Investigation of the efficiency and long term performance of various sub-surface irrigation configurations under field conditions

Thesis submitted by

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Contents

Certificate of Authorship

I

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Abstract

Subsurface Drip Irrigation (SDI) has shown great potential for increasing crop yield and uniformity, while decreasing water use and off-site impacts. SDI accomplishes this through suppling water directly to the plant root-zone at a rate closely matching that required for optimum growth. Fully realising this potential is limited by a number of issues : 1. Emitter flow rates are in excess of the soils infiltration capacity which can potentially lead to disruption of soil structure and water surfacing or tunnelling, 2. the point source nature of available products limits lateral water distribution which affects application uniformity between emitters and the potential to establish a crop planted some distance from the emitter, 3. deep drainage can be a problem depending on soil type and irrigation management.

This research introduces a new SDI product designed to address these issues. Capillary Root Zone Irrigation® (CRZI) comprises a combination of both impermeable and highly conductive materials designed to produce a wider lateral wetting pattern, while reducing drainage and surface tunnelling. The research followed an ever-focussing path, consisting of 4 field trials and a computer modelling component. The field experiments commenced with comparison of a broad range of pressurised and non-pressurised subsurface irrigation products growing an annual crop. The next trial concentrated on comparing performance of CRZI with commercially available Drip Tape under strict irrigation schedule control. This was followed by a trial concentrating on just one, very important growth stage – crop establishment. Developed in parallel with the annual crop experiments was a vineyard which analysed product performance with a perennial crop, over a longer time frame. And finally, being conscious that all experimentation had been performed in the one soil type, a simulation model was introduced, in an attempt to gauge expected outcomes in other soils.

The major outcome of the research found that CRZI and Drip Tape performed similarly throughout the experiments but through very different soil wetting methods. The high flow rate of Drip Tape caused water to travel rapidly to the soil surface, resulting in surface lateral distribution being dominated by overland flow. CRZI introduced water to the soil at a fraction of the area-based flow rate of Drip Tape (30 mm hr^{-1} *vs* 3200 mm hr^{-1}), resulting in little surfacing and therefore meeting more closely the goals of SDI.

The also explained why over 50% of buried drip emitters developed tunnels in the vineyard *vs* 5% with CRZI. If using SDI for germination in Hanwood Loam then installation depth should be no more than 0.2 m and seed should not be planted more than 0.5 m from the irrigation source.

The computer modelling found CRZI to provide the greatest benefit in coarse textured soils, due to its ability to maintain a small saturated zone high in the soil profile, from which water could move laterally through capillarity. The modelling also found that high frequency irrigation application (pulsing) has potential to hold wetted zones higher in the soil profile.

While performing the research, several new methods were introduced. Plant bioassays were used to identify differences in wetting methods. This allowed direct appraisal of how the systems affected plant growth, without relying on traditional surrogates such as soil water status instruments. Irrigation control software/hardware was produced which allowed flexible variation of daily irrigation amount, pulsing, and soil water status feedback. Through the modelling work, the research also offered the first investigation of the mechanism behind irrigation pulsing effects on wetted zone geometry.

List of Figures

List of Tables

List of Abbreviations

CRZI – Capillary Root Zone Irrigation
CSIRO – Commonwealth Scientific and Industrial Research Organisation
DAS – Days after sowing
ET – Evapotranspiration
ET_c – Evapotranspiration (crop)
ET_o – Evapotranspiration (reference)
EM38 – Electromagnetic Induction Meter Model 38
FEM – Finite Element Mesh
GSF – Grains Security Foundation
K_s – Saturated hydraulic conductivity
MIA – Murrumbidgee Irrigation Area
NMM – Neutron Moisture Meter
PE – Polyethylene
PSA – Particle Size Analysis
RWU – Root Water Uptake
SDI – Subsurface Drip Irrigation
SDR – Specific Discharge Rate
SIP – Subsurface Irrigation Pipe
SWC – Soil Water Content
WUE – Water Use Efficiency

1 Sub-surface Drip Irrigation – A Review

1.1 Introduction

Competition for the world's water resources is ever-increasing. The partitioning of these resources between urban, agricultural and environmental use, is increasingly becoming a major issue in both national and international arenas (Tisdell, 1995). Efforts are being made to increase the efficiency with which water is used in each of these areas.

Irrigation area water balance studies in Australia show an average 30% of irrigation application passes through the root zone and becomes either groundwater recharge, or is intercepted by drainage networks and contributes to waterway pollution (AATSE, 1999; Charlesworth and Meyer, 1996).

Drip irrigation is an example of a technology which offers many environmental and management advantages over other forms of water application and is currently being advocated by Australian agricultural and water supply agencies eg. QLD Rural Water Use Efficiency Initiative, Murrumbidgee Irrigation HortVision 2010. Buried, or Subsurface Drip Irrigation (SDI), presents even further opportunity for efficiency savings by way of reducing losses to evaporation, not relying on the soil surface for water transmission, and potentially avoiding replacement due to field cultivation when compared with surface drip (Camp, 1998).

The Capillary Root Zone Irrigation (CRZI) concept was developed from a plant nursery product, Bottom-Up™ (manufactured by Bottom-Up Irrigation, Sydney, Australia). Bottom-Up is manufactured primarily for raising potted plants on benches. The product consists of a laminar sheet of geofabric protected on top by weed matting and underneath by polyethylene. Water is supplied to one edge of the geotextile by drip tape and distributes across the mat. Pots placed on the weed-mat protected geofabric draw water through capillary rise, unlike high frequency microsprinkler systems which water the whole glass house interior.

Capillary Root Zone Irrigation was developed to extend the qualities of Bottom-Up into the broader irrigated agriculture and turf industries. Whereas Bottom-Up is produced in sheets to fit glasshouse benches, CRZI is cut in long strips and buried in the soil beneath the crop. The product is therefore an adaptation of subsurface drip irrigation (SDI).

The CRZI Research Program was designed to gain a comprehensive knowledge of the product through a hierarchy of phases :

1. Computer modelling.

Due to the high cost and risk involved in research and development, computer simulation was used to provide a first estimate of likely outcomes. While no replacement for actual trials, such techniques can help to focus research direction by defining the bounds of possible scenarios (Kirby and Knight, 1996; Kirby *et al*, 1996).

2. Small scale box trials.

As an intermediate step between computer simulation and field-testing, small box trials were used. Perspex walled boxes allowed for visual appraisal of different product configurations.

Included in this part of the project was a separate analysis of geotextile hydraulic properties. Using special equipment the rate of water flow through the membrane was measured in response to loading (Miller, 2002).

3. Large scale, multi-crop, field testing.

At the top end of the trial hierarchy lies field testing, which provides as closely as possible the conditions under which the commercial product operates.

The final level is the investigation to be covered by this thesis.

General objectives of the study are :

i). To compare the water use efficiency of CRZI with other commercially available products.

ii). To determine CRZI wetting patterns.

iii). To investigate the most efficient irrigation management for CRZI.

iv). To suggest improved design based on an understanding of soil wetting processes.

1.2 Advantages/ Disadvantages of Sub-surface Irrigation systems

1.2.1 Problems of soil structural decline around emitters in SDI

Water applied through capillarity (eg. SDI) may contribute to maintaining a 'soft' soil (Cockcroft, 1995). Tension wet soil aggregates are indeed more stable (resistant to slaking) than those wet rapidly by surface means (Lanyon *et al*, 1998). Cockcroft (1995) defines a 'soft' soil as not exceeding 1MPa penetration resistance and featuring a high proportion of pores greater than 0.03 mm in diameter. Such soils allow fast drainage and re-aeration following a rainfall/irrigation event, promote deeper rooting patterns and higher root length density. Reasons as to why water percolating downwards through the profile is not conducive to soft soil may be that i) particles are washed into micropores, causing blockage, ii). the gravitational pull of water molecules passing down a micropore causes disaggregation of soil particles, iii). overburden pressure on weak aggregates.

1.2.2 Water Use Efficiency

One definition of Water Use Efficiency (WUE) is crop yield produced per unit of water applied. Enhancement may be made through either increased yield and/or decreased water application. To optimise WUE the irrigation system should 1) exhibit good distribution uniformity and be flexible enough to allow frequent watering, 2) be able to maintain a portion of the soil at optimum water content, 3) be buried to reduce evaporation and 4) be free from emitter plugging and leaks (Phene, 1995). Subsurface drip irrigation is the only system capable of meeting these requirements. The above guidelines ensure there is uniform water application throughout the field, crop water stress is avoided, and water does not leave the system unproductively through soil evaporation or drainage.

In comparing water balances for surface and sub-surface irrigated corn, Evett *et al* (1995) found up to a 10% water saving in the latter system. Almost all the difference was accounted for by soil surface evaporation prior to canopy closure (Leaf Area Index <4.2). Two sub-surface depths were trialed (0.15 m and 0.3 m) with the deepest giving the least evaporative loss. An additional point made through this study, was that the deeper placed system also produced greater drainage beyond the root zone, highlighting the critical role of management in extracting the potential advantages of buried irrigation sources.

