

The soil-water retention curve was determined using the program RETC developed by M. van Genuchten, J. Simunek, F.J. Leij and M. Sejna and consists solely of a code for quantifying the hydraulic functions of unsaturated soils. Data was collected using pressure plate analysis equipment on intact soil core samples. Two replicates were utilised to reduce possible errors in final calculations. The depths that were represented by the soil core samples were 0-10 cm, 10-20 cm, 20-30 cm and 30-50 cm.

The pressure plate experiment was a lengthy process with a range of pressure's applied to each representative soil core sample. The range of pressures applied were 30, 50, 75, 100, 250, 500 and 1500 kPa. Equilibrium of samples to each pressure was deemed to have occurred once no further water was able to be extracted. The gravimetric water content was determined by weighing each sample and conducting the necessary calculations. Once calculated it was then converted to a volumetric water content using the bulk density found for soil core samples taken on the same day in the same location.

Following the completion of the laboratory tests and required calculations, parameters were inputted into RETC as required. To calculate the soil-water retention curve the type of problem was first required to be selected. As we were only concerned with the retention of the soil-water it was decided that the type of fitting required would be retention data only (Figure 4-1).

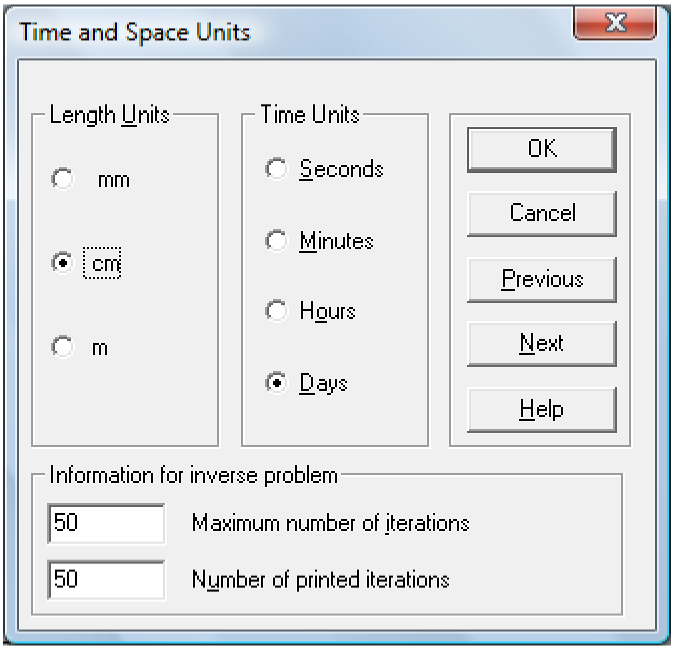


Heading:
Welcome to RETC

Type of Fitting
○ Both retention data and conductivity/diffusivity data
● Retention data only
○ Conductivity/diffusivity data only
○ No fitting (Forward problem)

Figure 4-1 RETC Type of Problem selection screen

The time and length units were selected (Figure 4-2) and were chosen based on those used in HYDRUS-2D. For all modelling purposes the length units used were centimetres whilst the time units were days. A number of options were available for fitting the data collected (Figure 4-3) and it was decided that the van Genuchten-Mualem model would be best suited.

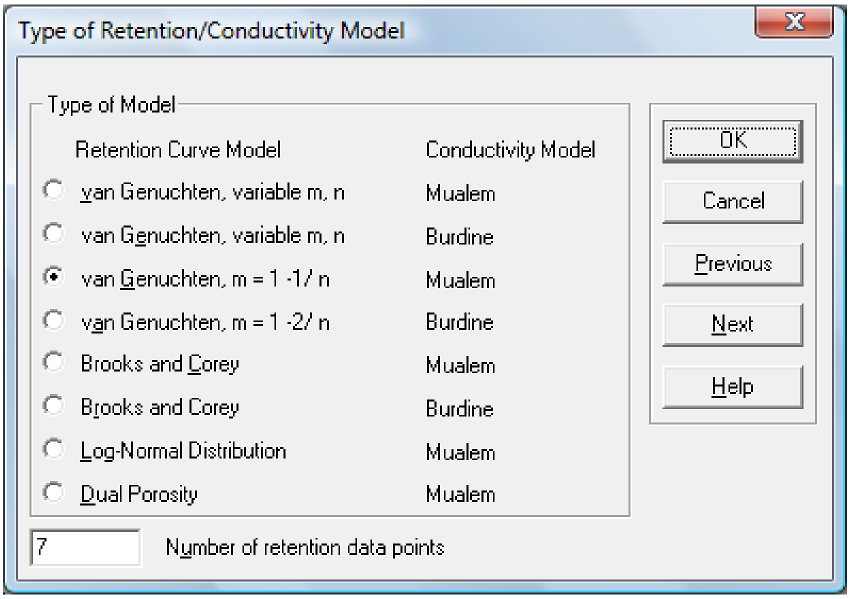


Length Units
○ mm
● cm
○ m

Time Units
○ Seconds
○ Minutes
○ Hours
● Days

Information for inverse problem
50 Maximum number of iterations
50 Number of printed iterations

Figure 4-2 RETC Time and space units selection screen



Type of Retention/Conductivity Model

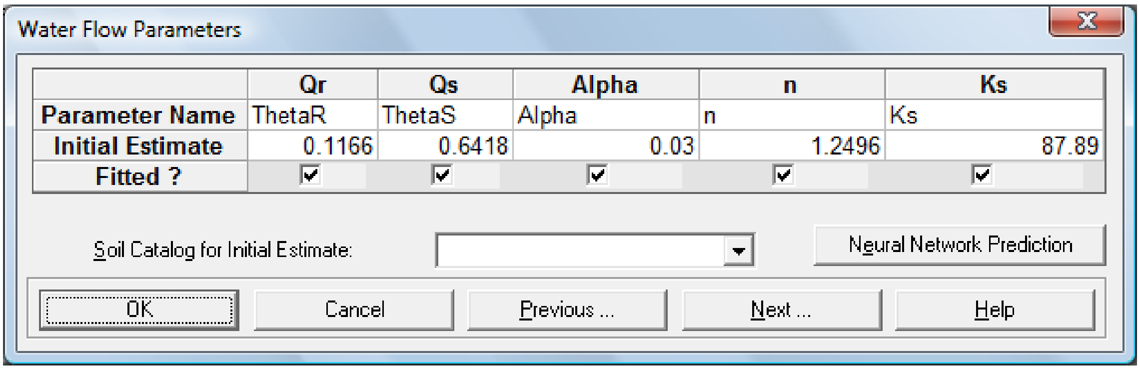
Type of Model

	Retention Curve Model	Conductivity Model
○	van Genuchten, variable m, n	Mualem
○	van Genuchten, variable m, n	Burdine
●	van Genuchten, m = 1 -1/ n	Mualem
○	van Genuchten, m = 1 -2/ n	Burdine
○	Brooks and Corey	Mualem
○	Brooks and Corey	Burdine
○	Log-Normal Distribution	Mualem
○	Dual Porosity	Mualem

7 Number of retention data points

Figure 4-3 RETC Type of retention model selection screen

Initial estimates of soil-water flow parameters were entered into the Water Flow Parameters screen (Figure 4-4). To assist in a quicker and more precise solution of the soil-water retention curve the Neural Network Prediction option was used to select the initial soil parameters. In this the soil particle size distribution data previously calculated was entered and the initial estimates of soil parameters were estimated by the inbuilt catalogue. In this screen the parameters to be fitted and optimised were also selected.



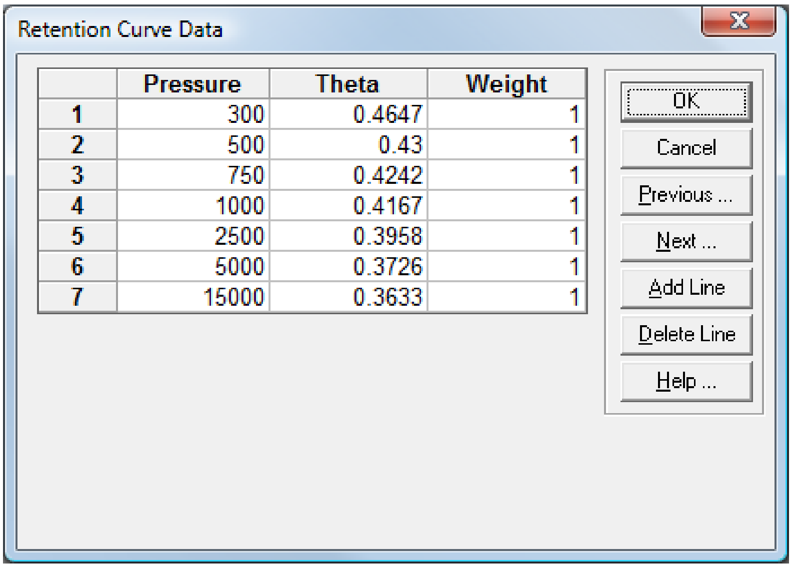
Water Flow Parameters

	Qr	Qs	Alpha	n	Ks
Parameter Name	ThetaR	ThetaS	Alpha	n	Ks
Initial Estimate	0.1166	0.6418	0.03	1.2496	87.89
Fitted ?	☑	☑	☑	☑	☑

Soil Catalog for Initial Estimate:

Figure 4-4 RETC initial input screen for water flow parameters

The final requirement to produce the soil-water retention curve was the entering of the retention curve data collected from the pressure plate analysis. This was completed in the Retention Curve Data screen (Figure 4-5). After entering all of the required parameters and initial estimates for each depth range RETC was run.



	Pressure	Theta	Weight
1	300	0.4647	1
2	500	0.43	1
3	750	0.4242	1
4	1000	0.4167	1
5	2500	0.3958	1
6	5000	0.3726	1
7	15000	0.3633	1

Figure 4-5 RETC input screen for retention data collected from laboratory analysis

RETC determined the values for the residual water content, saturated water content, and Alpha and n (curve fitting parameters) for each depth and replicate. The median value of each variable determined by RETC was found for the different depths, these can be seen in Table 4-4. The soil-water retention curves for each replicate and depth can be seen in Figure 4-6 to Figure 4-13.

Table 4-4 Soil-water flow parameters as calculated by RETC for a trial site located on the Eastern Darling Downs

Depth	**0-10 cm**
Parameter	Median Value
ThetaR	0.335075
ThetaS	1.365425
Alpha	0.8571
n	1.37896

Depth	**20-30 cm**
Parameter	Median Value
ThetaR	0.429995
ThetaS	1.06974
Alpha	0.18296
n	1.34604

Depth	**10-20 cm**
Parameter	Median Value
ThetaR	0.257985
ThetaS	0.66454
Alpha	0.380495
n	1.213765

Depth	**30-50 cm**
Parameter	Median Value
ThetaR	0.406855
ThetaS	0.86482
Alpha	0.220575
n	1.308955

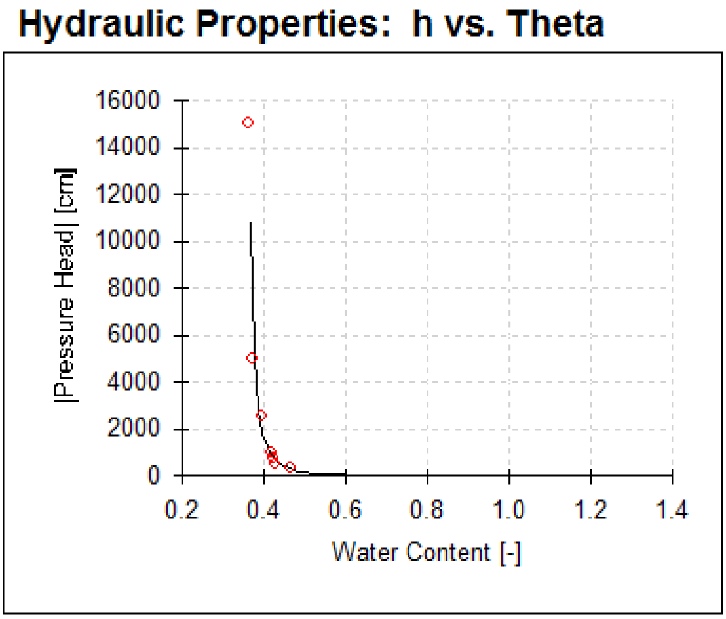


Figure 4-6 Soil-water retention curve for 0-10 cm replicate one for the trial site located on the Eastern Darling Downs

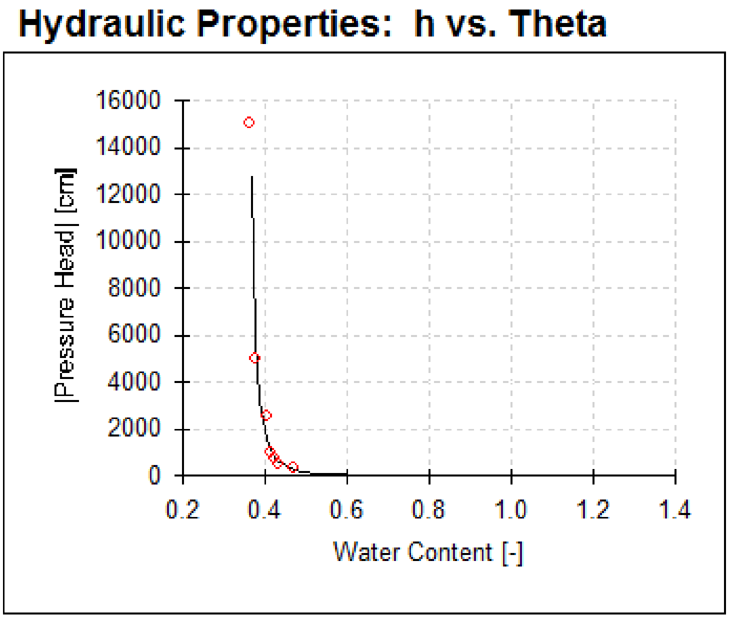


Figure 4-7 Soil-water retention curve for 0-10 cm replicate two for the trial site located on the Eastern Darling Downs

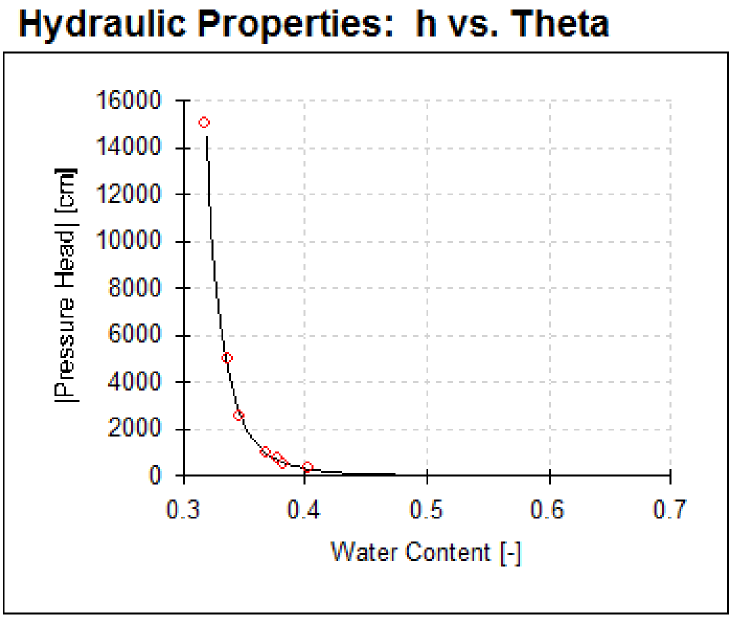


Figure 4-8 Soil-water retention curve for 10-20 cm replicate one for the trial site located on the Eastern Darling Downs

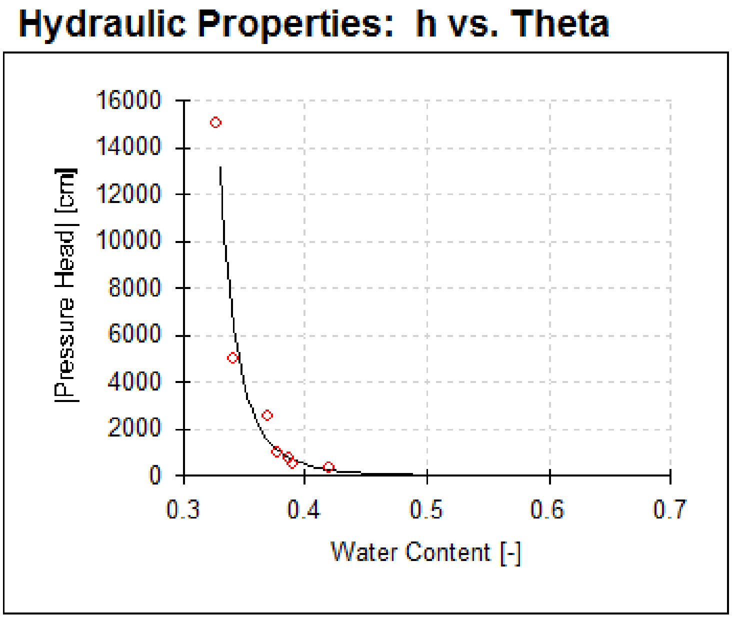


Figure 4-9 Soil-water retention curve for 10-20 cm replicate two for the trial site located on the Eastern Darling Downs