In a lysimeter study, Phene *et al*, (1989) found a 50% and 75% reduction in evaporation from a bare soil surface when irrigated by SDI, compared with high and low frequency surface drip, respectively.

Growing SDI irrigated lucerne in Central Queensland, Australia, Harris (1997) reported a three year average 25% increase in WUE, when compared to the regional average for spray irrigation.

Careful management of SDI systems growing corn in Kansas, brought a 25% irrigation reduction (Lamm et al, 1995), while still maintaining good yields. Another surface/subsurface drip comparison failed to record any significant differences in yield or water use and concluded that, on the soils used, proper irrigation management is more important than the application method to avoid water deficit/surplus stresses (Howell *et al*, 1995).

Tomatoes with SDI, showed a significant increase in WUE over low frequency surface drip irrigation in California (Phene, 1995). This particular study clearly demonstrated the advantages of the nutrient and water control potential of SDI. Over three years, tomato yield was doubled and WUE increased by 70% through careful application of nitrogen, phosphorus, and potassium through the irrigation system, when compared with surface drip.

A disadvantage of high frequency irrigation may be that it lowers the buffer capacity of the soil to handle rainfall events and hence may in fact reduce the WUE. Such results were reported in the United States by Caldwell *et al* (1994), who found a seven day time-based schedule and a 50 mm depletion-based schedule, gave significantly greater WUE and significantly less percolation loss, than shorter time-based or lower depletion-based schedules.

1.2.3 Economics

When compared with a centre pivot sprinkler system, Dhuyvetter *et al* (1995) found SDI generated greater returns to management and investment, but could not overcome the annual ownership costs associated with the greater initial investment SDI required. This study also concluded that the relative returns were sensitive to the system's useful life, the initial investment and relative crop yields.

An economic comparison of SDI, flood, hand shift, side roll, and travelling irrigator on lucerne in central Queensland, Australia, found that SDI had the highest Net Present Value and was second to hand shift in Internal Rate of Return (Harris, 1995). Moreover, irrigation in the locality in which this study was carried out, is from an over-allocated aquifer and SDI has the potential to significantly increase returns from this limited water resource.

In an analysis comparing the economics of changing from furrow irrigation to either centre pivot or SDI in the Burdekin (QLD) region, centre pivot was more profitable than SDI (Qureshi *et al,* 2001).

1.2.4 SDI Wetting Patterns

Interest in wetting patterns under SDI has resulted in a number of studies addressing this topic from both field trial and theoretical directions. In a sandy loam, soil Earl and Jury (1977) found that the wetting pattern from a single surface emitter extended to 0.6m during a daily irrigation schedule and 1m if water was replaced weekly. Using soil water tension measuring equipment in a clay loam soil, Hanson *et al.* (2000) measured lateral wetting past 0.5m and greater than 0.8m deep (Figure 1.1). In a lighter silt loam, wetting was restricted to a 0.4m lateral diameter (Figure 1.2).

Computer modelling has also been used to investigate differences in SDI wetting patterns. Cote *et al* (2002) used the HYDRUS-2D model to compare the wetting patterns in contrasting soil types from SDI buried at 30cm. The simulations showed : i) the elongated shape of the wetting pattern in sandy soil with no water reaching the surface, ii). the spherical shape of a wetting pattern in silt soil and iii). duplex soils have potential to perch water and reduce deep percolation (Figure 1.3).

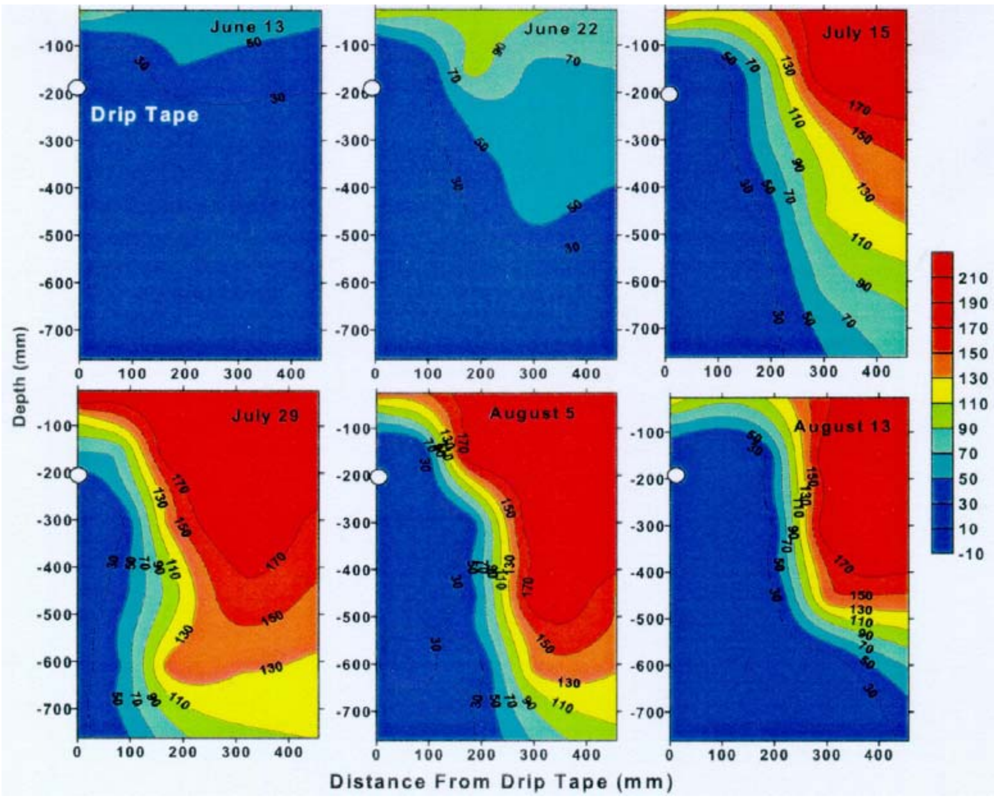


Figure 1.1. Patterns of soil moisture tension (centibars) in a clay loam soil (Hanson *et al.* 2000).

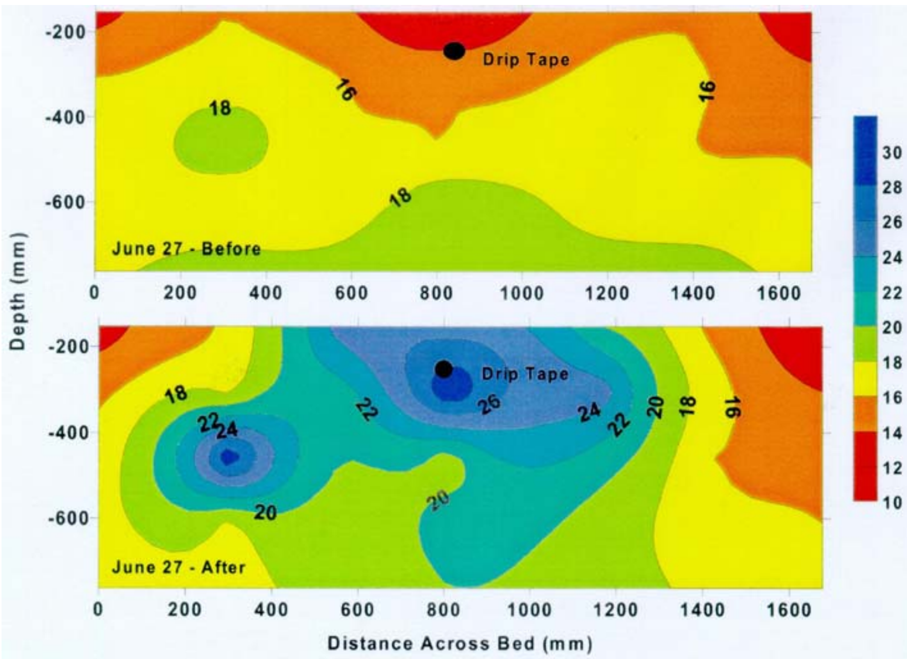


Figure 1.2. Patterns of volumetric soil water content in a silt loam (Hanson *et al.* 2000)

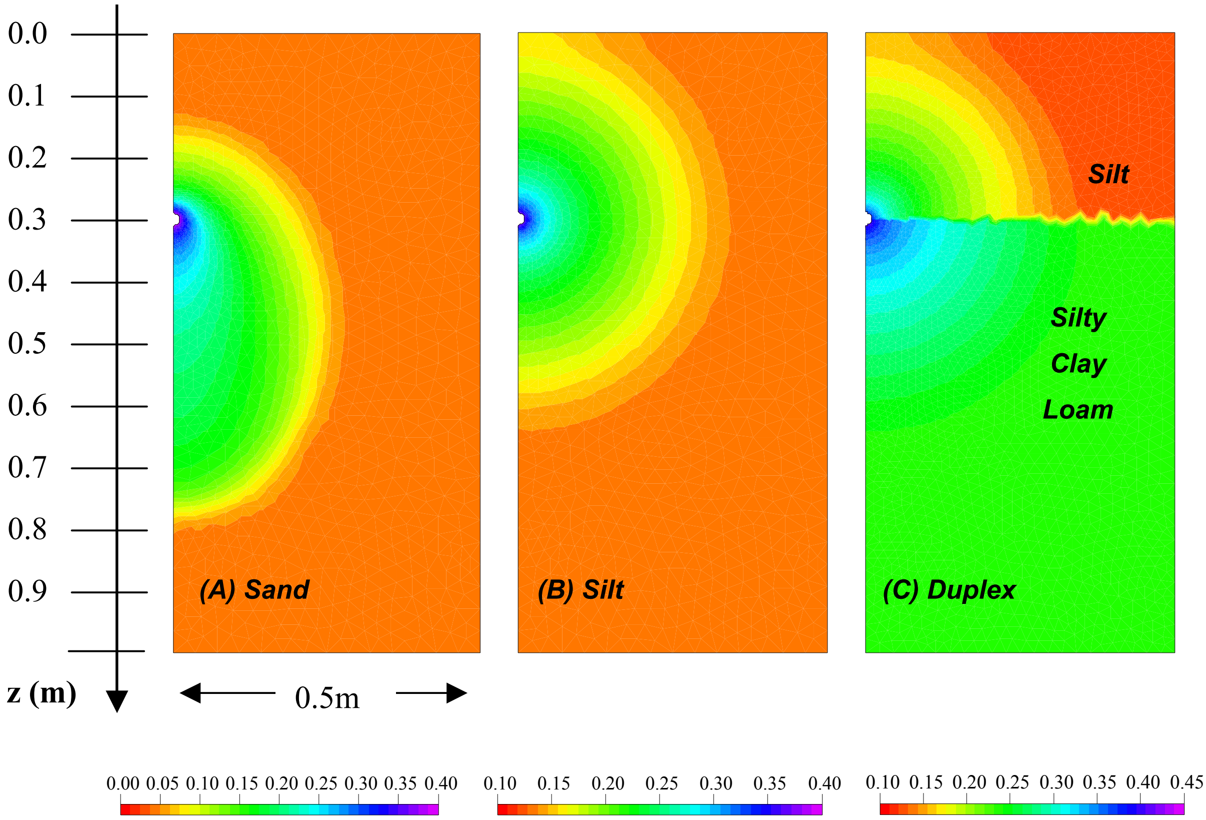


Figure 1.3. Simulated water content distribution around the emitter for 6.3 L of cumulative infiltration for (A) sand, (B) silt and (C) duplex soil (Cote *et al,* 2002).

1.2.5 Irrigation Pulsing

Pulse irrigation may be defined as a series of irrigation time cycles, each with two phases, operating and redistribution (Karmeli and Peri, 1974). Pulse irrigation may also be arbitrarily defined as application of two or more irrigation events in one day.

Pulsing is promoted anecdotally for SDI as a means to optimise upward and lateral water movement from a buried irrigation source, while reducing drainage. Maintaining as small a volume of saturated soil as possible but replenishing it frequently, maximises the capillary flow, while minimising gravitational and macropore flow (Selker *et al,* 1995).

Claude Phene is one practitioner to give definite advice on pulsing frequency. His suggestion is that no more than 1 mm should be applied at a time and at least half an hour redistribution should be allowed between pulses (Phene, pers comm). However, the motivation behind this recommendation is based solely on minimising plant stress, by maintaining a constant soil water content, through supplying water at approximately the rate it is being used.

Irrigation pulsing research from the 1970's (Karmeli and Peri, 1974; Zur, B., 1976), focussed on reducing the application rate from the available water emitters. Controlling the volume of saturated soil during the infiltration process requires an application rate in the range of 0.5-2.0 mm/hr, a rate that none of the then available emitters was capable of (Zur, B. 1976).

In the only source of actual research involving pulsing SDI, Slavin (1980) found that irrigation application efficiency (defined as wetted front height rise over wetted soil volume) was indeed improved with shorter irrigation cycles.

The minimum pulse time is subject to the time required for the whole irrigation system to reach operating pressure ('fill time') (Hanson *et al,* 1997). The higher the fill time/ operating time ratio, the lower will be the distribution uniformity. Claude Phene's recommendation is the fill time should not exceed 5% of the operating time.

A further effect of high frequency schedules is reduced uniformity caused by drainage after a dripline depressurises (Hanson, pers comms). Water runs to the lower end and causes greater application there. Low pressure flushing valves, flushing mains and emitters that close when the pressure drops, may help avoid this problem. Recently, a drip product has become available that maintains a full pipe after the irrigation ceases and so will significantly reduce fill time. It does this by employing a rubber diaphragm which covers the exit orifice as soon as the pressure inside the lateral decreases to a lower limit.

1.2.6 Crop Establishment

One of the most challenging issues faced when using SDI for crop establishment is uniform provision of sufficient water to the seed for germination. A survey in California found that <10% of growers used their buried drip systems to establish the crop and those who did used installation depths less than 0.1 m (Burt and Styles, 1994). All others opted for sprinkler irrigation aided establishment.

Another problem with SDI establishment is apparent when sowing into saline soil. Here, irrigation is relied on to leach the salt away from the seed which is very sensitive in the early stages of establishment. Where SDI is used, ‘leaching’ of the salt upwards and concentration around the seed will occur with drastic consequences on establishment (Burt and Styles, 1994). Establishment with SDI relies on unsaturated water movement from the buried source to the seed/seedling site. The process is therefore affected by distance from seed to water source, evaporative demand, and hydraulic conductivity that is affected by soil texture, structure, and antecedent water content.

One of the most commonly discussed aspects of SDI is installation depth. In fact, a whole archive of the Trickle-L Internet list server is devoted to this subject (http://www.mif.org, 2001). Determining the appropriate depth of installation will always be challenging, and requires consideration of :

i) soil structure and texture
ii) crop/root development patterns
iii) bed permanency
iv) cultivation depth
v) whether crop establishment is to be carried out using the buried system
vi) disturbance of the pipe during crop harvest
vii) Location of crop line relative to drip line

The complexity inherent in this list has prevented tabulation of recommendations for installation depths of SDI systems (Burt and Styles, 1994). The difficulty in balancing the variables in the above list, explains why use of SDI for crop establishment is considered risky. Crop establishment is critical to final yield and consequently irrigators seek to reduce risk by using a second irrigation system at this initial stage.

1.3 Soil Water Sensing

One of the methods for comparing the relative efficacy of SDI configurations is by analysing their wetting patterns. The rates of water emission, depth of placement, soil type, plant root distribution, root water uptake patterns (RWU), and distance from emitter, will all impact on the vertical (upward and downward) and horizontal movement of water.

To accomplish this a variety of tools are available to measure soil water content (SWC). These range from simple, inexpensive procedures for obtaining one reading, to expensive sensors capable of tracking SWC change with time.

In periods of peak evaporative demand the timing of SWC readings are critical, due to the interaction of irrigation water applied and concomittant removal by roots. If delayed too long after irrigation, RWU will change the increase in soil water content.

A comprehensive guide to 25 soil water monitoring products can be found in Charlesworth (2001) and additional features are explained in Coelho and Or (1996) and Bristow (1996). The methods for measuring the soil water status used in this research are discussed below.

Gravimetry

Gravimetric soil water content determination involves the weighing of a known volume of soil before and after drying. The mass loss and sample bulk density are converted to the water content of the sample expressed in volumetric terms eg cubic centimetres of water per cubic centimetre of soil.

Gravimetry is recognised as the simplest method for measuring SWC and is commonly used as a reference for other methods. However, non-standard methods may bring significant errors (Gardner, 1986). These include varying definitions of ‘dry soil’, drying temperature and duration, and weighing balance accuracy.

Tensiometry

Tensiometers measure water potential, or the amount of energy required to remove water from the soil matrix. A soil water characteristic curve is needed to convert water potential to water content.

A tensiometer consists of a sealed, water-filled tube with a porous ceramic cup on one end in contact with the soil. The porous cup allows water to pass into or out of the tube, depending on the hydraulic potential existing between the water in the tube and the soil. To measure the potential in the tube (= soil potential), either a direct reading dial or a rubber septum are placed in the closed end. A portable pressure transducer is used for those tensiometers with a rubber septum (Cresswell, 1993).

Neutron Scattering.

Neutron emitting radiation sources have been used to measure SWC since the late 1940's. Hydrogen nuclei have the distinct characteristic of thermalizing, or slowing, neutrons and it is this property which is utilised by the neutron scattering method, as most of the hydrogen in soil is associated with water molecules (Gardner, 1986). *Fast* neutrons are introduced to the soil where thermalization and deflection take place and a percentage return to the source where they are counted. The fact that the process relies on deflection means the volume of soil penetrated by neutrons varies with the proximity, or amount, of hydrogen atoms. Therefore the SWC determines the sphere of measurement. Van Bavel *et al*. (1956) found measurement radii ranging from 16 cm at saturation, to 70 cm for a near dry soil.