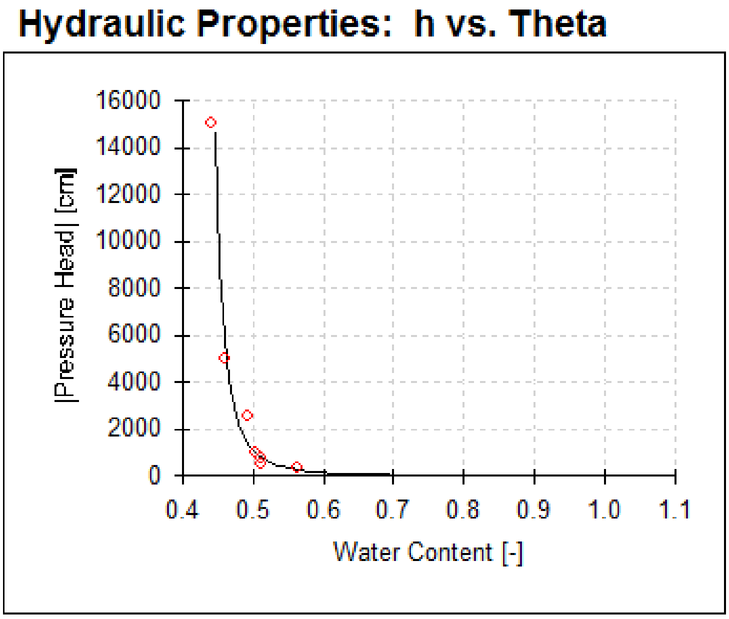


Figure 4-10 Soil-water retention curve for 20-30 cm replicate one for the trial site located on the Eastern Darling Downs

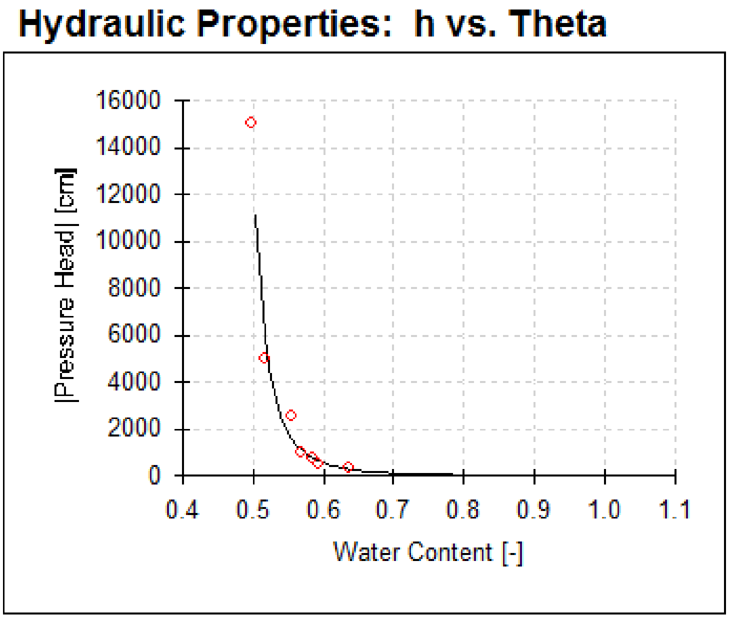


Figure 4-11 Soil-water retention curve for 20-30 cm replicate two for the trial site located on the Eastern Darling Downs

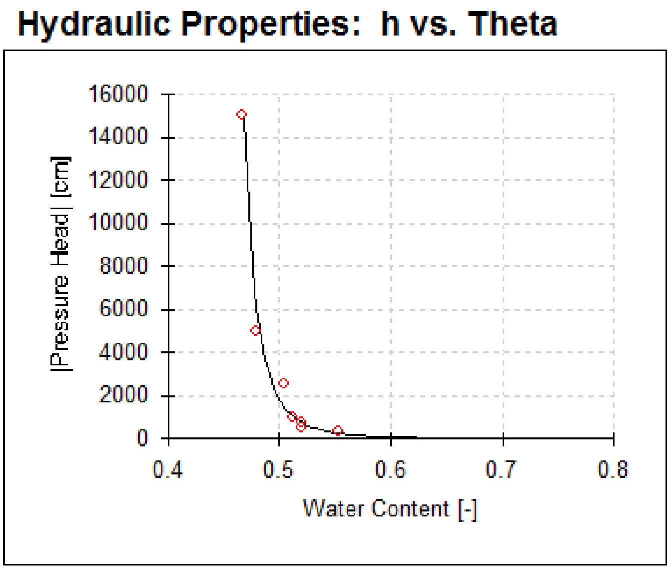


Figure 4-12 Soil-water retention curve for 30-50 cm replicate one for the trial site located on the Eastern Darling Downs

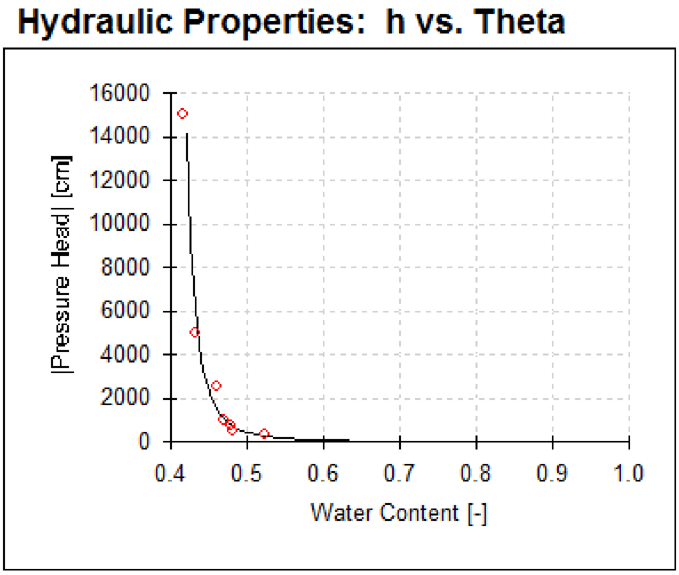


Figure 4-13 Soil-water retention curve for 30-50 cm replicate two for the trial site located on the Eastern Darling Downs

4.2.3 Final Model Parameterisation

In order to model the trial several decisions and assumptions had to be made. It was decided that to model the crop season it would be required to be split into five stages. The first stage was used to model the field in which the crop would be planted from the date of the initial soil core samples, 11th of December 2008, to the day before planting, 27th of January 2009. The second stage was then identified as the stage at which the root system was assumed as being the smallest for the crop season. From observations it was identified that the crop grew substantially when large subsequent rainfall events occurred and so it was assumed that until this point the root system was relatively shallow and small in volume. This led to the second stage of the season being from the 28th of January 2009 to the 11th of February 2009, a period of 15 days.

The third stage was identified to be during the high growth period until the change to trickle irrigation. This was a period of 11 days from the 12th of February 2009 to the 22nd of February 2009. The fourth stage of the crop was from the date of the installation of the trickle irrigation, 23rd of February 2009, to the date of harvest, 12th of March 2009. The final stage was therefore from the day after harvest, 13th of March 2009, to the date of the final soil core samples, 24th of March 2009.

The first and fifth stage of the model were required to be separate from the cropping season as there would be no root uptake of water and nutrients occurring in the system at these times. The changes in the rootzone volume and depth throughout the trial also had to be changed, between the second and third stage, as the amount of water and nutrients that were able to be extracted at the very start of the season changed dramatically towards the end of the season. This was caused by the substantial increase in the rootzone volume and depth.

The initial values of nitrate nitrogen concentration used, in stage one, were those found by the external laboratory (Table 3-2). The initial values of all subsequent stages were the final values of the preceding stages. This was also the method used for establishing the initial moisture content values of stages two through five.

The weather data collected by the weather station was used as the input for the Time-Variable Boundary Conditions. The data required for input included rainfall, evaporation and potential transpiration. Irrigation and fertigation data were also entered via the Time-Variable Boundary Conditions editor. The input data can be seen in Table 4-5.

Table 4-5 Time-variable boundary conditions input data for a trial located on the eastern Darling Downs, Queensland (adapted from McKeering et al. 2009).

Date	Day Number	E_{soil} [cm]	T_{crop} [cm]	Rain [cm]	Irri. [cm]
11-Dec	1	0.87		1.58	
12-Dec	2	0		0.02	
13-Dec	3	0		0.38	
14-Dec	4	0		0.00	
15-Dec	5	0		0.00	
16-Dec	6	0		0.00	
17-Dec	7	0		0.00	
18-Dec	8	0		0.00	
19-Dec	9	0		0.00	
20-Dec	10	0		0.00	
21-Dec	11	0		0.00	
22-Dec	12	0		0.00	
23-Dec	13	0		0.00	
24-Dec	14	0		0.00	
25-Dec	15	0		0.00	
26-Dec	16	0		0.00	
27-Dec	17	0		1.98	
28-Dec	18	0.52		0.70	
29-Dec	19	0.66		0.00	
30-Dec	20	1.08		0.00	
31-Dec	21	0.43		0.00	
1-Jan	22	0		2.49	
2-Jan	23	0.42		0.00	
3-Jan	24	0.65		0.00	
4-Jan	25	0.68		0.00	
5-Jan	26	0.42		0.00	
6-Jan	27	0.33		0.00	
7-Jan	28	0		0.00	
8-Jan	29	0		0.00	
9-Jan	30	0		0.00	
10-Jan	31	0		0.00	
11-Jan	32	0		0.00	
12-Jan	33	0		0.00	
13-Jan	34	0		0.00	
14-Jan	35	0		0.00	

Date	Day Number	E_{soil} [cm]	T_{crop} [cm]	Rain [cm]	Irri. [cm]
15-Jan	36	0		0.00	
16-Jan	37	0		0.00	
17-Jan	38	0		0.00	
18-Jan	39	0		0.00	
19-Jan	40	0		0.00	
20-Jan	41	0		0.00	
21-Jan	42	0		0.00	
22-Jan	43	0		1.38	
23-Jan	44	0.52		0.00	
24-Jan	45	0.48		0.44	
25-Jan	46	0.78		0.20	
26-Jan	47	0.65		0.00	
27-Jan	48	0		0.00	
28-Jan	49	0	0.06	0.04	1.48
29-Jan	50	0.61	0.07	0.12	1.48
30-Jan	51	0.66	0.08	0.00	0.99
31-Jan	52	0.57	0.07	0.20	0.74
1-Feb	53	0.54	0.07	0.00	0.74
2-Feb	54	0.52	0.07	0.00	0.74
3-Feb	55	0.55	0.07	0.00	0.49
4-Feb	56	0.73	0.09	0.00	1.24
5-Feb	57	0.78	0.1	0.00	1.24
6-Feb	58	0.93	0.11	0.00	1.24
7-Feb	59	0.83	0.1	0.00	1.24
8-Feb	60	0.7	0.09	0.00	1.24
9-Feb	61	0.96	0.12	0.00	1.38
10-Feb	62	0.52	0.07	0.02	0
11-Feb	63	0.57	0.1	0.00	0
12-Feb	64	0.62	0.11	0.00	1.14
13-Feb	65	0.35	0.07	0.24	0
14-Feb	66	0.29	0.08	0.76	0
15-Feb	67	0.4	0.16	0.00	0
16-Feb	68	0.36	0.18	0.30	0
17-Feb	69	0.27	0.16	0.90	0
18-Feb	70	0.25	0.2	0.64	0
19-Feb	71	0.33	0.31	1.40	0
20-Feb	72	0.26	0.3	0.82	0
21-Feb	73	0.26	0.35	0.02	0
22-Feb	74	0.29	0.44	0.00	0
23-Feb	75	0.23	0.47	0.00	0.3
24-Feb	76	0.18	0.46	0.00	0.3

Date	Day Number	E_{soil} [cm]	T_{crop} [cm]	Rain [cm]	Irri. [cm]
25-Feb	77	0.09	0.28	0.00	0.3
26-Feb	78	0.12	0.32	0.00	0.3
27-Feb	79	0.14	0.43	0.00	1.29
28-Feb	80	0.1	0.44	0.00	0.69
1-Mar	81	0.08	0.48	0.00	0.89
2-Mar	82	0.06	0.49	0.78	0.69
3-Mar	83	0.03	0.53	0.00	0.59
4-Mar	84	0	0.54	0.02	0.89
5-Mar	85	0	0.62	0.02	0.89
6-Mar	86	0	0.43	0.00	0.89
7-Mar	87	0	0.48	0.00	0.79
8-Mar	88	0	0.52	0.00	0.89
9-Mar	89	0	0.55	0.00	0.89
10-Mar	90	0	0.43	0.00	0.69
11-Mar	91	0	0.42	0.00	0.4
12-Mar	92	0	0.33	0.00	
13-Mar	93	0.64		0.00	
14-Mar	94	0.45		0.00	
15-Mar	95	0.28		0.00	
16-Mar	96	0.71		2.92	
17-Mar	97	0.56		0.02	
18-Mar	98	0.45		0.00	
19-Mar	99	0.53		0.00	
20-Mar	100	0.47		0.00	
21-Mar	101	0.33		0.28	
22-Mar	102	0.4		0.02	
23-Mar	103	0.26		0.00	
24-Mar	104	0.24		0.00	

4.3 Hydrus-2D Modelling Results

After completing the modelling of the five stages with a domain of 20 cm width and 50 cm depth it was identified that the general patterns occurring were reasonable and expected. Definite root extraction was visible and application of water and nutrients could also be identified.

The following results show the pattern of water movement from five days after the initial soil core samples to the date of the final soil core samples.

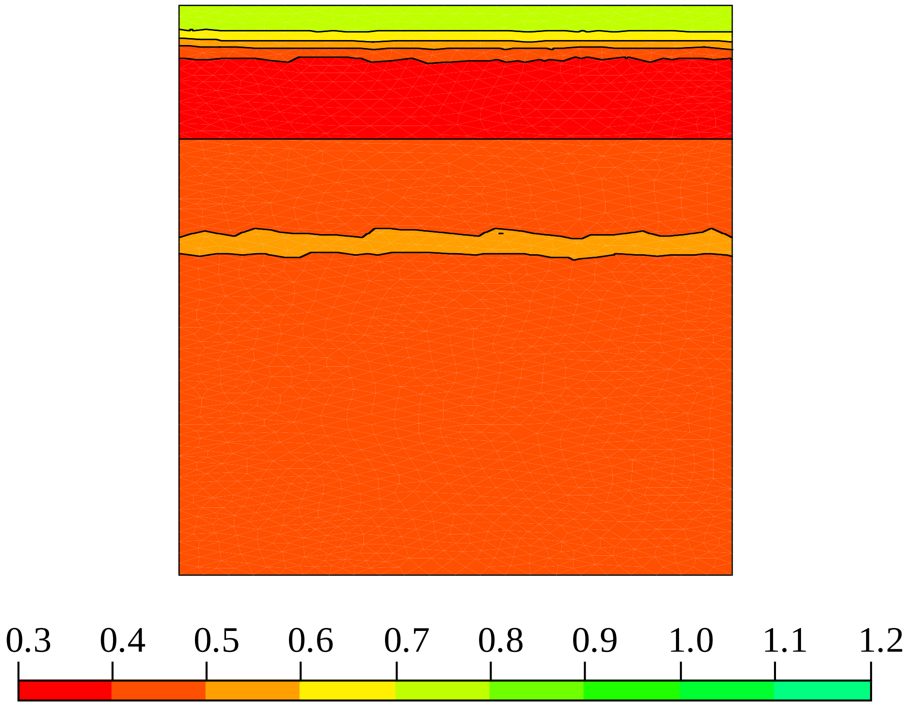


Figure 4-14 Soil water content 16th of December 2008 for the trial site located on the eastern Darling Downs, Queensland.

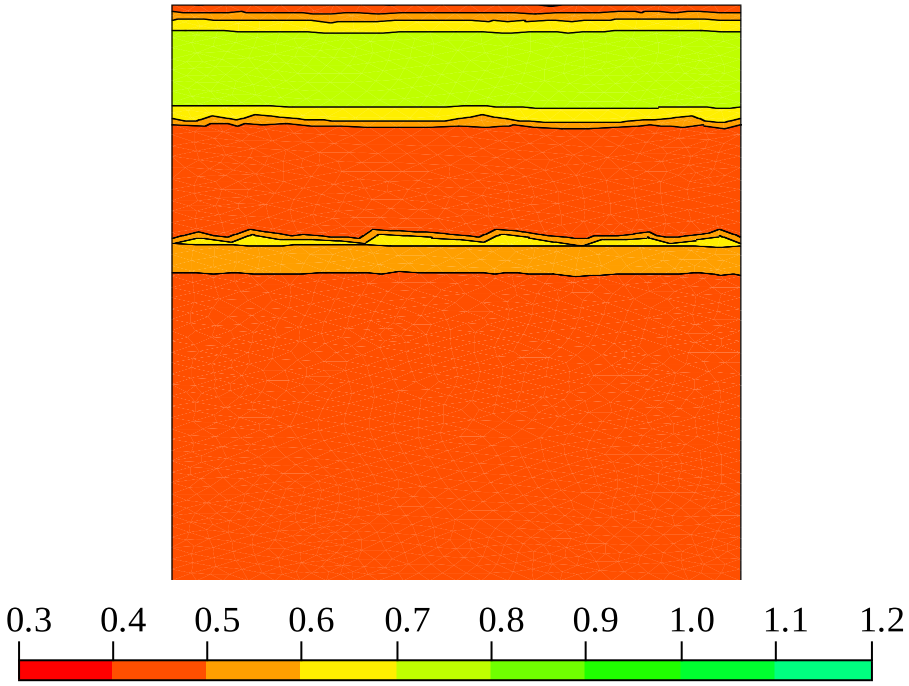


Figure 4-15 Soil water content 27th of January 2009 for the trial site located on the eastern Darling Downs, Queensland.