The method requires the installation of access tube, into which the radiation source is lowered. This means that after initial installation, measurements are non-destructive. As the process relies on the probability of capturing a percentage of the neutrons emitted, the accuracy of the reading is proportional to the reading duration. Acceptable accuracy was found for Riverina soils by using a single 32 second reading (Meyer, 1992).

Heat Dissipation.

The heat capacity of water (4180 J kg^{-1} K^{-1}) is significantly higher than that of soil (800-1000 J kg^{-1} K^{-1}). As the heat capacity of dry soil remains a constant, the heat capacity of the soil/ water whole is driven by water content.

A sensor employing this principle (Bristow *et al.* 1994) uses two needle probes inserted into the soil. One probe emits a finite quantity of heat and the second, a short distance away, records maximum temperature rise following the emission. The temperature rise is inversely proportional to the SWC.

Time Delay Reflectometry (TDR).

TDR relies on the dielectric of the soil/water/air system varying with SWC. The dielectric constant of pure water is 80, that of soil solids is 3 to 7, and that of air is 1. TDR measures the velocity of a signal along a transmission line or wave guide and this velocity varies with dielectric attenuation of the soil. The time taken for a signal to reflect back from the end of the wave guides is measured and relates inversely to the SWC (Dalton, 1992).

1.4 Automated Irrigation Systems

A major consideration when decreasing irrigation application is the increasing importance of management expertise. The problems facing irrigation areas show that irrigation scheduling must rely on more objective methods. Direct measurement of the soil or plant water status via an array of available equipment, is the best method to ensure accurate scheduling.

Phene (1996) uses the analogy of modern vehicle engines where recent gains in fuel efficiency have only been possible through the use of real time feedback systems, which continually adjust ignition timing and fuel mixture.

Having greater knowledge of the soil water status is only half the answer to greater irrigation efficiency. The irrigation system must be flexible enough to allow it to be controlled, to maintain optimal soil water content. A well designed pressure irrigation system allows for such control with the inclusion of solenoid operated valves and electronic timers.

Numerous researchers have electronically closed the loop between the soil water data acquisition and irrigation control networks to produce automated systems. A wide range of sensors have been used including soil matric potential (Phene *et al* 1973; Mears *et al,* 1979; Phene and Howell, 1981), plant heat dissipation (van Bavel, 1995), infrared sensing (Smith *et al.* 1989).

When relying on sensor-based irrigation four assumptions are being made : a) irrigation water is being distributed with a high level of uniformity, b) crop is of uniform size and distribution, c) water depletion from the soil is uniform and mostly by ET, and d) the soil water sensor is placed within a part of the root zone which is representative of the crop water extraction pattern (Phene and Howell, 1981).

In the first attempt at simulating an automated sub-surface irrigation system, van Bavel *et al* (1973) based their model on a layered soil profile using a water characteristic expression derived by Klute (1951) and assumed a constant hydraulic conductivity: water content relationship for all layers. Their model suggested that for light clay soil, a 2 hour irrigation time with 40 hours redistribution would maintain a constant soil water content in "average" demand conditions.

For a manager to rely on such systems the equipment must provide feedback on problems such as non-uniform sensor readings, flow fluctuations, and pressure variation. Thomson (1996) outlined a decision support system which 1) provided for sensor input comparison and identification of any sensor which was significantly different, indicating an equipment or installation fault, 2) used sensor data to determine root zone extent and adjust irrigation depth, and 3) output a water application confidence level based on the number of sensors used.

1.4.1 Sensor Placement

Sensor type and non-uniformity of water application, root water uptake and soil properties, must be considered when choosing the position of sensor installation for sensor-based irrigation scheduling systems.

Placing a water potential sensor in a zone of high root water uptake, may cause fluctuations beyond the instrument's maintainable tension range. Installing any sensor close to an emitter will result in readings insensitive to SWC change especially, as the frequency of application increases. The edges of the wetted zone will also show low variation in SWC due to lower rooting density.

The aims of sensor placement are 1) to define an effective source of plant available soil water and 2) to choose a site which shows an acceptable response time to both irrigation application and root extraction. Compromise can be made between sensor location and re-irrigation threshold (or setpoint) choice (Coelho and Or, 1996). Enhancement of response time can be made by placing the sensor closer to the water source, decreasing the irrigation threshold (re-irrigate at lower SWC) and lowering the irrigation volume (van Bavel *et al*, 1973).

1.5 Modelling Soil Water Flow

Solutions to the general flow equation have occupied many workers since the turn of the century (Hillel, 1980). When used as a part of agronomic modelling where *seasonal* changes are important, the programming complexity and data requirement of the general flow equation may be replaced with computationally simpler models. An example of these is SWAGMAN-Destiny® (Godwin and Meyer, 1995), a daily increment model which 'cascades' water between soil layers at a rate limited by the layers' hydraulic conductivity. At the seasonal scale this model performs as well as the WAVES (Dawes and Short, 1993) model which is based on the general flow equation (Zhang *et al,* 1997). However, the time scale relevant to soil water content changes during and between high frequency (<1 hour) irrigation scheduling, is measured in seconds and minutes. This scale is required to analyse the problem of SDI wetting extent, and the general flow equation is capable of handling very small time steps. Further complicating the system is the interaction between wetting and rooting patterns, as roots will grow where the soil is wet, and through extraction will change the wetted pattern (Coelho and Or, 1996).

The above models are one dimensional 'point' simulations. The HYDRUS-2D model simulates water movement in two dimensions (Simunek *et al*, 1995). The package consists of the SWMS-2D code (Simunek *et al*, 1994) for simulating water flow, heat and solute movement in two-dimensional, variably saturated media. Around this code is wrapped a Windows based Graphic User Interface to enable easy preparation of input files, database management, and graphic presentation of model results.

The program numerically solves the Richard's equation for unsaturated water flow using Galerkin-type linear finite element schemes. A separate program, MESHGEN-2D, is used for finite element mesh (FEM) preparation. Output options include text, graphs or animation of time-step, two-dimensional water content or pressure head distribution.

HYDRUS-2D uses either the van Genuchten equation (van Genuchten, 1980) (see section 1.5.2), modified van Genuchten (Vogel and Cislerova, 1988) or the Brooks and Corey equation (Brooks and Corey, 1964) for description of both the soil water retention [$\Psi(\theta)$] and conductivity function [$K(\theta)$] hydraulic properties. Material distribution, boundary and initial conditions and observation points are added directly to the FEM.

1.5.1 Modelling Water Flow from a Buried Source

One of the challenges facing proponents of SDI is a choice of installation depth and emitter spacing recommendation, with respect to soil type. The large expense of these systems means permanent SDI installation is far more desirable than single seasonal use, or the labour intensive practice of rolling up surface tape before/after harvest and reinstalling with the next crop.

Regression models have been developed to relate vertical upward water movement from SDI to irrigation timing (Slavin, 1980). However, these were very specific to the soil, emitter spacing, flow rate, and laboratory conditions used in the experiment. The study also concluded that shorter cycling produced greater wetted volume, as well as vertical height rise, in a given application time, thus improving water use efficiency. Cycles down to 1.5 hours were tested. With recent advances in irrigation automation technology, much shorter application times are now practicable. Phene (pers comm, 1997) recommends 30 minutes irrigation followed by 30 minutes redistribution to maximise the time the plant root zone spends in optimal water content, while minimising the risk of drainage.

Analytical solutions have been used to predict unsaturated water movement in the vicinity of buried sources. Oron (1980) introduced a sink term to the flow equation to represent simultaneous root water uptake. In seeking a process to aid drip irrigation design, Coelho and Or (1996) improved the plant uptake function by fitting a function which better described temporal and spatial changes in uptake intensity. Another approach developed for surface drip irrigation assumed the shape of the wetted zone to be a truncated ellipsoid, the dimensions of which became design objectives (Zur, 1996).

Models (and modellers) of the soil-water-plant system are faced with the omni-present dilemma of output accuracy *versus* input requirement. To assume the soil is homogeneous is extremely simplistic but to adequately describe three dimensional spatial variability requires a high data input.

For permanent SDI installation to be practical, the placement depth must be a compromise between being deep enough for cultural practices and shallow enough to allow for sufficient water to reach the rootzone through capillarity. Modelling of this system has potential to offer broad installation guidelines.

1.5.2 Parameter Requirement for Modelling Water Movement.

As previously discussed, the water retention or moisture characteristic curve and hydraulic conductivity *versus* head curve are of vital importance in investigating water flow through soil. The information is gained primarily through studying soil cores taken from the field into the laboratory using suction and pressure plate procedures similar to those described in Loveday (1974).