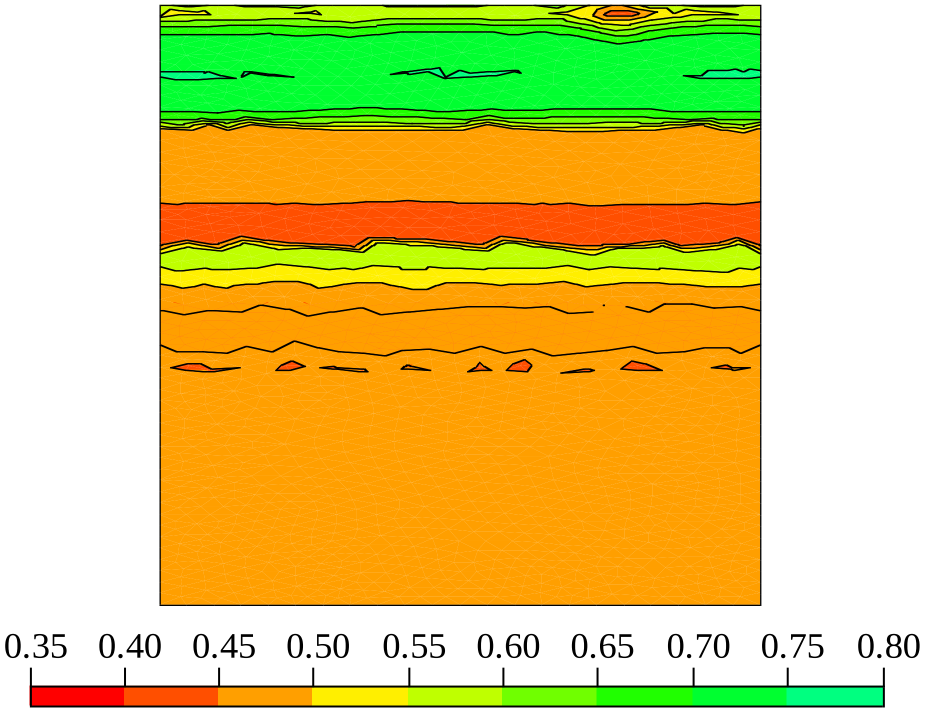


Figure 4-16 Soil water content 29th of January 2009 for the trial site located on the eastern Darling Downs, Queensland.

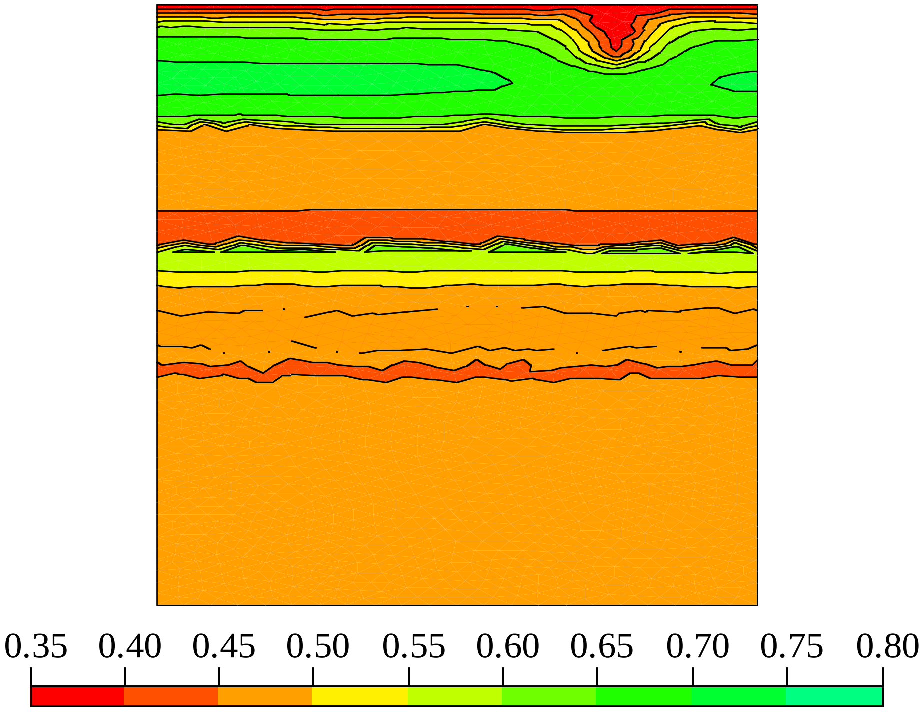


Figure 4-17 Soil water content 7th of February 2009 for the trial site located on the eastern Darling Downs, Queensland.

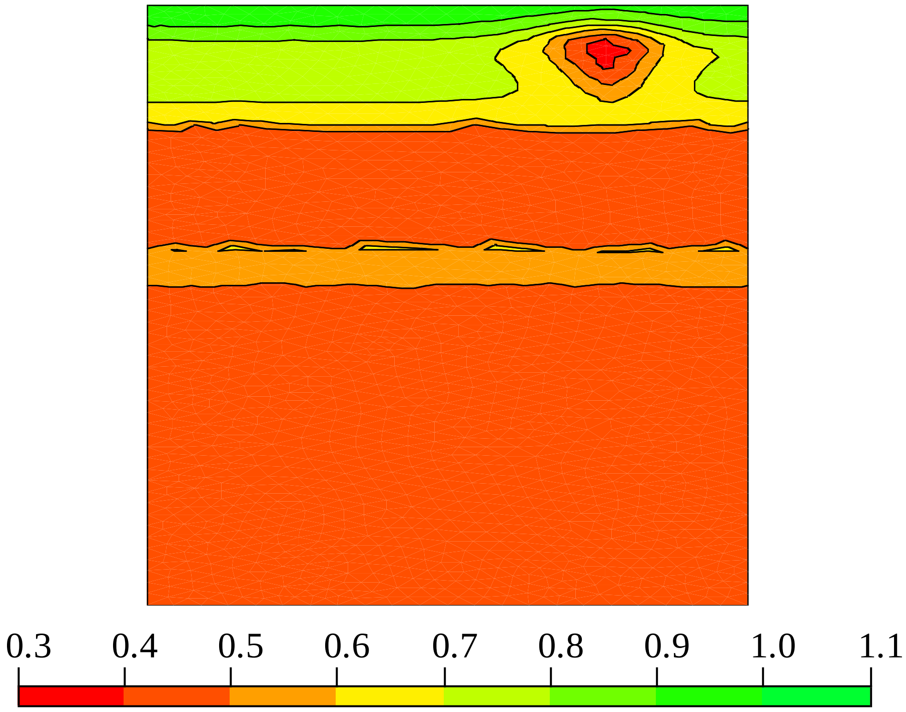


Figure 4-18 Soil water content 17th of February 2009 for the trial site located on the eastern Darling Downs, Queensland.

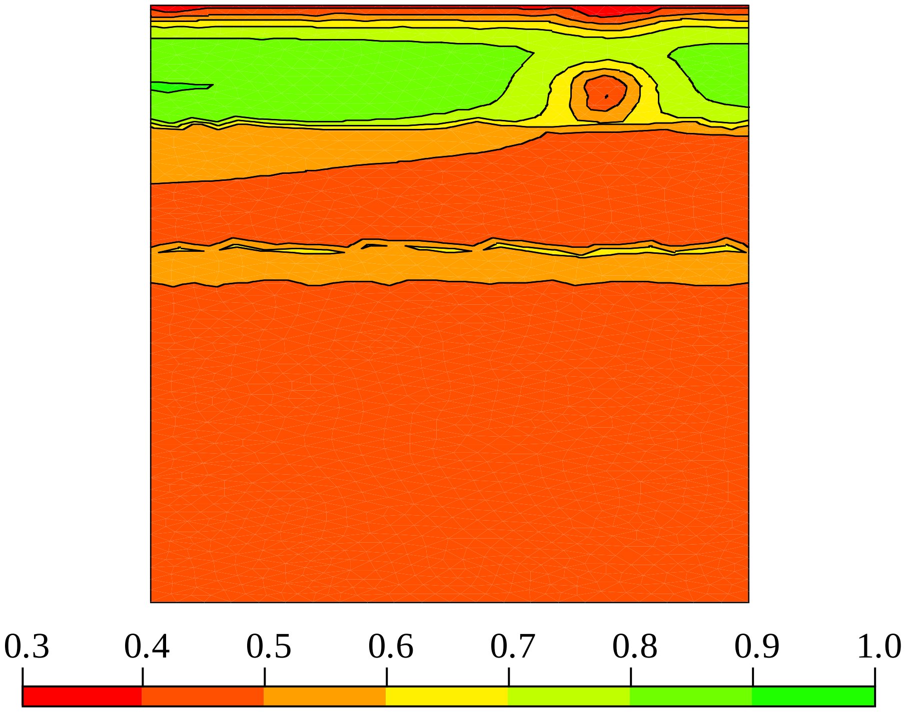


Figure 4-19 Soil water content 23rd of February 2009 for the trial site located on the eastern Darling Downs, Queensland.

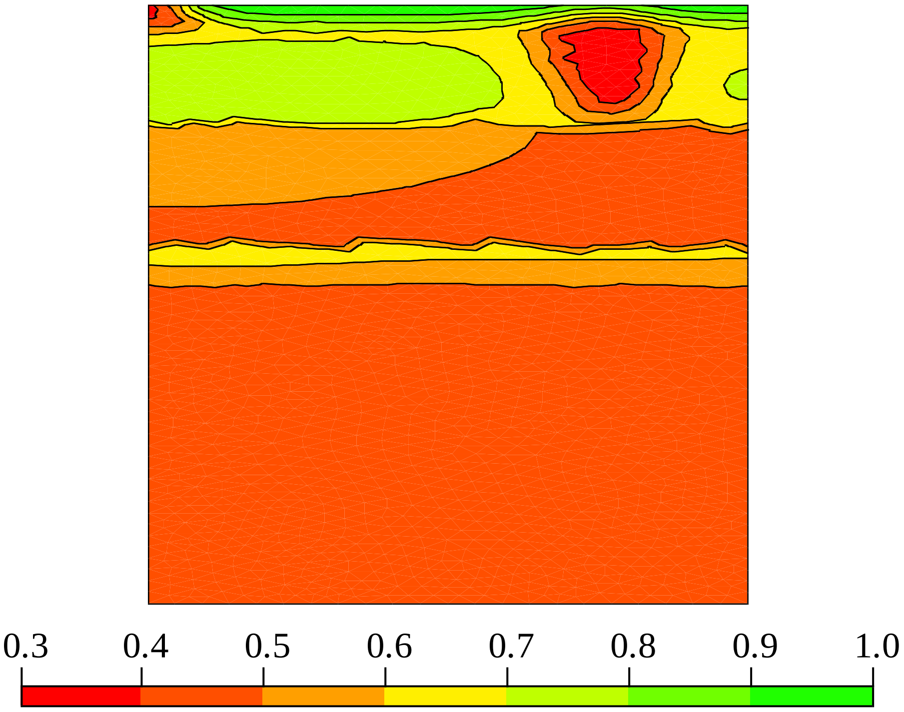


Figure 4-20 Soil water content 2nd of March 2009 for the trial site located on the eastern Darling Downs, Queensland.

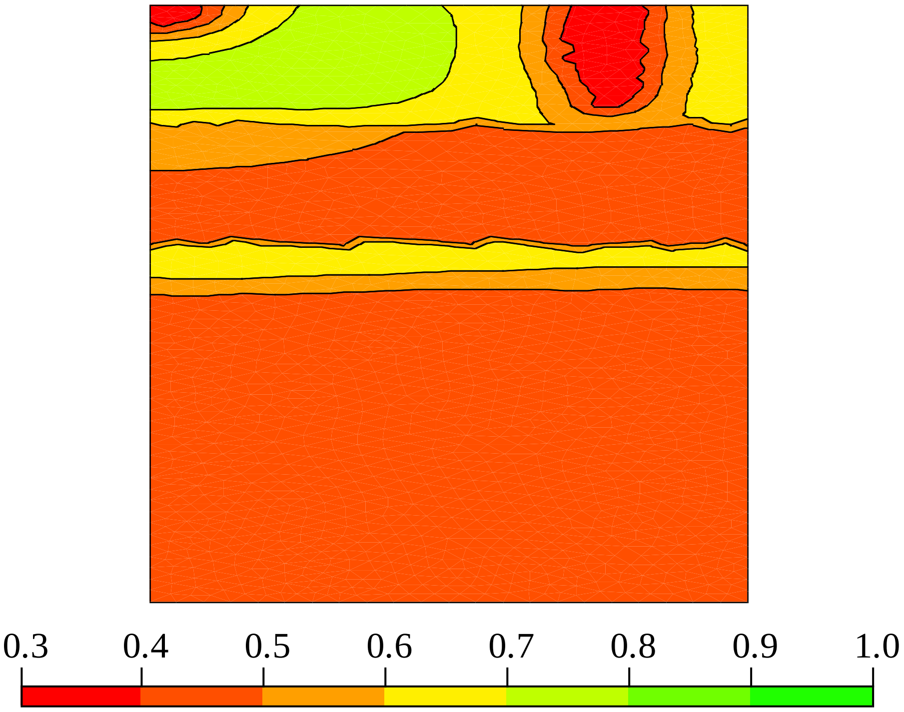


Figure 4-21 Soil water content 12th of March 2009 for the trial site located on the eastern Darling Downs, Queensland.

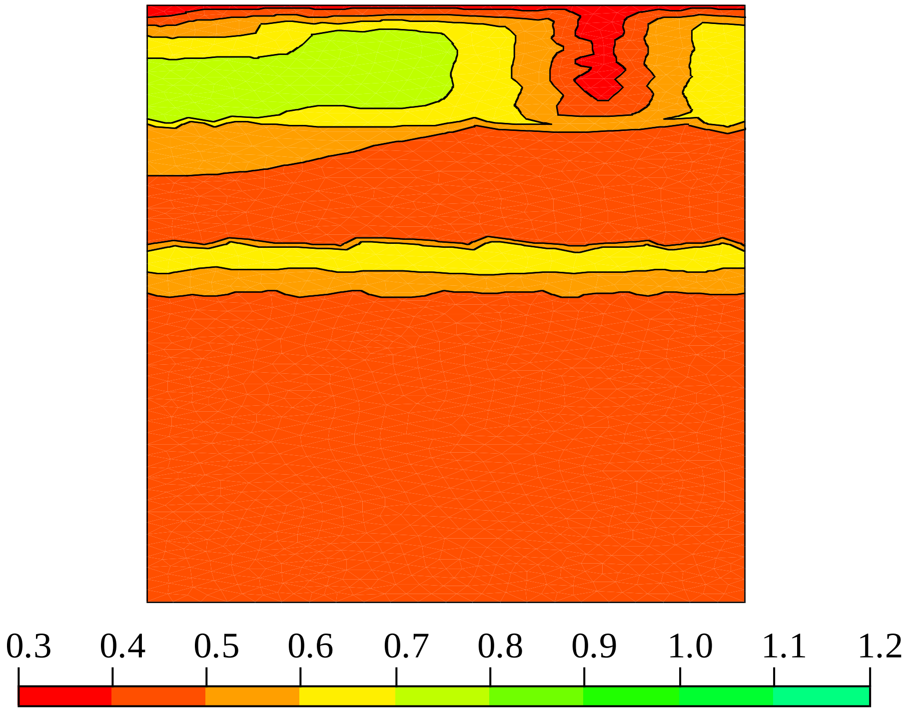


Figure 4-22 Soil water content 13th of March 2009 for the trial site located on the eastern Darling Downs, Queensland.

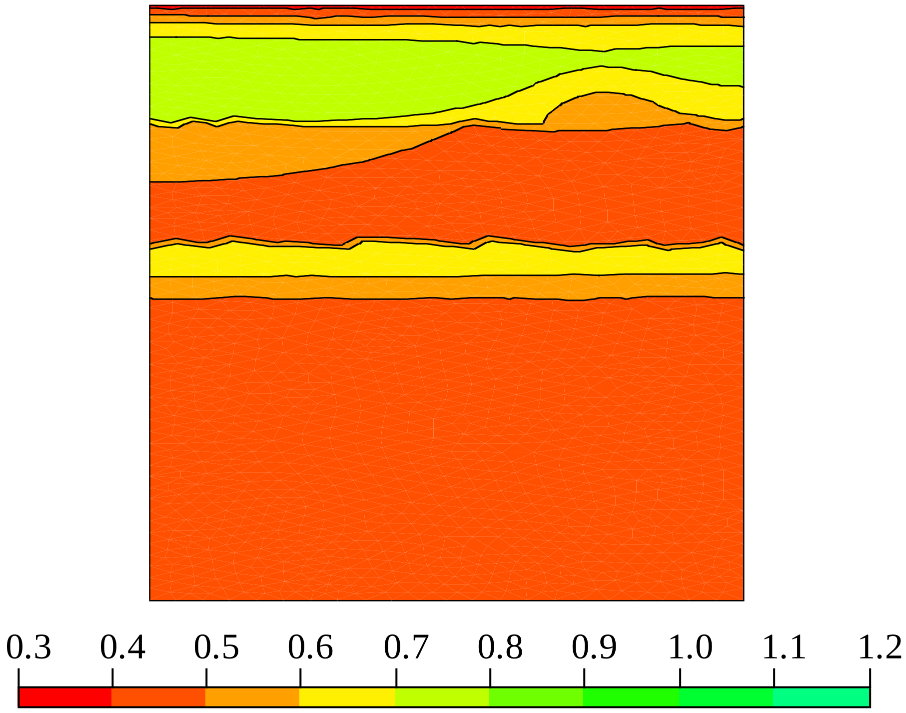


Figure 4-23 Soil water content 24th of March 2009 for the trial site located on the eastern Darling Downs, Queensland.

The following results show the movement of nitrate nitrogen from five days after the initial soil core samples to the day of harvest.

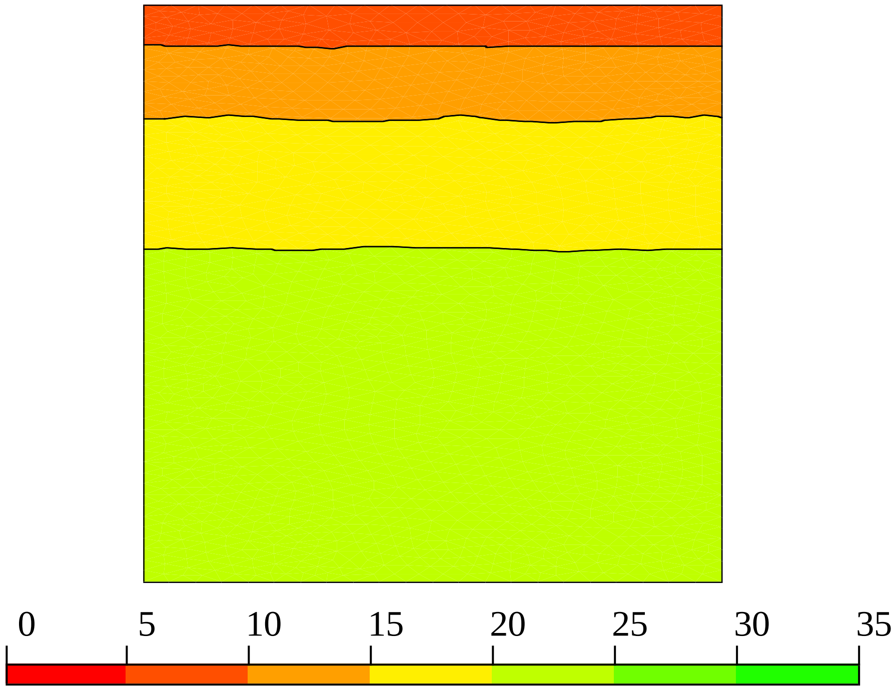


Figure 4-24 Soil nitrate content 16th of December 2008 for the trial site located on the eastern Darling Downs, Queensland.

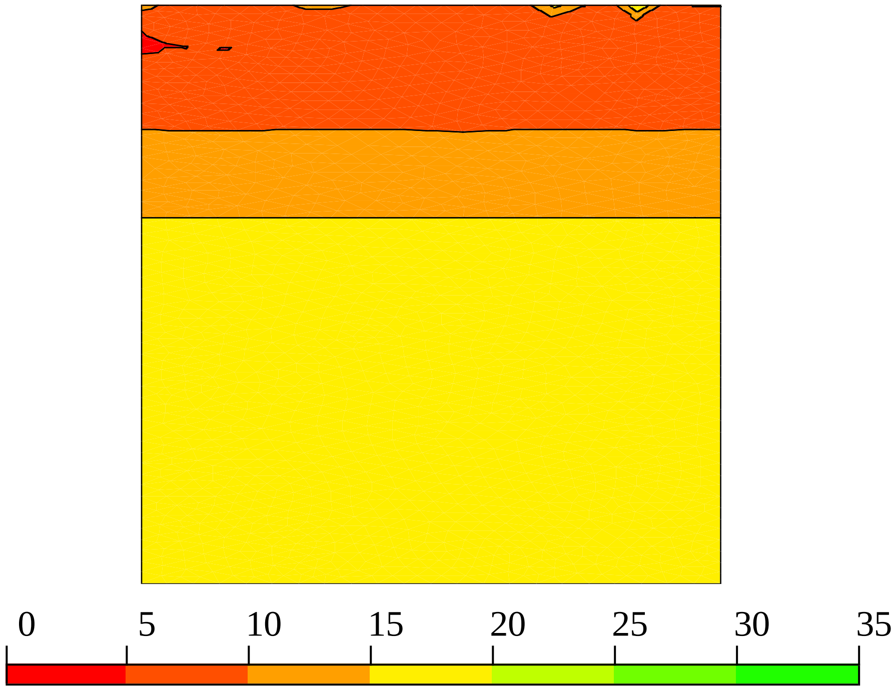


Figure 4-25 Soil nitrate content 27th of January 2009 for the trial site located on the eastern Darling Downs, Queensland.

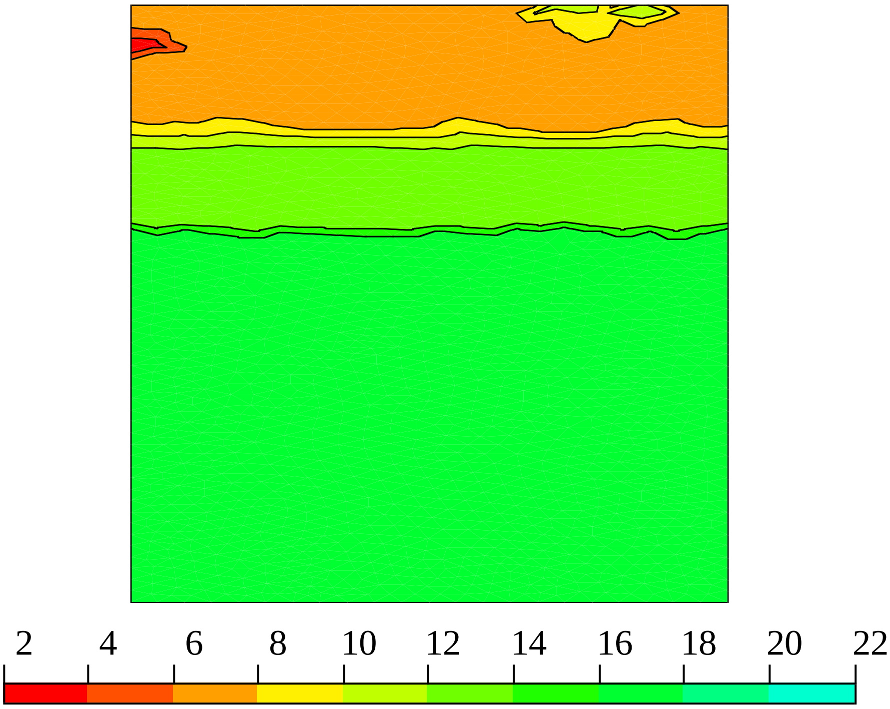


Figure 4-26 Soil nitrate content 29th of January 2009 for the trial site located on the eastern Darling Downs, Queensland.

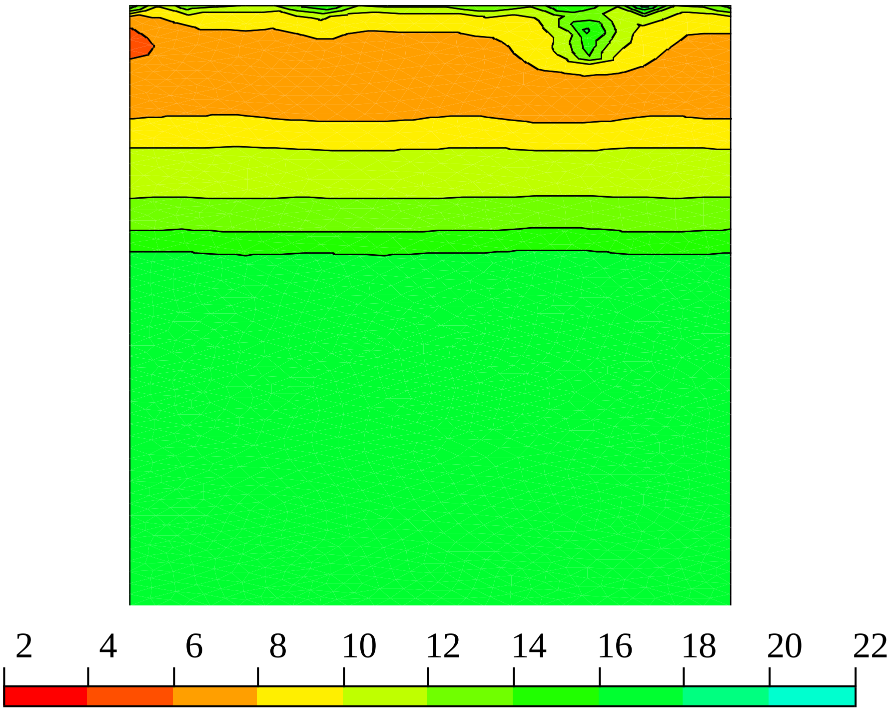


Figure 4-27 Soil nitrate content 7th of February 2009 for the trial site located on the eastern Darling Downs, Queensland.

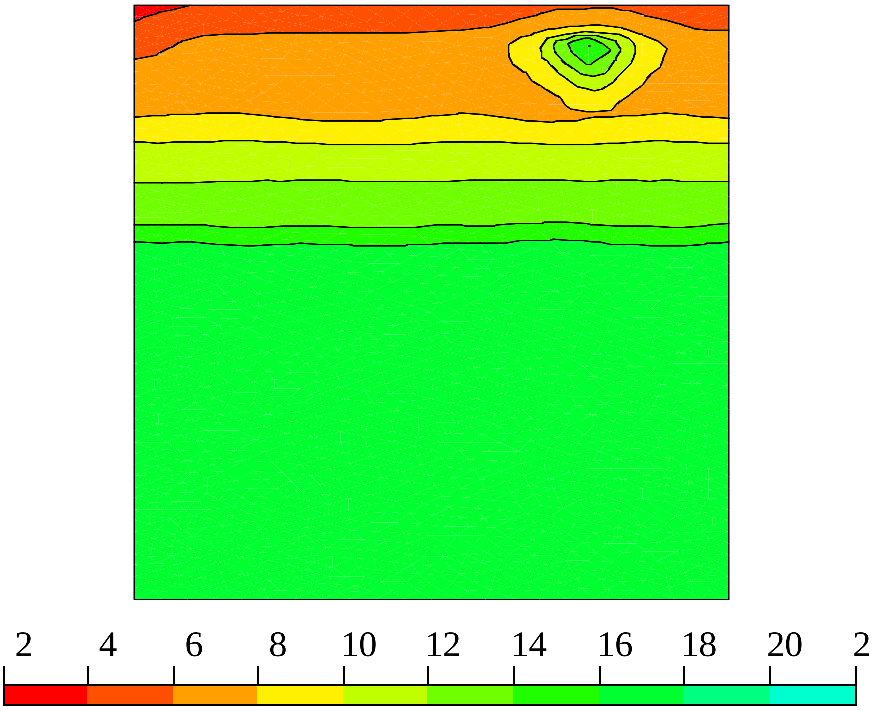


Figure 4-28 Soil nitrate content 17th of February 2009 for the trial site located on the eastern Darling Downs, Queensland.

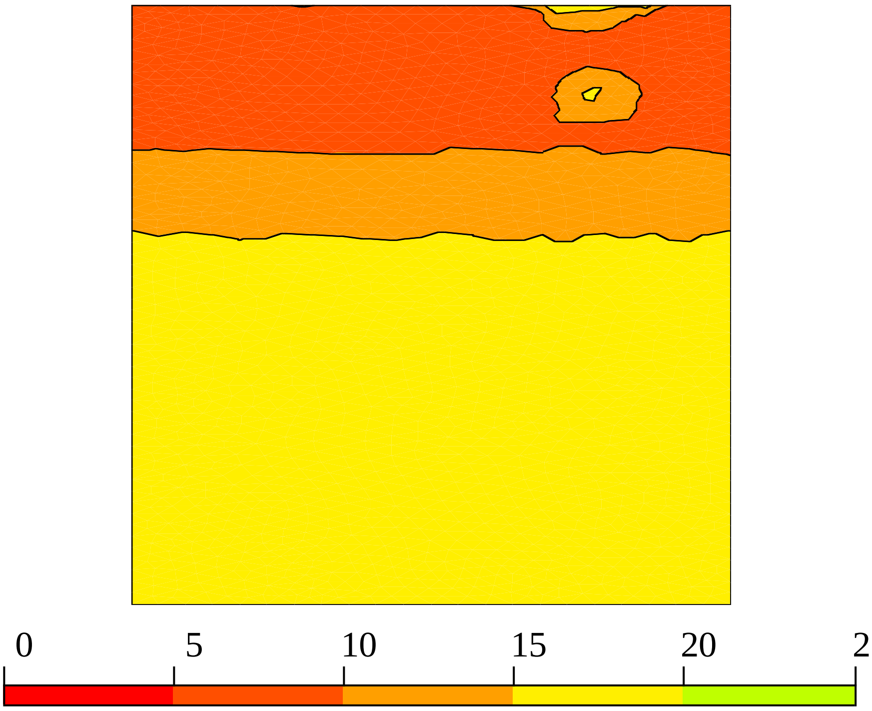


Figure 4-29 Soil nitrate content 23rd of February 2009 for the trial site located on the eastern Darling Downs, Queensland.

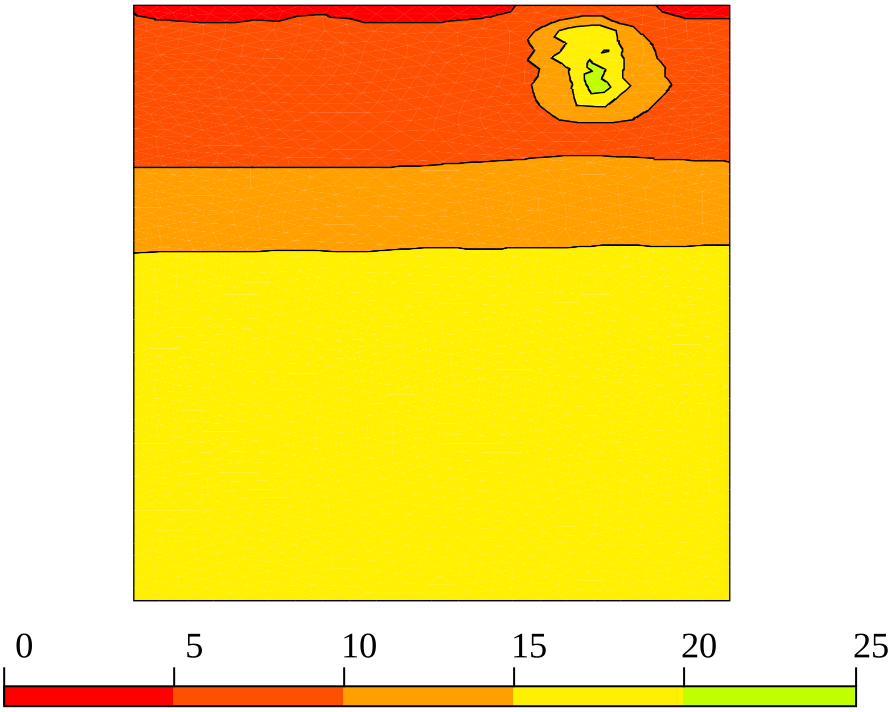


Figure 4-30 Soil nitrate content 2nd of March 2009 for the trial site located on the eastern Darling Downs, Queensland.

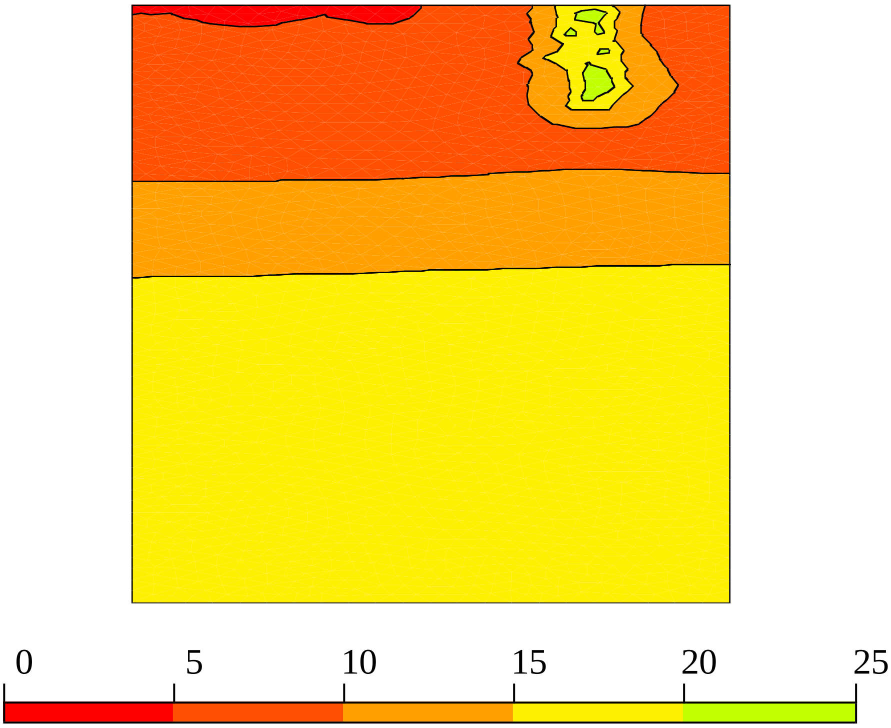


Figure 4-31 Soil nitrate content 12th of March 2009 for the trial site located on the eastern Darling Downs, Queensland.

4.4 Discussion

General trends can be seen in the movement of water and nutrients through the profile and by plant extraction. This suggests that there is validity in using a model to identify optimum irrigation and fertigation management practices. A comparison of the final results shows that although the general trends have been produced by the model the final output values do not match the values measured through laboratory analyses of collected soil samples.

The results obtained suggest that further calibration and validation of the model is required. Investigation of fewer stages may reduce possible errors in the changing of initial moisture content and solute concentration between stages. This however may not be the solution as larger errors may possibly arise from lesser accuracy in the definition of the rootzone. Investigation into the use of a larger number of stages may prove to generate an optimum solution. With the use of more stages the crop rootzone can be more accurately defined for the duration of the trial. As the rootzone volume and depth changes continually, to a time later in the season, it would be easier and more precise to model this with a larger number of model stages.

4.5 Conclusions

The use of a soil water movement model such as HYDRUS-2D is a valid approach to identifying the optimum irrigation and fertigation management practices for horticultural production systems. Careful calibration of the model is required with soil parameterisation needing to be completed as accurately as possible.

Modelling of the conducted trial was possible for a lettuce crop grown on a Red Ferrosol, however inaccuracies in parameterisation resulted in outcomes being marginally different to those that were physically measured.

Chapter 5 Conclusions

Through the collection of irrigation and fertigation applications and soil-water and nutrient movement data under commercial field conditions it was possible to evaluate the current irrigation and fertigation management practices being utilised. It was found that deep drainage was occurring throughout the season and nitrate and water would have been moving below the rootzone of the lettuce crop. It was found that deep drainage and nitrate leaching would be influenced by the irrigation design and management practices as well as in-season rainfall and soil physical conditions.