To represent this information in a form useable by water flow models which solve Richards equation requires its description by a function flexible enough to account for curve shape changes throughout the range of soil types, while relying on a small number of readily measured parameters. Some of these functions were listed previously. The van Genuchten functions (van Genuchten, 1980) for water retention and hydraulic conductivity are presented below (Equation 1.1 and 1.2),

$$\theta(h) = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{(1+|\alpha h|^n)^m} \quad h<0$$
$$\theta(h) = \theta_s \quad h \geq 0$$
Equation 1.1

$$K(\theta) = K_s \theta_e^{0.5}[1-(1-\theta_e^{1/m})^m]^2 \quad h<0$$
$$K(\theta) = K_s \quad h \geq 0$$
Equation 1.2

where : θ = water content (m^3 m^{-3})

K = hydraulic conductivity (m s^{-1})

K_s = saturated hydraulic conductivity (m s^{-1})

θ_r and θ_s = residual and saturated water content (m^3 m^{-3})

θ_e = effective water content = $\frac{\theta - \theta_r}{\theta_s - \theta_r}$

α = empirical constant (m^{-1})

n = empirical constant (-)

m = empirical constant = 1-1/n (-)

h = pressure head (m)

The empirical constants are fitting parameters which affect the shape of the curve.

There are two methods for deriving these parameters. Firstly, they can be obtained by fitting the function to measured water retention data. The RETC (RETension Curve) (van Genuchten *et al*, 1991) computer code uses a nonlinear least-squares parameter optimisation method for estimating these values. Secondly, the parameters can be made unknowns and solved for by using the general flow equation to simulate a flow experiment, this technique is commonly called 'inverse modelling'.

1.6 Uniformity of Water distribution

Two types of water application variation occur in drip irrigation pipe, i) emission rate differences between individual emitters and ii) uniformity variation in the row space between two emitters. Inter-emitter variation is caused by head (or friction) loss or blockage. The following equation (Burt and Styles, 1994) is used to describe this difference in *distribution uniformity (DU)* and is the standard parameter by which drip systems are designed :

$$DU = \frac{Average\ low quarter\ of\ water applied\ to plants\ in\ a field}{Average\ depth\ of\ water applied\ to plants} \quad \text{Equation 1.3}$$

The amount of water applied is calculated from emitter flow rates measured at various points in the dripper line. The DU is a measure of the uniformity of emitter flow rate.

As drip irrigation pipe is a collection of point sources in series, there will be differences in application rate and amount in the row space between the emitters. Such difference is not covered by the DU calculation. The variation will be greater with wider spaced emitters and coarser textured soil. In fact, with current design criteria, a system's DU will remain constant whether it is placed in sand, clay or on bitumen. Appropriate drip product design (emitter spacing and flow rate) incorporates knowledge of the soil texture but must use an average value, as textural changes within a row cannot be accounted for.

1.7 SDI 'Amendments'

A number of materials have been used to enhance water movement in soil either attached to an SDI product or as an addition to the water.

As previously stated, there is potential for SDI to increase drainage below the root zone, particularly in coarse textured soils or where irrigation management is less than optimal. This is due to the decreased 'infiltration opportunity depth' ie. the depth between the drip tube and the bottom of the root zone. Exacerbating this problem is the fact that the elliptical patterns for root water uptake and SDI wetting are opposite. Approximately 40% of a plants total water extraction occurs in the top 25% of the root zone (Hung, 1994) whereas the dominating gravitational component of soil water movement ensures greater water content beneath the irrigation source (see Figure 1.4).

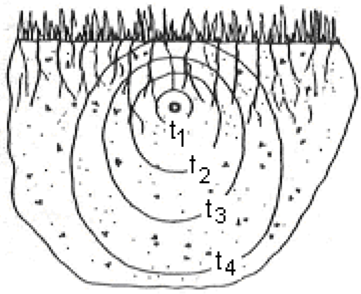


Figure 1.4. Typical wetting pattern of SDI in sandy loam soil (Welsh *et al,* 1995).

1.7.1 Polyethylene

The use of a V-shaped, continuous sheet of PE under the drip tube has the potential to increase the saturated zone width and volume above the drip line and provide a barrier to downward water movement (Welsh *et al,* 1995, Barth, 1999). This configuration increases the time water can move upwards and outwards through capillarity from the saturated area, before downward movement dominates. A small benefit (higher and wider wetted zone) was reported through the use of a 0.15 m wide polyethylene (PE) strip (Brown *et al*, 1996). With efficient scheduling, the saturated area could be limited to the extent of the PE underlain area resulting in a high proportion of the water moving by capillarity (Figure 1.5).

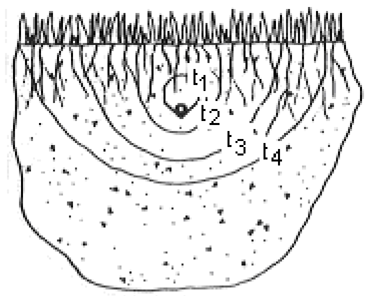


Figure 1.5. Potential change in wetting patterns through use of impervious polyethylene underlay (Welsh *et al,* 1995).

1.7.2 Geotextile

Geotextile is a generic name for materials made of woven or non-woven synthetic fibres with primarily engineering applications. Koerner and Bove (1987) state five functions for which geotextiles are used :

1. Separation eg. fine material from coarse material.
2. Reinforcement eg. dam banks.
3. Filtration eg. retain larger aggregates.
4. Drainage eg. beneath sport fields.
5. Moisture barrier eg. beneath road surfaces.

As geotextiles are primarily used in contact with soil, attempts have been made to describe water flow in terms of the soil hydraulic properties. Van der Sluys and Dierickx (1987) found Darcy's Law was not applicable to geotextile as flow was found to be turbulent and not laminar. They recommended expressing the transmissivity characteristic of geotextile as a flow rate for a given hydraulic head.

The readily compressable nature of geotextiles results in a large initial effect on transmissivity caused by loading stress, such as would occur when placed under soil. A plateau transmissivity is reached where further stress has little effect on transmissivity. This value is a function of textile thickness (Koerner and Bove, 1987) and can be 10^5x higher than a medium textured soil. It is the high transmissivity of geotextile which may be exploited as an amendment to drip products, by moving water quickly away from the drip emitters, potentially producing a more diffuse source.

1.7.3 Gypsum

In-solution gypsum is usually used as an irrigation water treatment where low soil water electrical conductivity (EC_w) (<0.6 dSm^{-1}) is limiting infiltration (Burt and Styles, 1994). Gypsum injection machines were first used in California in the late 1980's to treat infiltration problems. These problems were caused by high quality water (low EC_w) being used on undisturbed, low organic content soils. The machines were introduced to Australia in 1996, and have achieved success particularly in areas of sodic soil (Schulz, 1998). Loveday (1976) reported a 3-fold increase in hydraulic conductivity after top-dressed gypsum was applied to a soil of higher clay content in the Griffith area. However, he was using surface applied water. He concluded this improvement was mainly from an increase in electrolyte concentration.

1.8 Summary of Review

A summary of the literature review brings out the following main points.

SDI has great potential to decrease the amount of water we use to produce food and fibre crops. To ensure we maximise the efficiency of these systems, some basic improvements need to be made to currently available products and management practices :

1. Water application rates per unit soil area must be low enough to support ‘slow’ wetting of the soil, thus protecting the stability of soil aggregates. Low application rates per unit soil area may be attained by either specifically producing low flow emitters or by rapidly distributing water from higher flow emitters over larger areas before water enters the soil.
2. Control systems must include real-time sensor feedback and be flexible enough to maintain optimal soil water conditions at all stages of crop development.
3. Knowledge of soil hydraulic properties should be incorporated into the initial system design for flow rate and emitter spacing. This will extend the design criteria past a ‘system emission’ uniformity to a ‘soil receival’ uniformity.
4. A need exists for improved understanding of how system variables such as flow rate and irrigation pulsing, affect water distribution in different conditions. Conversely, products need to be developed that increase inter-emitter uniformity and lateral water movement while protecting against deep percolation.
5. It is an unfortunate point that a system which has such great potential to save water and is so poor at establishing a crop, that other systems (eg portable sprinklers) are used for this initial stage. Research is required to address this issue.

It is these challenges which the research topic will address.

1.9 Research Topic

Capillary Root Zone Irrigation (CRZI™) is a new SDI concept. The product attempts to modify a standard drip tape from being a point source to a line (or diffuse) source. It seeks to produce a wider lateral wetting pattern and greater uniformity between drippers, while reducing drainage beneath the root zone.

The product utilises the two SDI amendments introduced in the literature review in the following configuration :

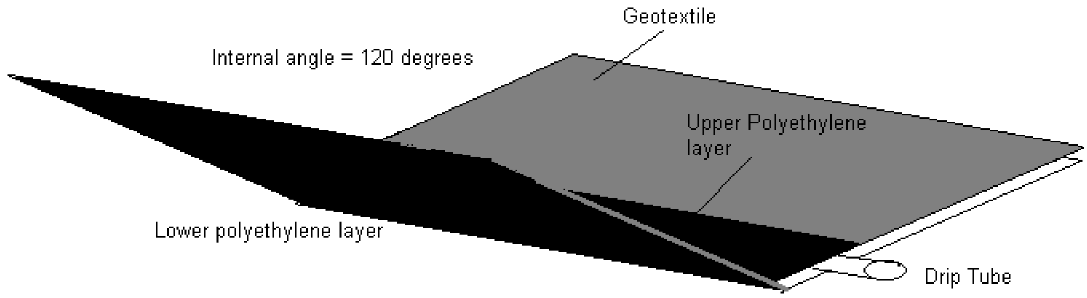


Figure 1.6. CRZI Configuration.