It was determined that the key to nitrogen management was to minimise the amount of nitrogen and water in the soil, whilst ensuring an adequate supply for plant growth. Current management practices allow for a large amount of water and fertiliser to be applied after transplanting, during a time when the plants roots are very shallow and plant requirements are very small. Measured data suggests that substantial nitrogen was lost to leaching before the plants had reached 20% groundcover. During the trial approximately one-fifth of the total nitrogen was applied during the week before harvest, if unused it is highly susceptible to leaching during the fallow period.

The potential for the use of HYDRUS-2D to model soil-water and nitrate movement for the trial was investigated. It was determined that it is a valid approach to determining the best management practices that will reduce deep drainage and nitrate leaching.

From the analysis of the field trial data, it is recommended that water and nutrient applications within the initial stages of a lettuce crop season be reduced. This can be accomplished by applying smaller, more frequent applications if required.

Continuation of this project is quite possible with several different paths requiring further investigation. It has been identified that additional work is required to identify appropriate design and management practices under a range of conditions. Substantial differences were observed between the soil solution nitrate and EC measurements obtained using different soil solution extractors installed at shallow depths. From this it has been identified that further research is required for the implications of these differences in terms of either the utility of the measurements obtained with either instrument and/or nitrate and EC movement.

With the potential for the use of a soil-water and nitrate movement model being identified further research into the calibration and validation of the model has potential to make optimum irrigation and fertigation management practices easier to identify without costly field trials. Further research could also lead to the model being able to be applied to different soil and crop types.

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Appendix A Project Specification

University of Southern Queensland

Faculty of Engineering and Surveying

ENG4111/4112 Research Project

PROJECT SPECIFICATION

FOR:	**Kimberley Jane Althaus**
TOPIC:	The Effect of Irrigation Management on Nitrate Movement Under a Lettuce Crop
SUPERVISOR:	Prof Steven Raine (Faculty of Engineering and Surveying, NCEA)
SPONSORHSIP:	National Program for Sustainable Irrigation (NPSI) National Centre for Engineering in Agriculture (NCEA)
PROJECT AIM:	The aim of this project is to investigate the effect of irrigation management practices on the level of nitrate movement under a lettuce crop.

PROGRAMME: (**Issue B, 19 August 09**)

1. Undertake a review of literature regarding nitrate leaching and soil water movement.

2. Plan field trial to evaluate irrigation and nitrate movement.

3. Conduct field trial and collect measurements on water and fertiliser application and movement.

4. Analyse field data to make recommendations on fertiliser and irrigation management practices to reduce nitrate movement.

5. If time permits, investigate potential to use HYDRUS-2D to model soil water and nitrate movement under different environmental conditions.

AGREED _______________________ (student) _______________________ (supervisor)

Date: / / 2009 Date: / / 2009

Co-examiner:____________________________

Appendix B Irrigation and Fertigation Data

Table B-1 Irrigation and fertigation data for the trial conducted on the eastern Darling Downs

Date	Total Irrigation (L/hydrant)	Total Irrigation (L/bed)	Fertiliser Rate (L/hydrant)	Fertiliser Rate (L/bed)	Fertiliser Applied (kg/ha)
28-Jan	30000	3750	30	3.75	12.099
29-Jan	30000	3750	30	3.75	12.099
30-Jan	20000	2500	0	0	0.000
31-Jan	15000	1875	5	0.625	2.016
1-Feb	15000	1875	5	0.625	2.016
2-Feb	15000	1875	5	0.625	2.016
3-Feb	10000	1250	0	0	0.000
4-Feb	25000	3125	10	1.25	4.033
5-Feb	25000	3125	5	0.625	2.016
6-Feb	25000	3125	5	0.625	2.016
7-Feb	25000	3125	5	0.625	2.016
8-Feb	25000	3125	5	0.625	2.016
9-Feb	28000	3500	10	1.25	4.033
10-Feb		0	0	0	0.000
11-Feb		0	0	0	0.000
12-Feb	23000	2875	15	1.875	6.049
13-Feb		0	0	0	0.000
14-Feb		0	0	0	0.000
15-Feb		0	0	0	0.000
16-Feb		0	0	0	0.000
17-Feb		0	0	0	0.000
18-Feb		0	0	0	0.000
19-Feb		0	0	0	0.000
20-Feb		0	0	0	0.000
21-Feb		0	0	0	0.000
22-Feb		0	0	0	0.000
23-Feb	6000	750	10	1.25	4.033
24-Feb	6000	750	3	0.375	1.210
25-Feb	6000	750	3	0.375	1.210
26-Feb	6000	750	3	0.375	1.210
27-Feb	26000	3250	6	0.75	2.420
28-Feb	14000	1750	6	0.75	2.420
1-Mar	18000	2250	9	1.125	3.630
2-Mar	14000	1750	6	0.75	2.420
3-Mar	12000	1500	5	0.625	2.016
4-Mar	18000	2250	7.5	0.9375	3.025
5-Mar	18000	2250	7.5	0.9375	3.025
6-Mar	18000	2250	7.5	0.9375	3.025
7-Mar	16000	2000	5	0.625	2.016
8-Mar	18000	2250	7.5	0.9375	3.025
9-Mar	18000	2250	7.5	0.9375	3.025

Date	Total Irrigation (L/hydrant)	Total Irrigation (L/bed)	Fertiliser Rate (L/hydrant)	Fertiliser Rate (L/bed)	Fertiliser Applied (kg/ha)
10-Mar	14000	1750	5	0.625	2.016
11-Mar	8000	1000	2	0.25	0.807
12-Mar		0	0	0	0.000
13-Mar		0	0	0	0.000

Appendix C EnviroSCAN Graphs

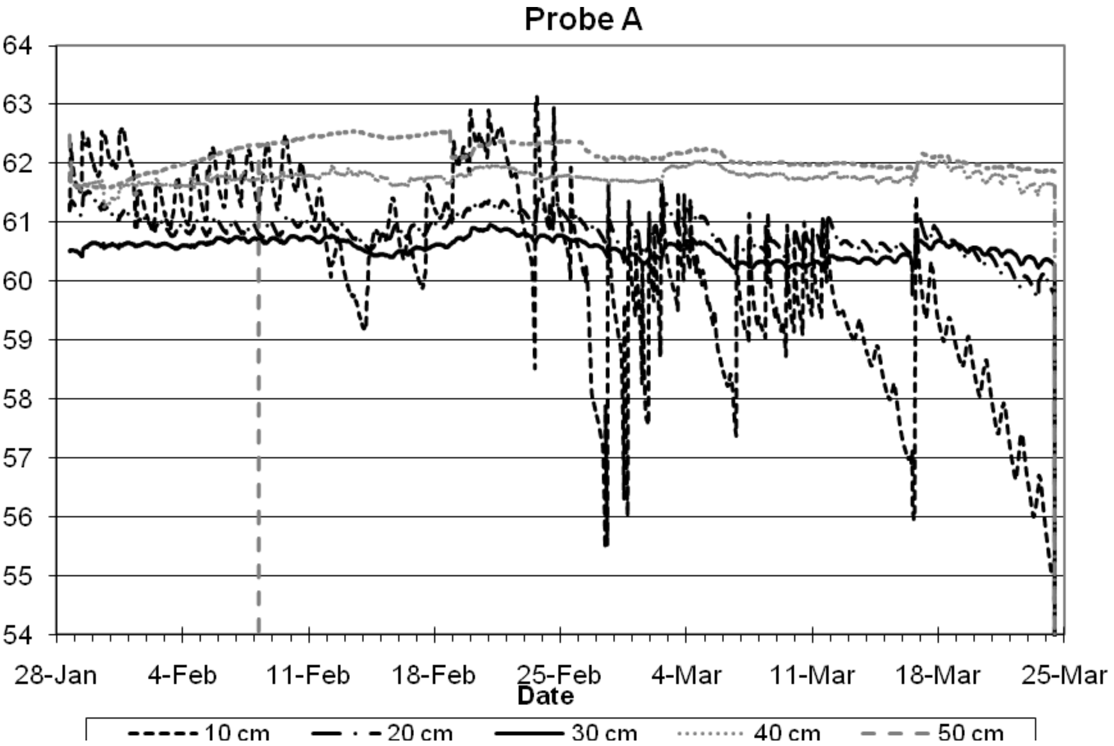


Figure C-1 Probe A relative soil moisture change for a sprinkler and drip irrigated lettuce crop on the eastern Darling Downs, Queensland.

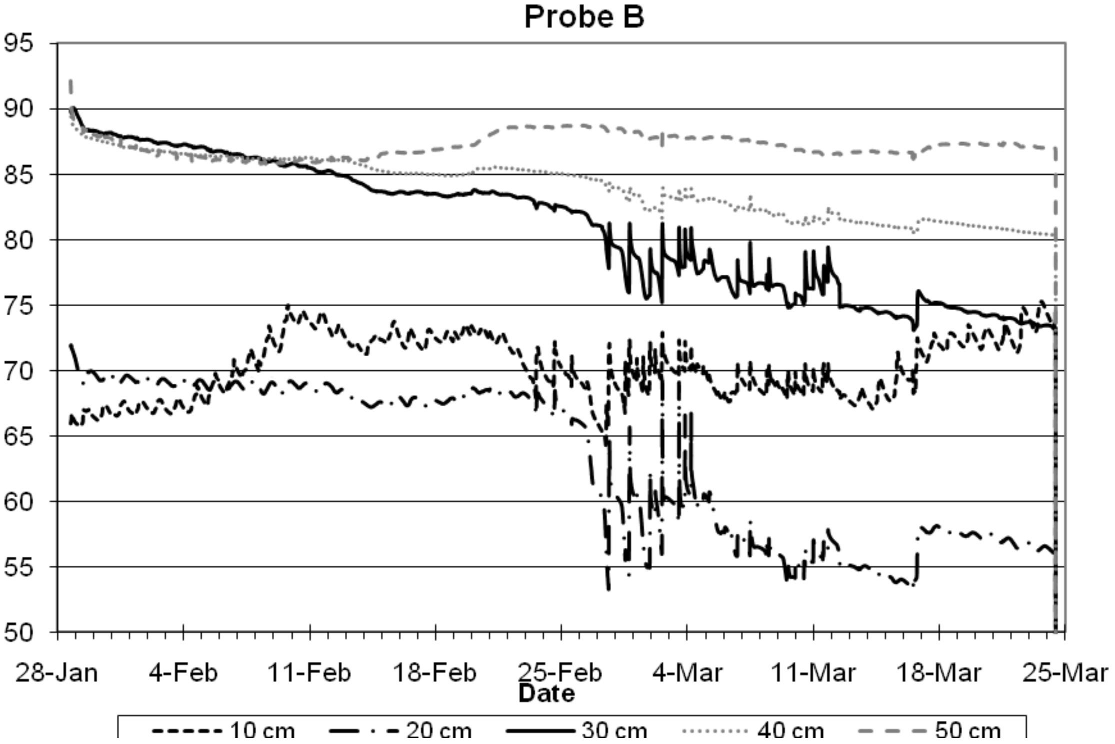


Figure C-2 Probe B relative soil moisture change for a sprinkler and drip irrigated lettuce crop on the eastern Darling Downs, Queensland.

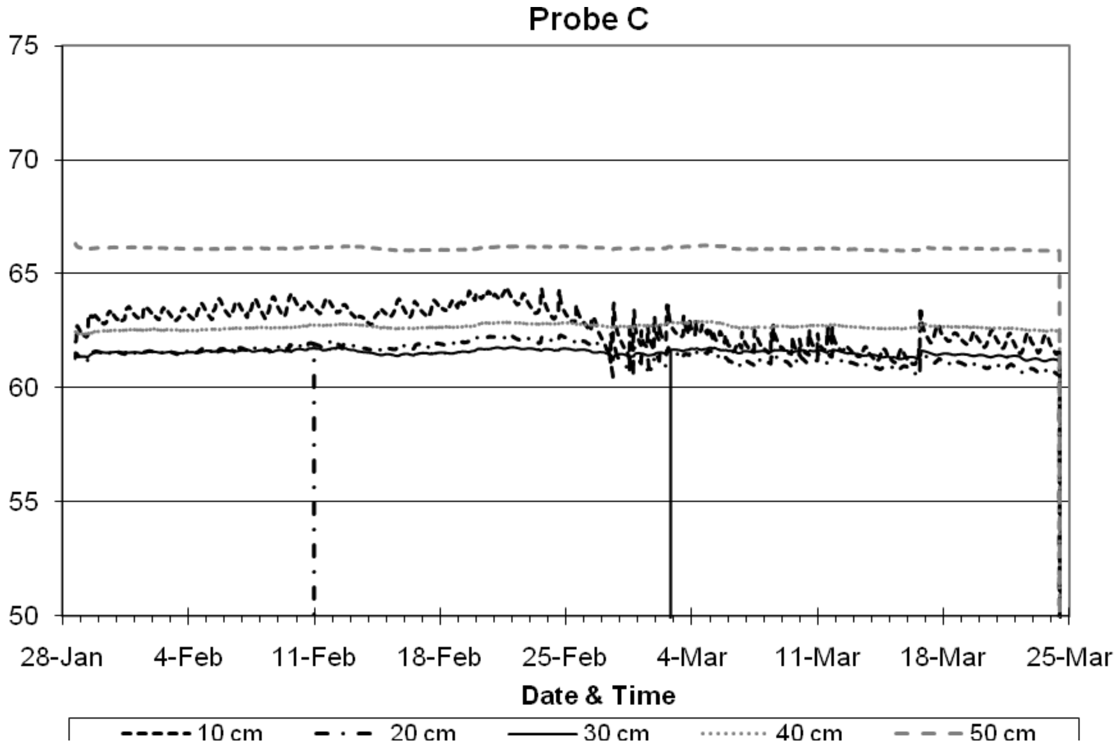


Figure C-3 Probe C relative soil moisture change for a sprinkler and drip irrigated lettuce crop on the eastern Darling Downs, Queensland.

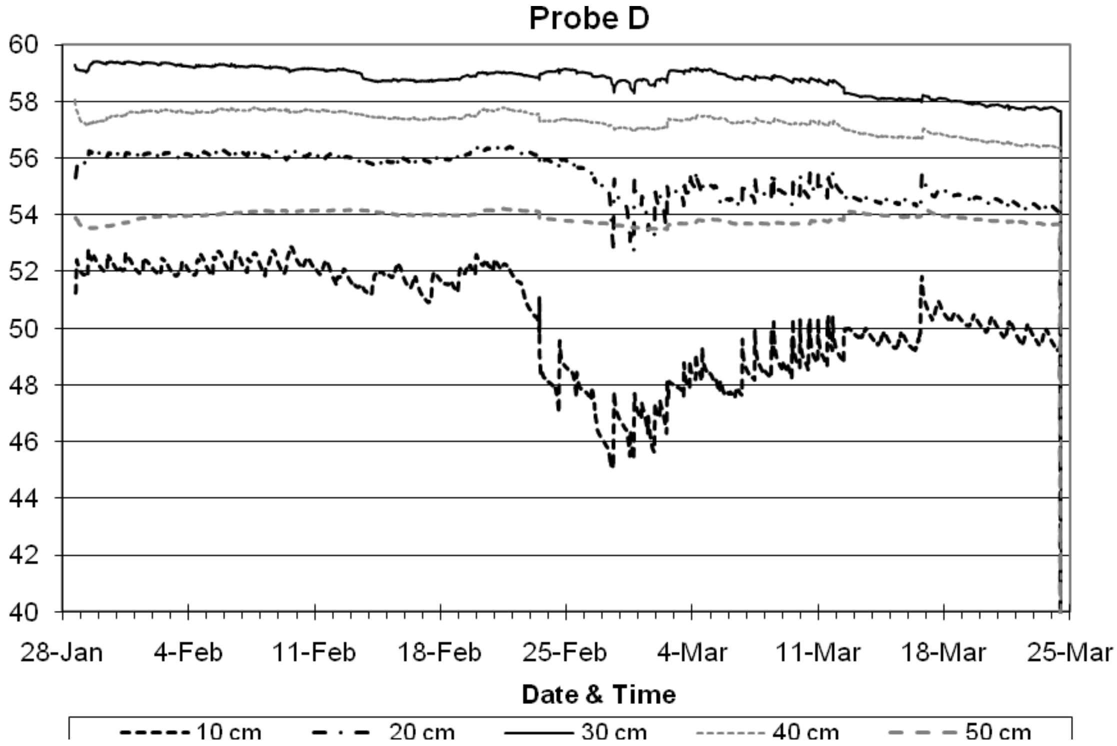


Figure C-4 Probe D relative soil moisture change for a sprinkler and drip irrigated lettuce crop on the eastern Darling Downs, Queensland.