The V-shaped product consists of a drip tube in between an upper layer of geotextile and an underlying layer of PE. The underlying PE layer maintains a reservoir of saturated soil within the 'V'. As explained in the previous section this soil water is available to move upwards and laterally from the reservoir while the PE layer reduces the downward component of water movement. The role of the geotextile layer is to move water quickly away from the emitter lateral to the dripline and towards the inter-emitter zone, creating a larger and more uniform infiltration area, independent of soil type. The upper PE layer serves to further spread water exiting the emitters and direct water away from the soil zone disturbed by installation.

This is a novel technique with potential to overcome many of the constraints faced by conventional SDI. Potential advantages are :

1. Greater inter-emitter and lateral water flow.
2. Reduced deep percolation losses.
3. Promotion of more stable soil structure.
4. More predictable results irrespective of soil type.
5. Better crop establishment.
6. More robust product with longer service life.

Potential disadvantages may be :

1. Greater initial financial investment.
2. Difficult to install.
3. Difficult to remove and greater mass to be disposed of.
4. Barrier to root growth. Roots may intrude into emitters causing blockage.
5. Increased risk of waterlogging.
6. Presence limits cultivation options.

2 General Objectives

In assessing the CRZI configuration there are essential goals which must be met in order to determine if the product will provide significant benefits over currently available SDI methods. These goals form the basis of the planned experimental schedule. The research was performed in four phases, commencing broadly and following an ever focussing path :

1. *Irrigation System Experiment*

   A broad range of SDI products were compared under field conditions with long row lengths. In addition to annual crops, a vineyard was established to allow comparison of longer term installations used with a perennial crop.

   The experiment was designed to :

   i. Compare irrigation distribution uniformity of chosen systems.
   ii. Examine root intrusion potential in CRZI.
   iii. Compare yield and water use efficiency between treatments.
   iv. Examine potential of products to cause tunnelling.

2. *Water Use Efficiency Experiment*

   The water use efficiency of CRZI and Drip Tape were compared using a higher level of irrigation management. The experiment was designed to :

   i. Construct an irrigation control system with sensor feedback that allowed flexible water management.
   ii. Measure crop establishment.
   iii. Compare the Water Use Efficiency of each crop stage between different configurations of the two product's

3. *Crop Establishment Experiment*

   To test each products ability to address the critical establishment phase of crop development this experiment was designed to :

   i. Measure differences in the extent of wetting patterns between several SDI configurations and installation depths.
   ii. Evaluate subsequent success in crop establishment.

4. *Extension of Problem Analysis*

All the field experiments were undertaken on the same soil type and concentrated on comparison with other irrigation systems and identifying processes affecting the performance of CRZI. The fourth phase of the project used a computer modelling approach to address the soil type and irrigation schedule choice to optimise the amount of water applied and shape of wetting pattern. The modelling was designed to :

i. Compare the soil wetting patterns of CRZI and Drip Tape in soil types other than those used in the field experiments.
ii. To consider the effect of irrigation pulsing and flow rate on the wetting distribution.

3 General Methods - Site Details and Product Description

3.1 Site Map

All experiments were performed in Field 1200 (Appendix, Figure 12.1) located at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Land and Water Laboratory, Griffith, New South Wales (34^{o}17'S, 146^{o}03'E, 130 m above mean sea level). The field was tile drained with lines 1.8 metres deep and 50-60 metres apart.

3.2 Soil

The soils in the Griffith area are predominantly red-brown earths. Red-brown earths are described as having differentiated horizons, represented by clay accumulation and presence of calcium carbonate in the illuvial horizons (Northcote, 1981).

Two soil types were represented in the field where the trials were undertaken :

3.2.1 Hanwood Loam

Hanwood Loam is characterised texturally by a light, loamy surface soil of 0.15-0.25 m thickness, a light clay subsoil extending to approximately 0.7-0.8 m, underlain by a sandier deep subsoil. Colour lightens from brown surface to light brown subsoil. A moderately low carbonate content exists below 0.5 m depth.

3.2.2 Yandera Loam

The main variations to the Hanwood Loam description is that Yandera Loam exhibits a grey, brown, yellow and rusty mottling in the subsoil clay layer and a lighter coloured, bleached sand deep subsoil (Butler, 1979).

3.2.3 Soil Survey

A soil survey was performed for the Water Use Efficiency experimental site (Appendix, Figure 12.1). Measurements included particle size analysis, electrical conductivity, and hydraulic properties.

Electrical conductivity

Electrical conductivity was measured using an EM38 instrument. Measurements were taken on a 10 m x 10 m grid for the 90 m x 50 m plot size. Salinity readings were calculated from the raw EM data using a calibration equation published by Slavich (1992).

The EM 38 survey indicated soil salinity levels (estimated electrical conductivity of the saturation extract ECe) ranging from 0.8 - 2.0 dSm^{-1} with most of the block below 1.5 dSm^{-1} (Figure 3.1). A level of 2.5 dSm^{-1} for the threshold above which yield decline may occur has been stated for cucumbers *(Cucumis sativus)* (Maas, 1990). Of particular interest is the narrow zone of low salinity which runs North/South down the 30 m line. Further examination revealed this to be a tile drain. Another drain should have been located at the 80-90 m mark but may have been blocked. From this data it was decided to avoid situating crop rows above the tile drain, as this may have biased the rows towards greater drainage.

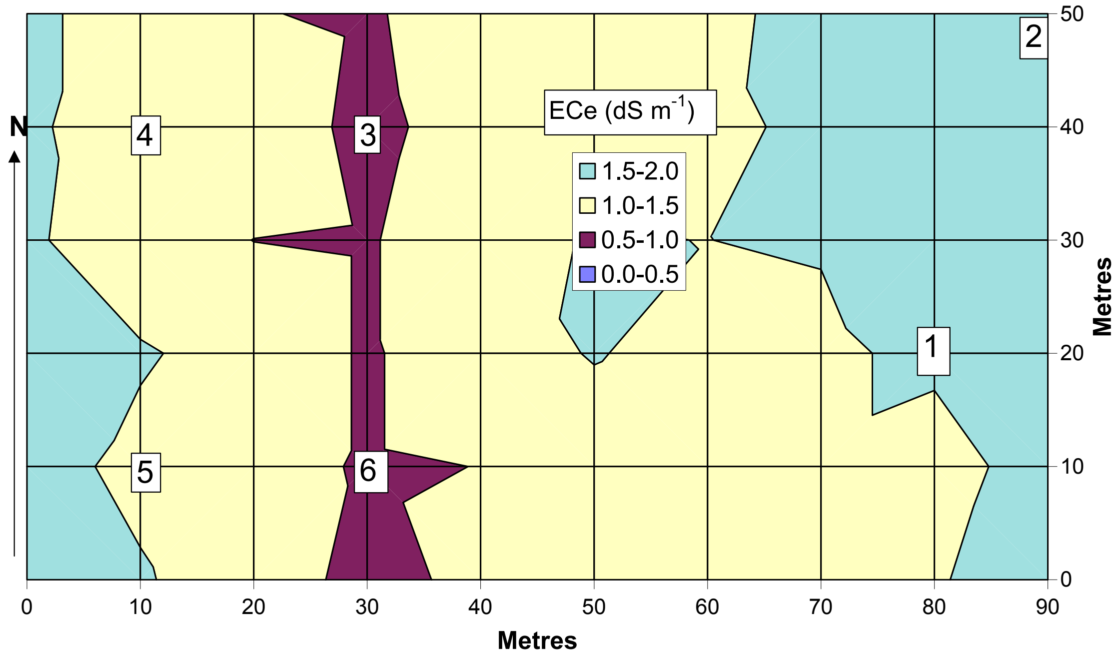


Figure 3.1. Field salinity survey from EM 38 data for Water Use Efficiency experiment site. Numbers indicate site of subsequent soil sampling.

Particle Size Analysis.

Six sites were selected from the resulting salinity contour plot. One soil core was taken at each site to a depth of 1m and separated into 0.1 m increments. A particle size analysis (PSA) was completed for each sample using the hydrometer method (Gee and Bauder, 1986).

The major feature of the mean PSA is the layer of higher clay content 0.4-0.65 m deep. The upper (0-0.4 m) and lower (0.7-1 m) show similar sand/clay percentage ratios of 70%/20% whereas the middle layer (0.4-0.7 m) has a mean sand/clay percentage ratio of 60%/35% (Figure 3.2).

This clay layer has important implications as water may tend to form a perched watertable above it and serve to even out differences between treatments.

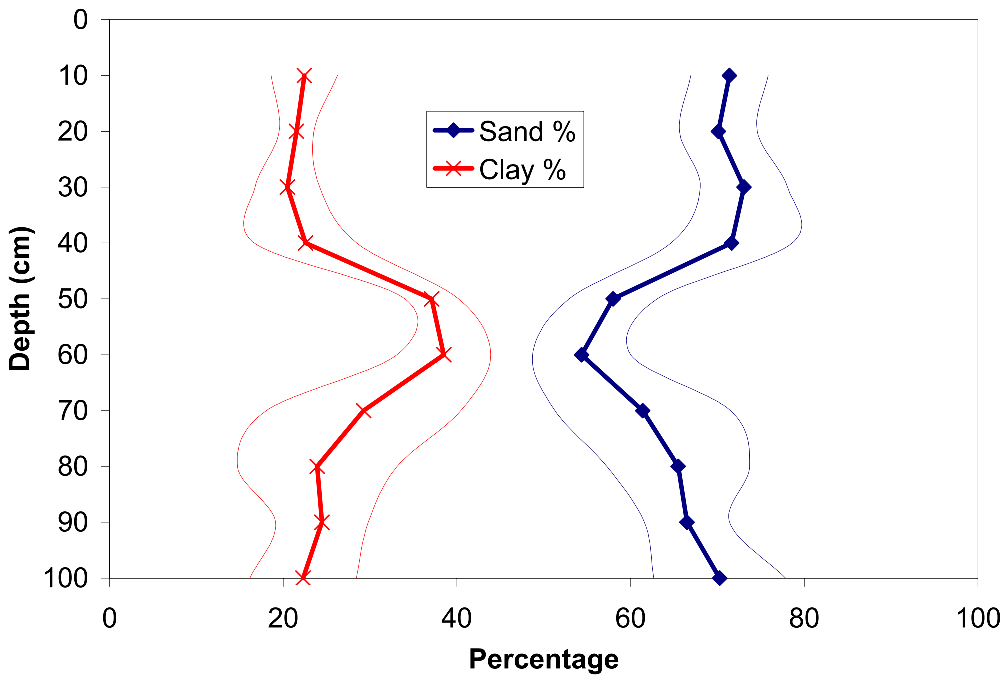


Figure 3.2. Water Use Efficiency trial site soil particle size analysis, with standard deviation envelopes.

Hydraulic Properties

To determine the hydraulic characteristics of the soil, a trench was dug and samples were taken with respect to the PSA. The profile as viewed from the trench appeared to be offset by approximately 0.2 m when compared with the spatially averaged, particle size analysis profile. Soil cores were taken by 50 mm diameter, 100 mm deep brass rings inserted vertically, using a drop hammer. Four cores were taken at each of three depths (0-0.1 m, 0.3-0.4 m and 0.6-0.7 m). These samples were analysed by suction/pressure plate methods (Klute and Dirksen, 1986) to give water retention properties at -1, -5, -10, -33, -60, -100, –500, and –1500 kPa. Cores were also placed on a 30 mm sand column and a disc permeameter was used to determine hydraulic conductivity at this potential (0.3 kPa).

After taking into account the 0.2 m offset discussed in the previous paragraph, the hydraulic properties of the different layers (Figure 3.3) match the data from the particle size analysis. The higher clay content of the middle layer results in a higher water content than the top and bottom layers at all tensions. It also exhibits a slightly lower initial gradient, indicating a greater proportion of smaller pore sizes.

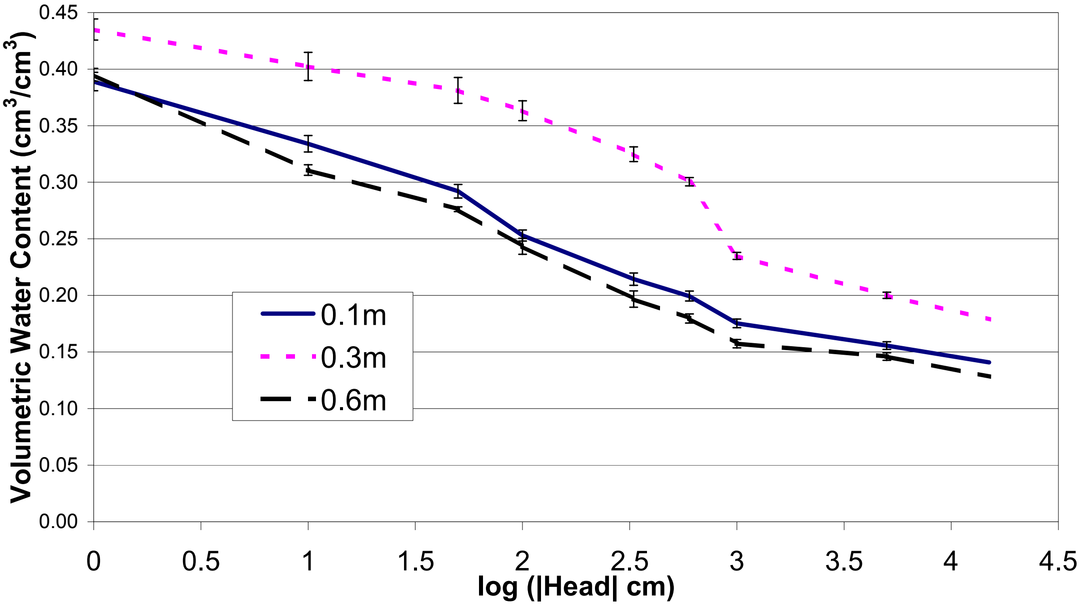


Figure 3.3. Soil water retention curves for trial site.

3.3 Climate

Griffith's climate may be described as semi-arid or 'Mediterranean' with hot summers, mild winters and a fairly even rainfall distribution (Table 3.1). June is the only month in which average rainfall exceeds reference evapotranspiration.

Hourly reference evapotranspiration (ETo) is calculated at the CSIRO weather station using the modified Penman formula, with Meyer wind function coefficients (Meyer, 1998).

Table 3.1. Mean monthly climate data (1962-92) from CSIRO weather station, Griffith, NSW.

Month	Max. Temp (^{o}C)	Min. Temp (^{o}C)	ETo (mm)	Rainfall (mm)
January	31.8	16.1	263	30
February	31	15.9	220	29
March	28.1	13.5	178	35
April	23.1	9.2	103	35
May	18.4	6.1	59	36
June	15	3.8	35	37
July	14.2	2.9	40	32
August	16.2	3.9	67	36
September	19.5	5.6	104	32
October	23.2	8.7	168	41
November	26.9	11.7	219	27
December	29.9	14.3	247	28
Total			1703	396

3.4 Capillary Root Zone Irrigation (CRZI) Product Summary

The CRZI product concept intended to both extend the lateral wetted width and improve the inter-emitter distribution uniformity of subsurface drip irrigation, while minimising drainage. A combination of materials was used in CRZI to achieve these objectives. Drip irrigation pipe is sandwiched between a 0.3 m wide impermeable polyethylene (PE) base and a geotextile overlay (Figure 1.6). The product was installed at the required soil depth in a 'V' shape with internal angle of approximately 120^{o}. The aim of the impermeable base was to maintain a small saturated zone, while minimising drainage past the root zone. The geotextile was a woven synthetic material of very high hydraulic conductivity. Its role was to move water rapidly away from the emitter, both along and perpendicular to the pipe, producing an *area* distributed water source, as opposed to a *line* or *point* source.

Summaries of CRZI configurations and pipe specifications that evolved during this research are shown in Figure 3.4 and Table 3.2.

Prototype 1 – "Perforated Pipe"

The first prototype used 19 mm diameter polythene pipe with drilled emitter holes. The hole diameter of 2.38 mm was large enough to reduce the need for expensive filtration. The emitter diameter resulted in a large flow rate of 15 L hr^{-1} at the nominal pressure. This was seen as a low cost product, easily manufactured, which may have application in developing countries where row lengths are generally shorter.

Prototype 2 – "Low Flow"

All subsequent versions used Drip Tape as the water source. This allowed CRZI to take advantage of the considerable technical information provided for this product. This information outlines emitter distribution uniformity (DU) variation, with respect to emitter flow rate, spacing and row length.

The Drip Tape used in the 'Low Flow' product was the manufacturers recommendation to provide 95% DU over a 200m length, using an emitter flow rate of 1.1 L hr^{-1} and Specific Discharge Rate (SDR) of 3.4 L $hr^{-1}m^{-1}$. This was the only prototype to have used two lines of Drip Tape.

Prototype 3 – "High Flow"

This prototype was designed to direct as much water as possible into the geotextile (as opposed to infiltrating directly in to the soil) through exploiting its high transmissivity, and thus enhancing inter-emitter and lateral distribution. To achieve this, a Drip Tape with high emitter flow rate (4 L hr^{-1}) and SDR of 8 L $hr^{-1}m^{-1}$ was chosen.

Prototype 4 – "Upper PE"

For the final prototype a 0.15 m polyethylene strip was added above the geotextile. The goal here was to dissipate water away from the emitter and the zone of soil disturbed during installation, while still using a low flow rate emitter. This was accompanied by a reduction in SDR to 5 L hr^{-1} m^{-1}.