Appendix D Nitrate and Electrical Conductivity Graphs

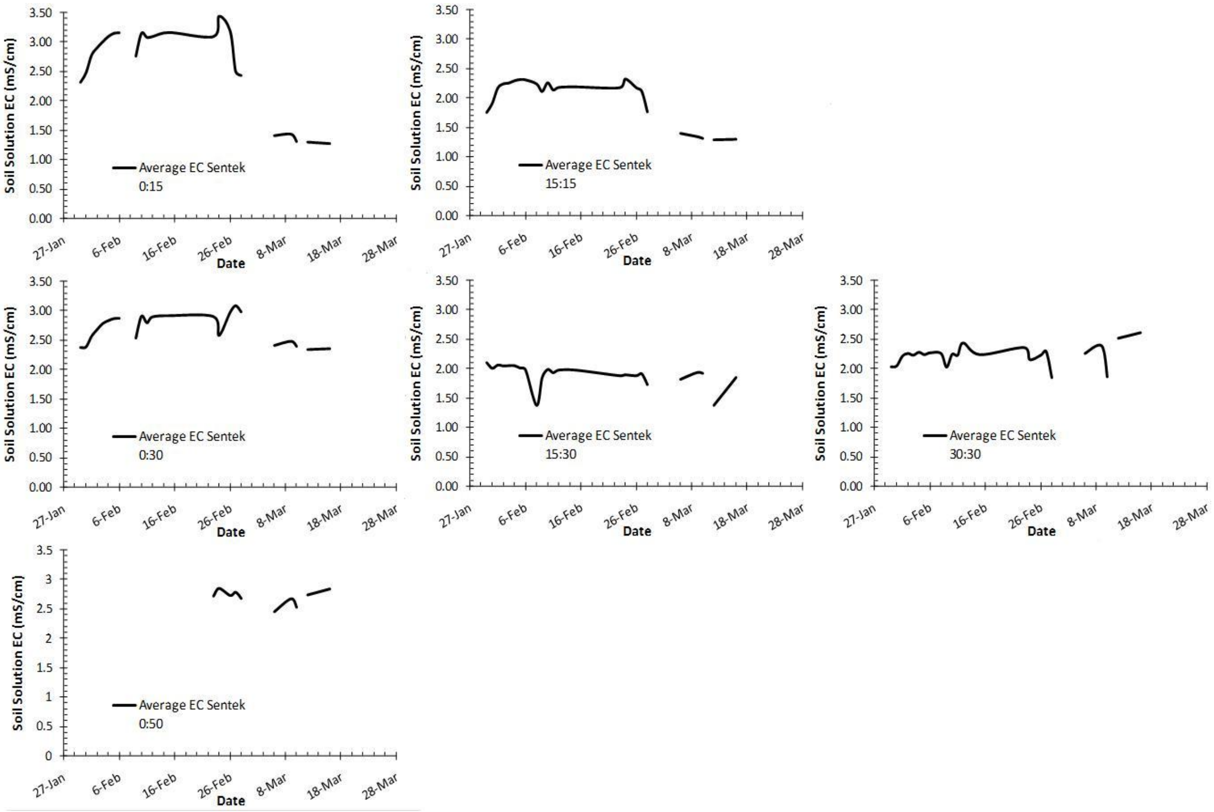


Figure D-1 Electrical conductivity of soil solutions collected using a Sentek SoluSAMPLER soil solution extractor during a lettuce crop on the eastern Darling Downs, Queensland. (Labels are horizontal distance in cm:depth in cm).

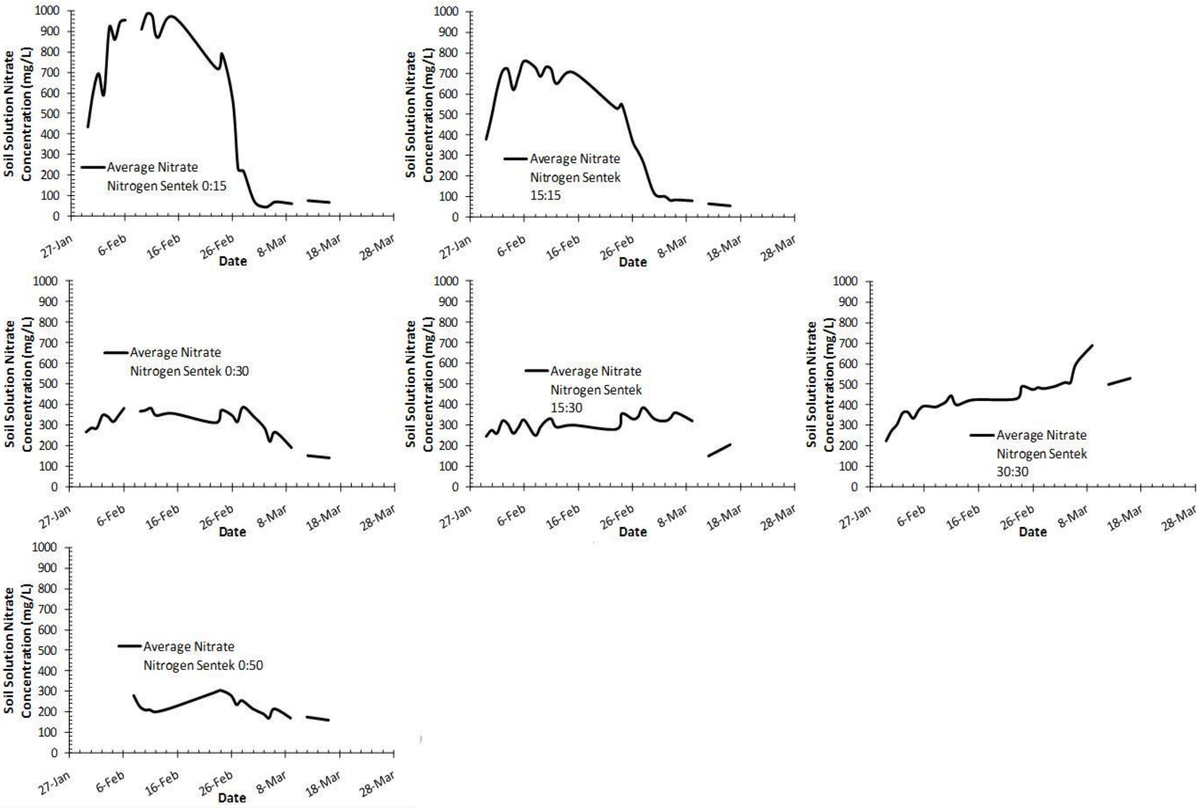


Figure D-2 Nitrate concentrations collected from the soil profile using Sentek SoluSAMPLER soil solution extractor during a lettuce crop on the eastern Darling Downs, Queensland. (Labels are horizontal distance in cm:depth in cm).

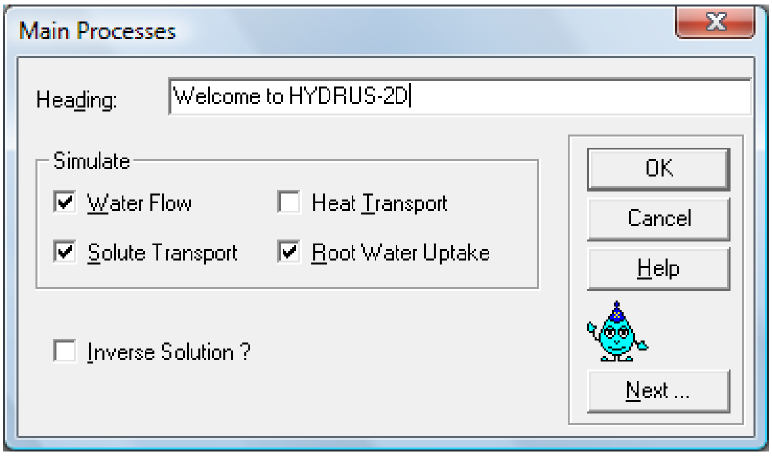
Appendix E Overview of HYDRUS-2D

Model Operation

Main Processes

The initial requirement for the model was the identification of the processes required to adequately represent the movements occurring within the soil profile, those selected can be seen in Figure E-1. In all simulations “Water Flow”, “Solute Transport” and “Root Water Uptake” modelling were selected. This is due to the dynamic events occurring within the soil with the input via irrigation and fertigation and removal through drainage and root extraction.

The inverse solution is a Marquardt-Levenberg type parameter estimation technique for the inverse estimation of soil hydraulic and solute transport and reaction parameters from measured transient or steady-state flow and transport data (Simunek & Sejna, 2007). This option can be used as a double check with the user selecting which parameters are to be optimised from the experimental data inputted (Simunek & Sejna, 2007).



Main Processes

Heading: Welcome to HYDRUS-2D

Simulate

☑ Water Flow ☐ Heat Transport

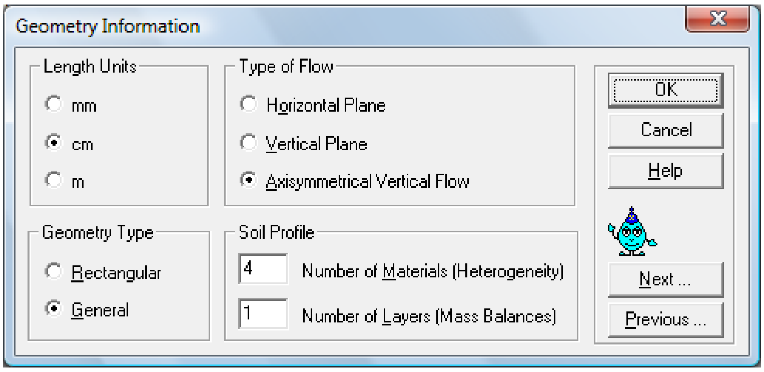
☑ Solute Transport ☑ Root Water Uptake

☐ Inverse Solution ?

Figure E- 1 Main Processes Screen- HYDRUS-2D

Geometry Information

Following the choice of the processes required to represent the problem, the general geometry information is inputted. This includes the length units, the type of flow, the geometry type and the number of materials within the soil profile. The geometry information selected can be seen in Figure E-2. For the purpose of this project the flow type was selected as axisymmetrical vertical flow due to the main irrigation method in question being drip irrigation. Axisymmetrical flow considers radially finite 3-dimensional geometry where the modelled 2-dimensional plane represents a 3-dimensional cylindrical shape (Rassam et al. 2004). All length measurements were given in centimetres whilst the geometry type was set to general. A general geometry type can handle more complex geometries (Rassam et al. 2004) and consists of a mesh compiled from numerous different shaped and sized triangles.


Geometry Information

Length Units
○ mm
● cm
○ m

Type of Flow
○ Horizontal Plane
○ Vertical Plane
● Axisymmetrical Vertical Flow

Geometry Type
○ Rectangular
● General

Soil Profile
4 Number of Materials (Heterogeneity)
1 Number of Layers (Mass Balances)

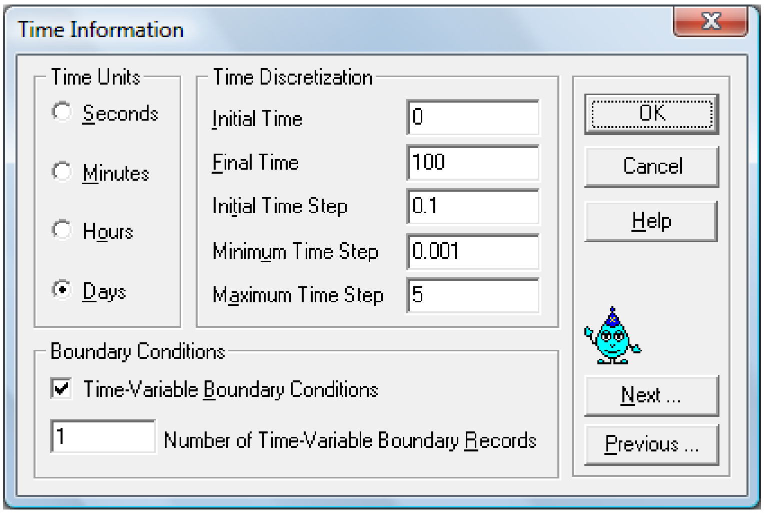
Figure E- 2 Geometry Information Screen- HYDRUS-2D

The number of materials (herein referred to as soil layers) represents the number of soil layers specified within the soil profile. The distribution of these layers is defined further into the model setup process. The number of layers does not affect the solution but provides more detailed mass balance calculations relevant to particular regions of interest (Rassam et al. 2004), and so therefore was left as one throughout this project.

Time Information

Within the time information dialog box are the options for selecting the time units, applying time discretisation and selecting the number of time-variable boundary conditions. The time units selection allow you to set the units to be used throughout the model and can be set to seconds, minutes, hours or days. All input variables are converted automatically if the units are changed during or after data entry (Simunek &

Sejna, 2007). The initial time is the starting time of the calculations whilst the final time is when calculations are completed.



Time Information

Time Units

○ Seconds
○ Minutes
○ Hours
● Days

Time Discretization

Initial Time: 0
Final Time: 100
Initial Time Step: 0.1
Minimum Time Step: 0.001
Maximum Time Step: 5

Boundary Conditions

☑ Time-Variable Boundary Conditions
1 Number of Time-Variable Boundary Records

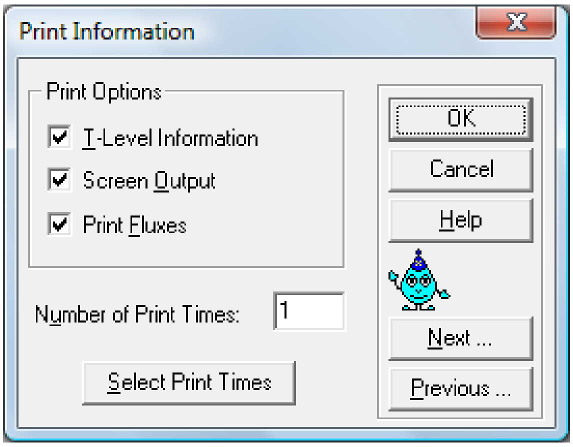
Figure E- 3 Time Information Screen- HYDRUS-2D

The initial time step is a function of the type of problem being solved, for example, for soils with highly nonlinear soil hydraulic properties a relatively small initial time step is required (Simunek & Sejna, 2007). The initial time step is used at the beginning of simulations and whenever the boundary conditions are changed considerably (Simunek & Sejna, 2007). The minimum time step is the lowest value that the time increment can go to during simulations. This value must be smaller than the initial time step, the interval between print times and the interval between time-variable boundary condition records (Simunek & Sejna, 2007). The maximum time step is the largest value that is allowed for the time increment. This number can be relatively large, but not greater that the final time value, as HYDRUS-2D selects the optimal time step during simulations.

Print Information

The print information dialog box allows the user to set the number of print times at which the detailed information will be printed. The detailed information includes pressure heads, water contents, concentrations, temperatures, fluxes, and the soil-water and solute balances (Simunek & Sejna, 2007).

T-Level Information and Print Fluxes concerns the mean pressure heads and concentrations, mean water and solute fluxes, cumulative water and solute fluxes, and time and iteration information (Simunek & Sejna, 2007). Screen Output is the option of whether or not information about the simulation run is to be printed to the screen during execution of the HYDRUS computational code (Simunek & Sejna, 2007). By selecting these options, see Figure E-4, all information will be printed.



☑ T-Level Information
☑ Screen Output
☑ Print Fluxes

Number of Print Times: 1

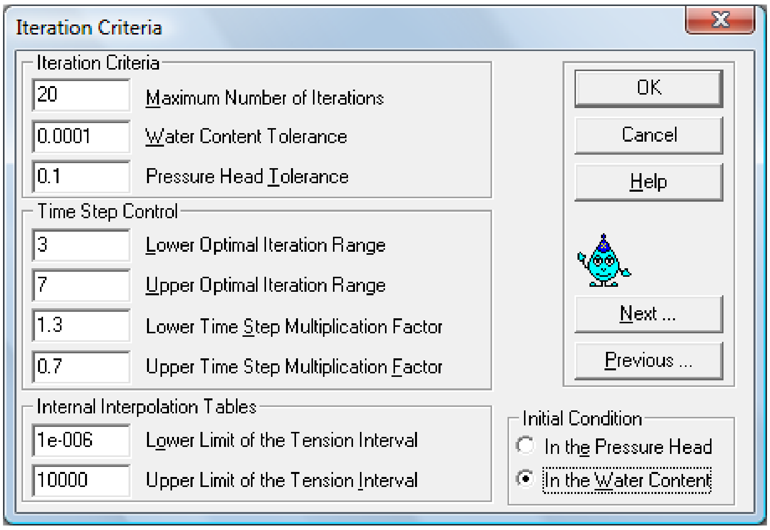
Figure E- 4 Print Information Screen - HYDRUS-2D

Iteration Criteria

The iteration criteria dialog box (Figure E-5) contains information related to the iterative process that is used to solve the Richard's equation (1931) (Simunek & Sejna, 2007) with the iterative process continuing until a satisfactory degree of convergence is obtained. This is parameterised by imposing an absolute pressure head or water content tolerance for which two successive iterations must be less than for a solution to be found.

In the Iteration Criteria section of the dialog box the maximum number of iterations during one time step are set, as well as the water content and pressure head precision tolerances (Simunek & Sejna, 2007). The format of the initial conditions is set by selecting either "In the Pressure Head" or "In the Water Content" in the Initial Condition section of this dialog box.

Other variables within this window are left at their default values as these have been identified as the optimum conditions in which to run the program.



Iteration Criteria

Iteration Criteria
20 Maximum Number of Iterations
0.0001 Water Content Tolerance
0.1 Pressure Head Tolerance

Time Step Control
3 Lower Optimal Iteration Range
7 Upper Optimal Iteration Range
1.3 Lower Time Step Multiplication Factor
0.7 Upper Time Step Multiplication Factor

Internal Interpolation Tables
1e-006 Lower Limit of the Tension Interval
10000 Upper Limit of the Tension Interval

Initial Condition
○ In the Pressure Head
● In the Water Content

Figure E- 5 Iteration Criteria Screen - HYDRUS-2D

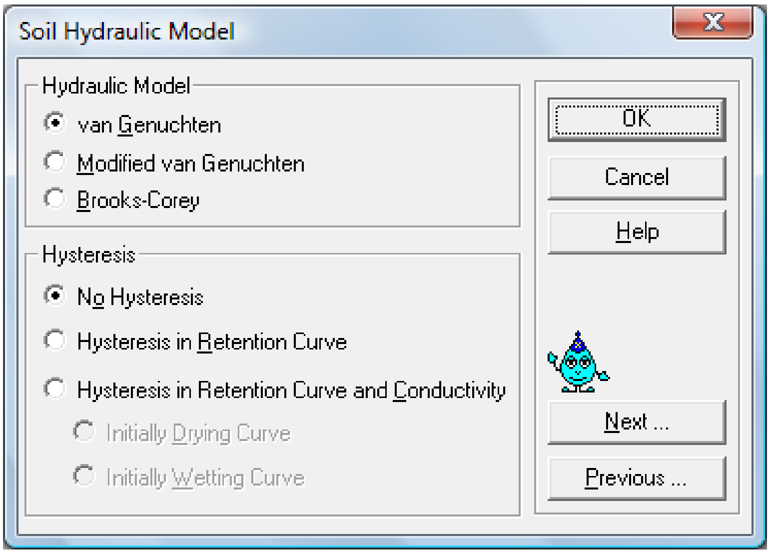
Soil Hydraulic Model

The soil hydraulic model window (Figure E-6) the hydraulic model used to describe the soil hydraulic properties is selected. It can be further advanced by the specification of whether or not hysteresis needs to be considered during the calculations (Simunek & Sejna, 2007).

The different models that can be selected include the van Genuchten, modified van Genuchten and the Brooks-Corey models. These models have been discussed in Section 2.4 *Soil-Water and Nutrient Modelling* within this paper.

Water Flow Parameters

The parameters associated with the soil hydraulic model are set in the water flow parameters dialog box (Figure E-7). Some coefficients are common with all three models with these being θ_r (Qr) and θ_s (Qs) denoting the residual and saturated water content, respectively, K_s (Ks) is the saturated hydraulic conductivity, and l is a pore connectivity parameter (Simunek & Sejna, 2007). A (Alpha) and n (n) are empirical coefficients that affect the shape of the hydraulic functions (Simunek & Sejna, 2007).



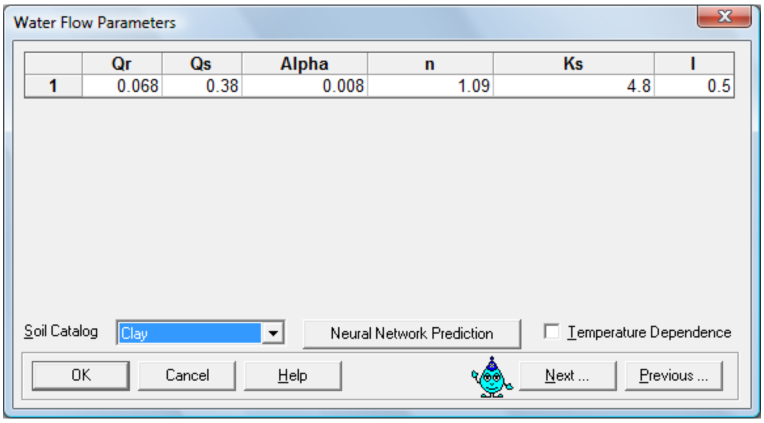
Soil Hydraulic Model

Hydraulic Model
● van Genuchten
○ Modified van Genuchten
○ Brooks-Corey

Hysteresis
● No Hysteresis
○ Hysteresis in Retention Curve
○ Hysteresis in Retention Curve and Conductivity
○ Initially Drying Curve
○ Initially Wetting Curve

Figure E- 6 Soil Hydraulic Model Screen - HYDRUS-2D

The modified van Genuchten model has four additional parameters which aim to increase the accuracy of the model. These parameters are θ_a (Qa) which represents a water content smaller or equal to θ_r (Qr), θ_m (Qm) which represents a water content larger or equal to θ_s (Qs), K_k (Kk) is the unsaturated hydraulic conductivity at water content θ_k, and θ_k (Qk), the water content associated with K_k.



Water Flow Parameters

	Qr	Qs	Alpha	n	Ks	l
1	0.068	0.38	0.008	1.09	4.8	0.5

Soil Catalog: Clay

☐ Temperature Dependence

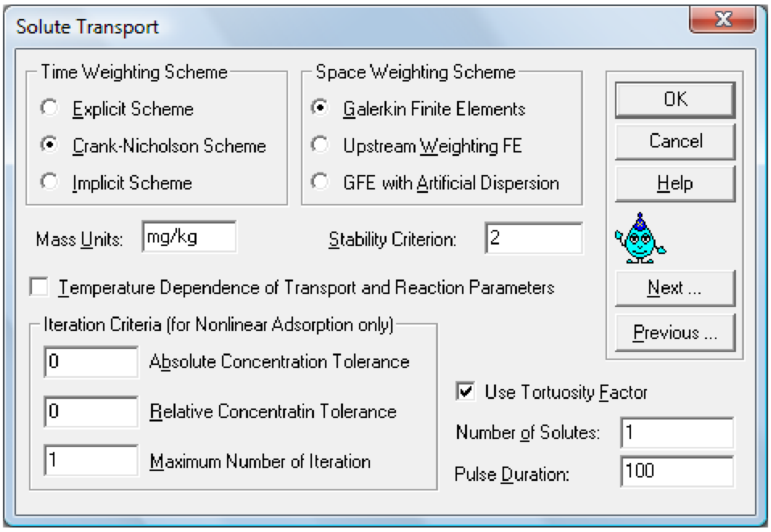
Figure E- 7 Water Flow Parameters Screen - HYDRUS-2D

The soil catalogue contains a list of selected soils from which the parameters mentioned above have been calculated. Caution needs to be used when using these parameter values as they only represent very approximate averages for different textural classes (Simunek & Sejna, 2007).

An alternative to the soil catalogue is the neural network prediction system. The neural network prediction program uses pedotransfer functions (PTFs) to predict van Genuchten’s water retention parameters and the saturated hydraulic conductivity based on textural information (Simunek & Sejna, 2007). The neural network prediction code in HYDRUS is coupled with the Rosetta Lite Dynamically Linked Library which was independently developed by Marcel Chaap (Simunek & Sejna, 2007). When using the neural network prediction function initial values of sand, silt and clay percentages as well as bulk density are entered.

Solute Transport

The solute transport dialog box (Figure E-8) sets out the basic information needed for defining solute transport problem. The iteration criteria, space and time weighting schemes, and additional solute information are defined in the solute transport window. The additional solute transport information includes mass units, pulse duration and number of solutes.



Time Weighting Scheme
○ Explicit Scheme
● Crank-Nicholson Scheme
○ Implicit Scheme

Space Weighting Scheme
● Galerkin Finite Elements
○ Upstream Weighting FE
○ GFE with Artificial Dispersion

Mass Units: mg/kg

Stability Criterion: 2

☐ Temperature Dependence of Transport and Reaction Parameters

Iteration Criteria (for Nonlinear Adsorption only)
0 Absolute Concentration Tolerance
0 Relative Concentratin Tolerance
1 Maximum Number of Iteration

☑ Use Tortuosity Factor

Number of Solutes: 1

Pulse Duration: 100

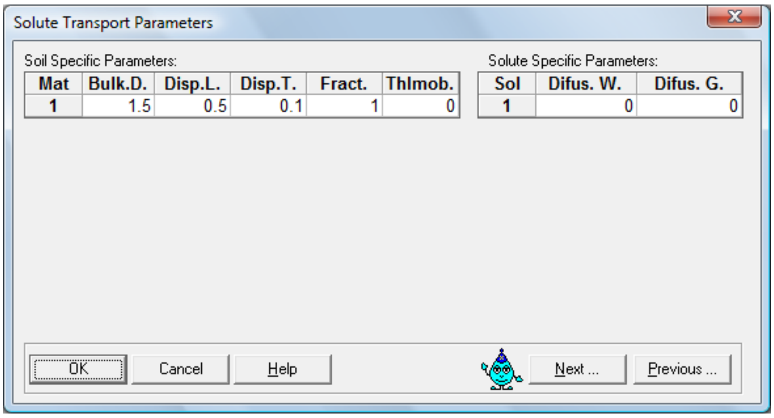
Figure E- 8 Solute Transport Screen - HYDRUS-2D

The time weighting scheme defines the temporal weighting coefficient, ε, used in the numerical solution of the transport equation (Simunek & Sejna, 2007). For the three different schemes the temporal weighting coefficient differs from 0.0 for the explicit scheme, to 0.5 for the Crank-Nicholson scheme and 1.0 for the implicit scheme. The Crank-Nicholson and implicit schemes lead to an asymmetric banded matrix whilst the explicit scheme leads to a diagonal matrix which is much easier to solve (Simunek & Sejna, 2007). The Crank-Nicholson scheme is recommended for solution precision, however the implicit scheme also leads to a numerical dispersion which is better in avoiding numerical instabilities (Simunek & Sejna, 2007). The explicit scheme is most prone to numerical instabilities with undesired oscillations, and is disabled in newer versions of HYDRUS-2D.

Three options are provided for the space weighting scheme. These are Galkerin Finite Elements formulation, the Upstream Weighting Finite Elements formulation, and the Galkerin Finite Elements formulation with Artificial Dispersion. Galkerin Finite Elements formulation is recommended in view of solution precision (Simunek & Sejna, 2007). Upstream Weighting Finite Elements formulation is an option to minimise problems with numerical oscillation when the concentration fronts are relatively steep (Simunek & Sejna, 2007). The numerical solution can also be stabilised with the Galkerin Finite Elements formulation with Artificial Dispersion, which limits or avoids undesired oscillation in the standard Galkerin finite element results (Simunek & Sejna, 2007).

The general solute information which can be set includes several functions. One is the number of solutes to be simulated simultaneously. The pulse duration is the time period which the concentration of solute is applied. Although the mass units are set they are simply printed on output files and displayed in graphs, they have no effect on the actual calculations. The stability criterion is the product of the dimensionless Peclet and Curant numbers (Pe.Cr) (Simunek & Sejna, 2007). The criterion is used in two ways, to either add artificial dispersion in the Galkerin Finite Elements with Artificial Dispersion scheme or to limit the time step for the Galkerin Finite Elements scheme (Simunek & Sejna, 2007). The tortuosity factor is a factor set according to, as stated by Simunek & Sejna, 2007, the formulation of Millington and Quirk (1991) that is used when the molecular diffusion coefficients in the water and gas phases are to be multiplied by a tortuosity factor.

The iteration criteria for solute transport is similar to that for water flow. The advection-dispersion solute transport equation becomes nonlinear when adsorption is considered (Simunek & Sejna, 2007). Similar to that used for the Richard’s equation (1931), an iterative process must then be used to obtain solutions (Simunek & Sejna, 2007). The iterative process continues until a satisfactory degree of convergence is obtained (Simunek & Sejna, 2007). The maximum number of iterations allowed during a time step is specified in this window with a recommended value of 10. Once the maximum number of iterations is reached by the program, the numerical solution is either terminated for problems involving transient water flow or restarted with a reduced time step (Simunek & Sejna, 2007).



Soil Specific Parameters:

Mat	Bulk.D.	Disp.L.	Disp.T.	Fract.	Thlmob.
1	1.5	0.5	0.1	1	0

Solute Specific Parameters:

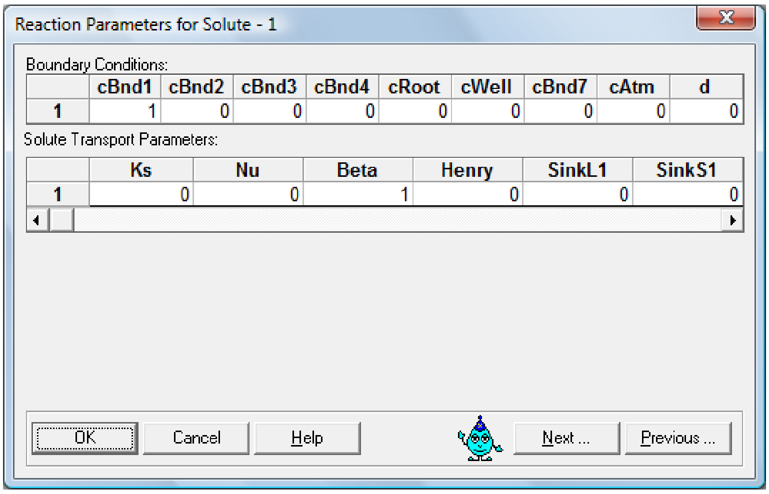
Sol	Difus. W.	Difus. G.
1	0	0

Figure E- 9 Solute Transport Parameters Screen - HYDRUS-2D

The soil and solute specific transport parameters are specified in the solute transport parameters dialog window (Figure E-9). Soil specific parameters include the bulk density, longitudinal dispersivity, transverse dispersivity, the immobile water content and the dimensional fraction of adsorption sites. The solute specific parameters are the molecular diffusion coefficient in free water and the molecular diffusion coefficient in soil air.

The solute reaction parameters and concentrations for boundary conditions are specified in the solute reaction parameters dialog box (Figure E-10). When multiple solutes are being modelled each solute has a separate reaction parameter dialog window. Several solute transport parameters are set for each soil material and are as follows (Simunek & Sejna, 2007):

- Ks – adsorption isotherm coefficient;
- Nu – adsorption isotherm coefficient;
- Beta – adsorption isotherm coefficient;
- Henry – equilibrium distribution constant between liquid and gaseous phases;
- SinkL1 – first-order rate constant for dissolved phase;
- SinkS1 – first-order rate constant for solid phase;
- SinkG1 – first-order rate constant for gas phase;
- SinkL1' – first-order rate constant for dissolved phase, as part of a solute decay chain;
- SinkS1' – first-order rate constant for solid phase, as part of a solute decay chain;
- SinkG1' – first-order rate constant for gas phase, as part of a solute decay chain;
- SinkW0 – zero-order rate constant for dissolved phase;
- SinkS0 – zero-order rate constant for solid phase;
- SinkG0 – zero-order rate constant for gas phase;
- Alpha – first-order rate coefficient for one-site nonequilibrium adsorption, mass transfer coefficient for solute exchange between mobile and immobile liquid regions.



Reaction Parameters for Solute - 1

Boundary Conditions:

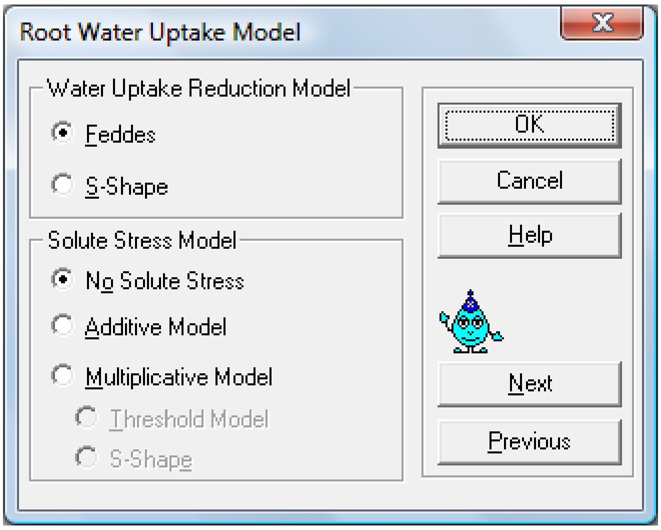
	cBnd1	cBnd2	cBnd3	cBnd4	cRoot	cWell	cBnd7	cAtm	d
1	1	0	0	0	0	0	0	0	0

Solute Transport Parameters:

	Ks	Nu	Beta	Henry	SinkL1	SinkS1
1	0	0	1	0	0	0

Figure E- 10 Reaction Parameters (Solute 1) Screen - HYDRUS-2D

The boundary conditions section of the solute reaction parameters dialog box (Figure E-10) sets the concentrations for time-independent boundary conditions. cBnd1 is the value of the concentration for the first time-independent boundary condition (Simunek & Sejna, 2007). This value is set to zero if there is no time-independent boundary condition to be specified, and the same principle is applied for cBnd2 through to cBnd4. The cRoot value is the value of the concentration for the fifth time-independent boundary condition (Simunek & Sejna, 2007). If water uptake is considered the cRoot is automatically used for the maximum concentration of water removed from the flow region by root water uptake (Simunek & Sejna, 2007). cWell is the value of the concentration for the sixth time-independent boundary condition (Simunek & Sejna, 2007). If there are internal sources specified, then cWell is automatically used for the concentration of water injected into the flow region through internal sources (Simunek & Sejna, 2007). cBnd7 is the concentration of the incoming fluid for a volatile type boundary condition at the soil surface; if there is no volatile boundary condition specified this is set to zero (Simunek & Sejna, 2007). cAtm is the concentration above the stagnant boundary layer for a volatile type boundary condition, which is set to zero if no volatile boundary condition is specified (Simunek & Sejna, 2007). The final parameter, d, is the thickness of the stagnant boundary layer for a volatile type boundary layer.



Root Water Uptake Model

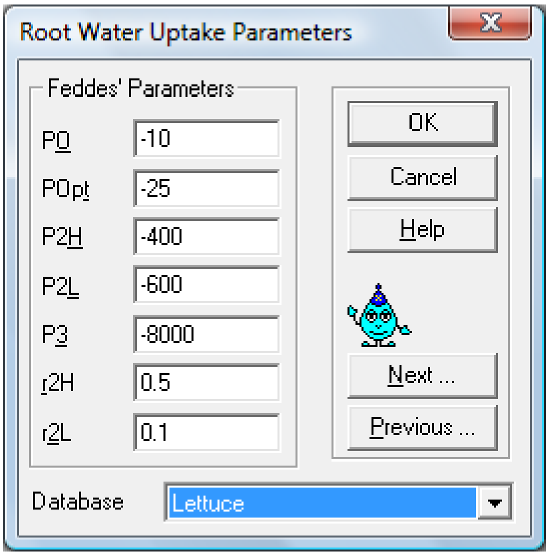
Water Uptake Reduction Model
- ● Feddes
- ○ S-Shape

Solute Stress Model
- ● No Solute Stress
- ○ Additive Model
- ○ Multiplicative Model
  - ○ Threshold Model
  - ○ S-Shape

Figure E- 11 Root Water Uptake Model Screen - HYDRUS-2D

Root Water Uptake Model

The root water uptake model dialog box (Figure E-11) allows to models to be selected. These models are the water uptake reduction model and the solute stress model. Two options for the water uptake reduction model are offered, a water stress response function suggested by Feddes et al. (1978) or an S-Shaped function suggested by van Genuchten (1985) (Simunek & Sejna, 2007). Either of these functions can be used to reduce the potential root water uptake to the actual water uptake rate. The effects of salinity stress on root water uptake can be neglected of considered by selecting either the No Solute Stress or Additive and Multiplicative models respectively.



Root Water Uptake Parameters

Feddes' Parameters

P0 -10

POpt -25

P2H -400

P2L -600

P3 -8000

r2H 0.5

r2L 0.1

Database Lettuce

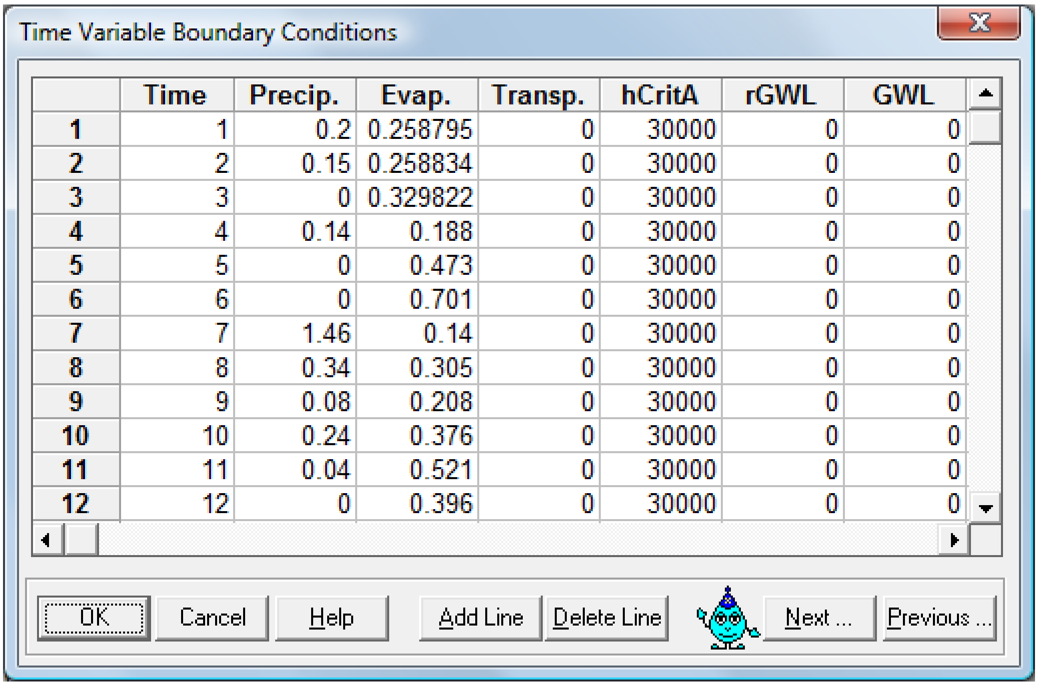
Figure E- 12 Root Water Uptake Parameters Screen - HYDRUS-2D

The root water uptake parameters window (Figure E-12) sets the water stress function parameters. Each of the parameters meanings are as follows (Simunek & Sejna, 2007);

- P0 – value of the pressure head below which roots start to extract water from the soil;
- POpt – value of the pressure head below which roots extract water at the maximum possible rate;
- P2H – value of the limiting pressure head below which roots can no longer extract water at the maximum rate (assuming a potential transpiration rate of *r2H*);
- P2L – same as P2H, but for potential transpiration rate of *r2L*;

- P3 – value of the pressure head below which root water uptake ceases (usually taken at the wilting point);
- r2H – potential transpiration rate;
- r2L – potential transpiration rate.

A database of crops has been written into the HYDRUS code and so values can simply be used from here if the crop. The values within the database have been found from extensive research in this area.



	Time	Precip.	Evap.	Transp.	hCritA	rGWL	GWL
1	1	0.2	0.258795	0	30000	0	0
2	2	0.15	0.258834	0	30000	0	0
3	3	0	0.329822	0	30000	0	0
4	4	0.14	0.188	0	30000	0	0
5	5	0	0.473	0	30000	0	0
6	6	0	0.701	0	30000	0	0
7	7	1.46	0.14	0	30000	0	0
8	8	0.34	0.305	0	30000	0	0
9	9	0.08	0.208	0	30000	0	0
10	10	0.24	0.376	0	30000	0	0
11	11	0.04	0.521	0	30000	0	0
12	12	0	0.396	0	30000	0	0

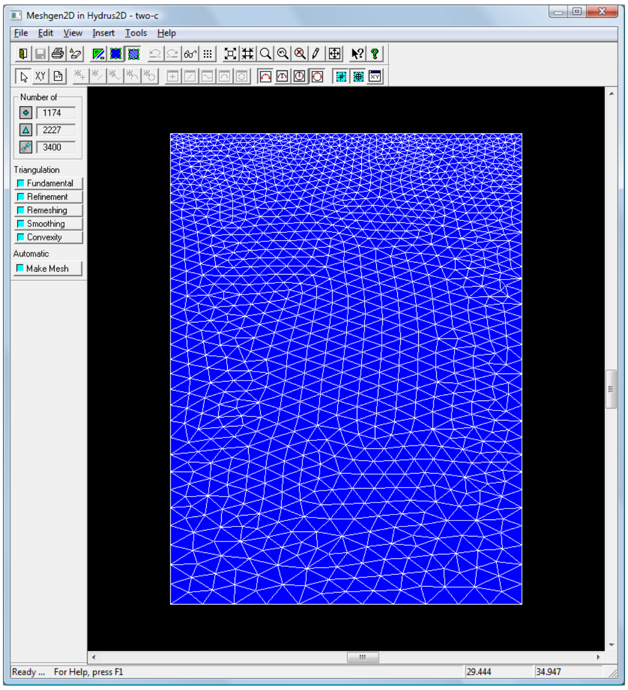
Figure E- 13 Time Variable Boundary Conditions Screen - HYDRUS-2D

Time Variable Boundary Conditions

Several variables that change through time are specified within the time variable boundary conditions dialog box (Figure E-13). Variables that can be inputted include the time for which a data record is provided, precipitation rate, potential evaporation, potential transpiration, absolute value of the minimum allowed pressure head at the soil surface (hCritA), variable flux (rGWL) and variable pressure head (GWL).

Mesh Generation

The soil profile being modelled can be defined using a rectangular or general geometry which is specified in the geometry information dialog box. Using the general geometry type you are able to specify the boundary curves of the transport domain which can be a combination of polylines, arcs, circles or cubical splines. A rectangular geometry is based on straight lines specified numerically. In both cases the transport domain is discretised into a structured finite element mesh. The shape and size of the transport domain and characteristics of the mesh are entered into the Meshgen2D window (Figure E-14).



Number of
1174
2227
3400

Ready ... For Help, press F1
29.444
34.947

Figure E- 14 Mesh Generation Screen - HYDRUS-2D

Boundary Conditions Editor

Dependent on the options selected to be modelled the boundary conditions editor allows multiple screens where the characteristics and initial conditions can be specified for the transport domain.

The first boundary condition that is generally entered is the water flow boundary conditions which can be seen in Figure E-15. There are several options available, however only atmospheric, variable flux, no flux and free drainage are utilised for the model being investigated.

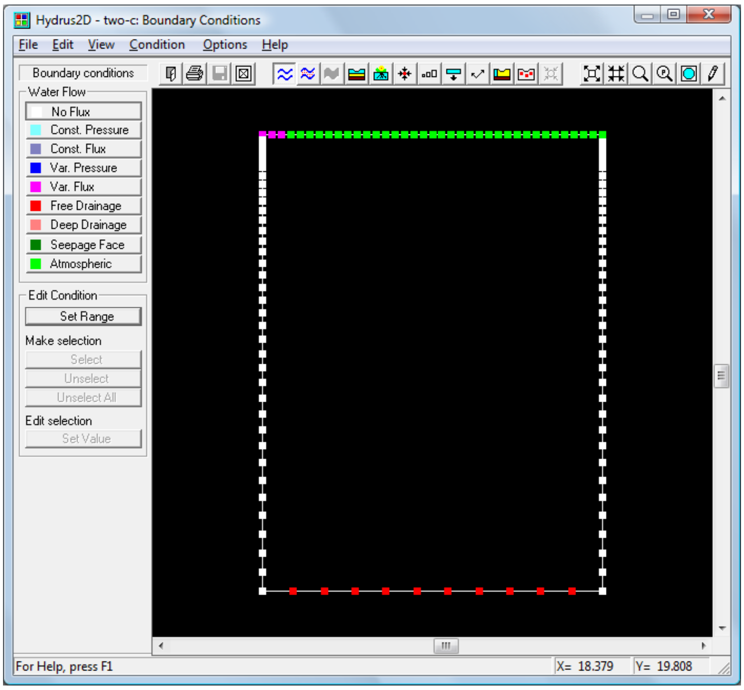


Figure E- 15 Water Flow Boundary Conditions Editor Screen - HYDRUS-2D

Following the specification of the water flow boundary conditions the solute transport boundary conditions are entered (Figure E-16). Three types of solute flux can be specified and are determined on the type of solute being modelled. The first, second and third type solute transport options have been detailed previously in this paper.

The material distribution screen (Figure E-17) allows the user to specify the breakdown of the transport domain into the different soil types that have been identified. The number of materials – soils – is specified earlier in the model development process in the geometry information screen.

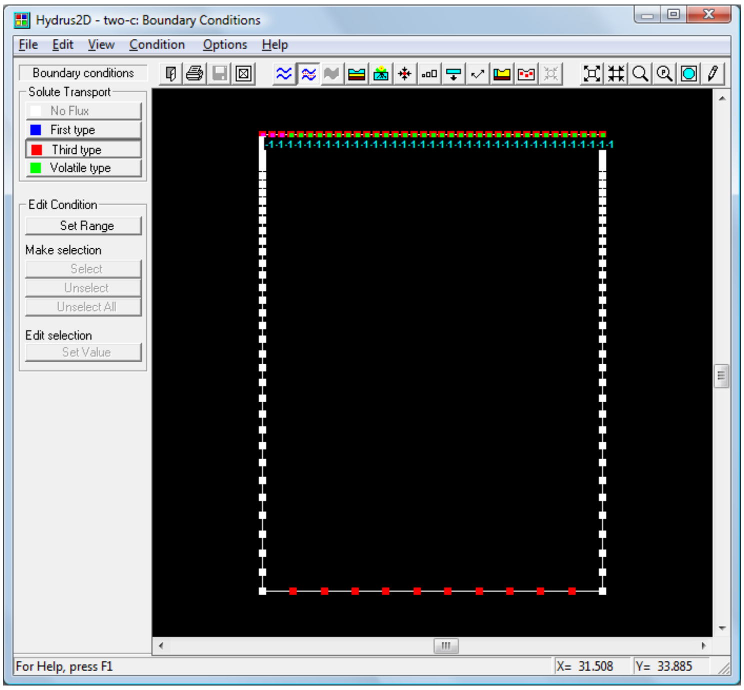


Figure E- 16 Solute Transport Boundary Conditions Editor Screen - HYDRUS-2D

When root water uptake is being modelled the distribution of the roots of the plant are specified in the root distribution editor screen (Figure E-18). The root distribution is one of the parameters that influence the breakup of the season as it is continually changing. The initial water content and solute concentrations are entered in the initial conditions editor screen (Figure E-19) by toggling between water content and concentration. The data entered here is where some of the initial conditions are used by HYDRUS for calculations are drawn from.

Information can be printed for specific areas within the transport domain by entering observation nodes in the observation nodes editor screen (Figure E-20). These points will often coincide with what has been trialled in the field or laboratory.

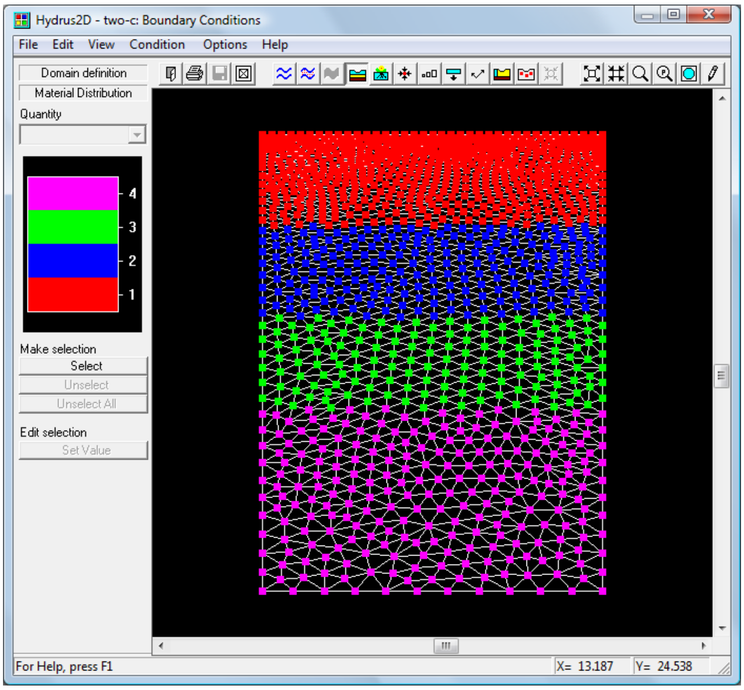


Figure E- 17 Material Distribution Editor Screen - HYDRUS-2D

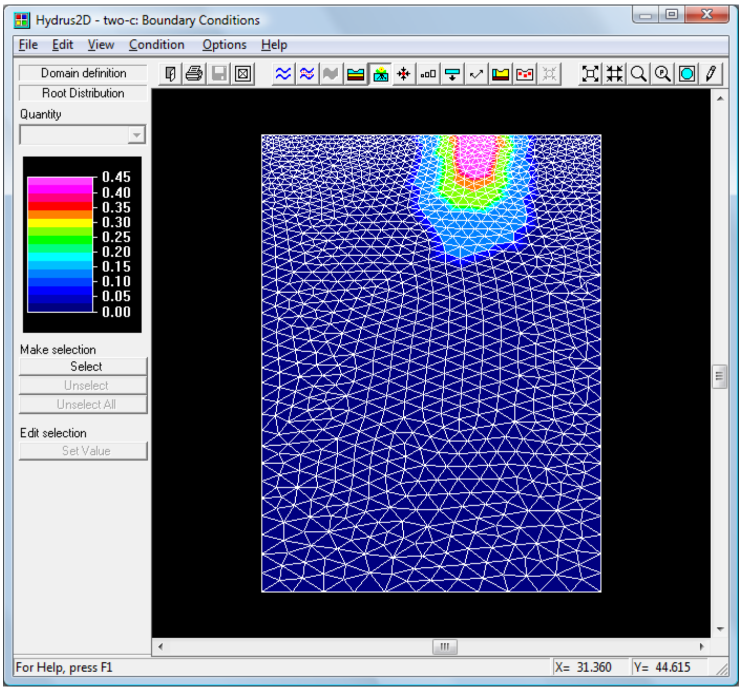
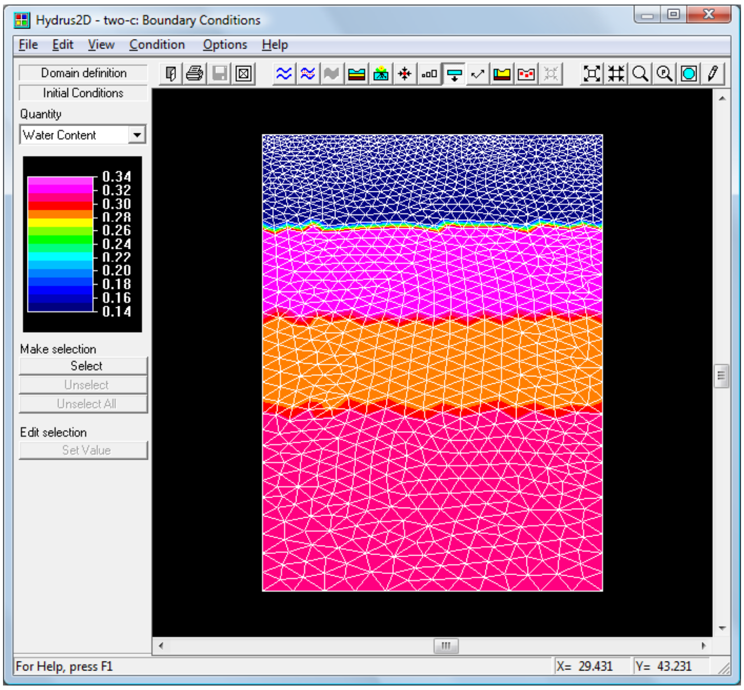


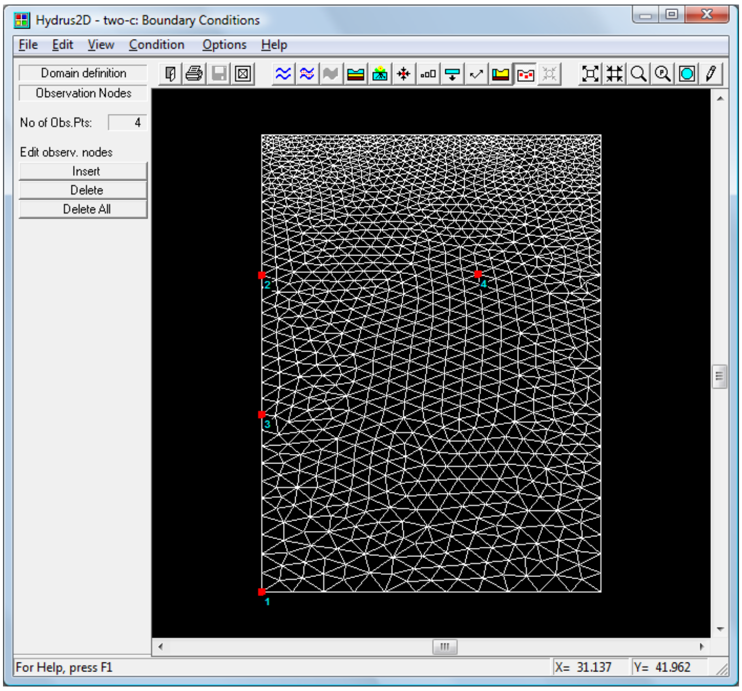
Figure E- 18 Root Distribution Editor Screen - HYDRUS-2D



Quantity: Water Content

X= 29.431 Y= 43.231

Figure E- 19 Initial Conditions Editor Screen - HYDRUS-2D



No of Obs.Pts: 4

X= 31.137 Y= 41.962

Figure E- 20 Observation Nodes Editor Screen - HYDRUS-2D