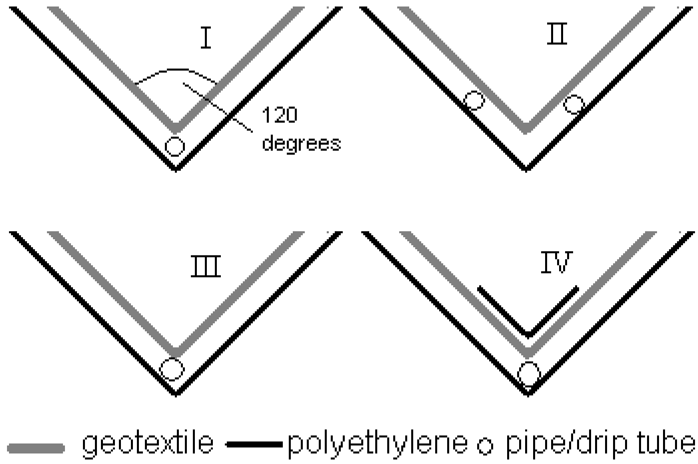


Figure 3.4. CRZI prototype evolution summary.

Table 3.2. CRZI prototype configuration and identification summary.

Prototype Name	Pipe Type	Emitter Spacing (m)	Nominal* Emitter Flow Rate (L hr^{-1})	Specific Discharge Rate (L hr^{-1} m^{-1})	Upper PE Barrier
1. Perforated Pipe	19 mm Polythene	3	15	5	No
2. Low Flow	22 mm T-Tape (TSX 710-30-340)	0.3	1.1	3.4	No
3. High Flow	16 mm T-Tape (TSX 510-50-800)	0.5	4	8	No
4. Upper PE	16 mm T-Tape (TSX 510-20-500)	0.2	1	5	Yes

* Flow rate stated for nominal pressure of 10 m

3.5 SDI Products Used for Comparison

Two commercially available products were used as comparison with the CRZI configurations :

3.5.1 Subsurface Irrigation Pipe

Subsurface Irrigation Pipe (SIP) is a corrugated plastic pipe with approximately 90 large holes per metre (Figure 3.5). The pipe is better known as a drainage product and is referred to as Draincoil or AgPipe. It was first used as an irrigation supply source in 1989 at CSIRO Horticulture, Merbein, Victoria (Clingleffer, 1996, pers comm). The product was introduced into the Murrumbidgee Irrigation Area (MIA) by growers in 1996. Approximately 60 ha were installed in the MIA in the 1996 season, almost exclusively in grapevines. All installations have used 50 mm diameter pipe. The main driver for use of SIP is that it is not pressurised and does not require filtration.

3.5.2 Drip Tape

Drip tape is a thin-walled plastic tube with evenly spaced non-pressure-compensating emitters in the form of slits or holes. Two tube diameters were used in the project, 22 mm and 16 mm with emitter spacing ranging from 0.2 – 0.5 m, and flow rate ranging from 1.1 – 4 L hr^{-1}. The brand used was T-Tape®.

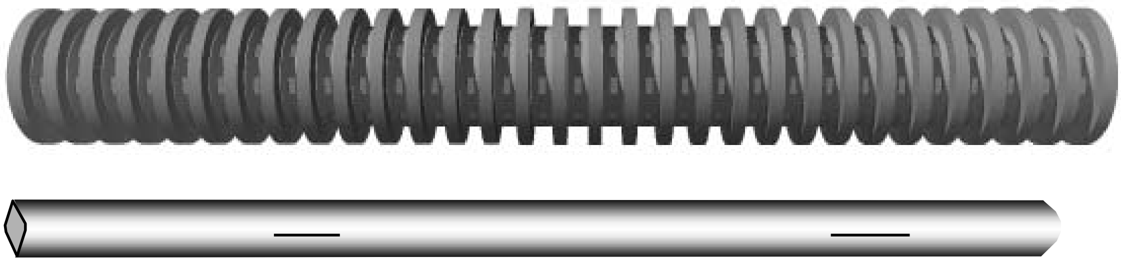


Figure 3.5. Subsurface Irrigation Pipe (SIP) (top) and Drip Tape (bottom).

3.5.3 Installation

The treatments were installed using three non-commercial pieces of equipment designed specifically for each product. The basic principle followed by each machine was for the irrigation pipe to be fed into a hole created by a metal foot, travelling at the desired soil depth (Figure 3.6). The large width of CRZI required special consideration. Two versions of the installation machine were used. The first prototype created a 0.3m trench at the front, laid the CRZI and, then refilled the trench at the rear. This method lead to great soil disturbance and required a high powered tractor to pull the machine through the soil. A major improvement in the machine configuration resulted in the product being folded and inserted into the soil via a small slot, similar to that from a Drip Tape machine. A wing on the base of the insertion foot then opened out the product at the installation depth.

Figure 3.6. Buried irrigation pipe insertion machinery. CRZI (left), Drip Tape (middle), SIP (right).

4 Irrigation System Experiment

4.1 Introduction and Objectives

The Irrigation System Experiment was the first large-scale field experiment using CRZI technology. Computer simulation had provided all previous understanding of CRZI performance (Kirby *et al*, 1996; Kirby and Knight, 1996). The experiment compared the performance of CRZI with that of other commercially utilised systems.

Objectives :

i). Compare the uniformity of water distribution along several sub-surface drip irrigation systems in the field.

ii). Examine root intrusion in CRZI in the field.

iii). Compare the production and water use efficiency of sweet corn grown with each irrigation system.

iv). Examine potential of products to cause tunnelling.

4.2 Methods

4.2.1 Treatments

Treatments (Table 4.1), five beds wide, were replicated in two blocks (see Appendix Figure 12.2). Beds were spaced at 1.83 m and were 200 m long.

Table 4.1. Treatments in the Irrigation System Experiment.

Treatment	Emitter Spacing (m)	Nominal Emitter flow rate (L hr^{-1})	Installation depth (m)
CRZI 'Perforated Pipe'	3	15	0.3
Drip Tape	0.3	1.1	0.15
CRZI Low Flow	0.3	1.1	0.3
Subsurface Irrigation Pipe (SIP)	90 holes per m	Soil infiltration rate	0.3

4.2.2 Soil Conditions Prior to Crop Sowing

Prior to the commencement of irrigation the soil had been subjected to 6 cultivations, including furrowing and bed-forming operations to create a tilth fine enough for seed establishment.

Weather conditions prior to and at the time of the paddock operations were drier than average and produced a 15% higher than average evaporative demand (Table 4.2).

The combination of high disturbance during a period of low rainfall and high evaporation contributed to the soil being both extremely dry and loose. The size distribution of aggregates was poor, with a large proportion of dust and 10-20 mm diameter clods with little in between. The mean seed bed soil water content was 0.03 cm^3cm^{-3}, while the bulk density was 1.24 g cm^{-3}.

Table 4.2. Weather conditions prior to irrigation in late December 1996.

	Sept		Oct		Nov		Dec		Totals
	Actual	Mean*	Actual	Mean*	Actual	Mean*	Actual	Mean*	Act./Mean
Max Temp (°C)	19.5	19.1	23.2	23.8	26.9	25.3	29.9	29.75	
Rain (mm)	27	32	32	41	24	27	23	28	106/128
ETo (mm)	124	104	193	168	240	219	301	247	858/738

* 30 years

4.2.3 Crop

Sweet corn was chosen as the first annual crop due to it being ideally suited to the district and season. Hybrid sweet corn (*Zea mays* cv Jubilee) was first sown on 20th Dec 1996 at a rate of 75,000 seeds per hectare (14 seeds per row metre) in two rows 450 mm from the bed centre (see Appendix, Figure 12.3). Depth of seed placement was 15 mm. To prevent soil borne insect damage, Lorsban was applied as a banded spray beneath the seed at the rate of 0.75 L ha^{-1}. Atrazine (3 kg ha^{-1}) was used to control broadleaf weeds.

Crop establishment was attempted using the buried irrigation systems but lateral wetting was insufficient to attain suitable emergence. The crop was then killed with a broad spectrum herbicide (glyphosate 3 L ha^{-1}) and replanted on 16th Jan 1997. The second crop was furrow irrigated until 24th Jan 1997 resulting in a good crop stand. Irrigation then reverted to the buried treatments.

A commercial harvest was carried out on 4th Apr 1997 (79 Days After Sowing) followed by a dry matter harvest on 14th May 1997 (118 DAS).

4.2.4 Irrigation Supply System

Water to the site was pumped from a concrete lined dam. Filtration was provided by a Filtomat® (Amiad, Eltham, Victoria) automatic self cleaning filter fitted with a 100 micron/ 150 mesh fine screen. A pressure regulator was set to maintain a constant 100 kPa to the whole field site.

An 80 mm PVC submain supplied the site with offtakes for each experiment. Each offtake was equipped with a gate valve and 32 mm flow meter and served two treatments (Figure 4.1). Only one treatment per offtake was operated at once, to ensure accurate flow meter measurement of actual volume delivered per treatment. Each lateral was controlled by a manually operated polythene tap.

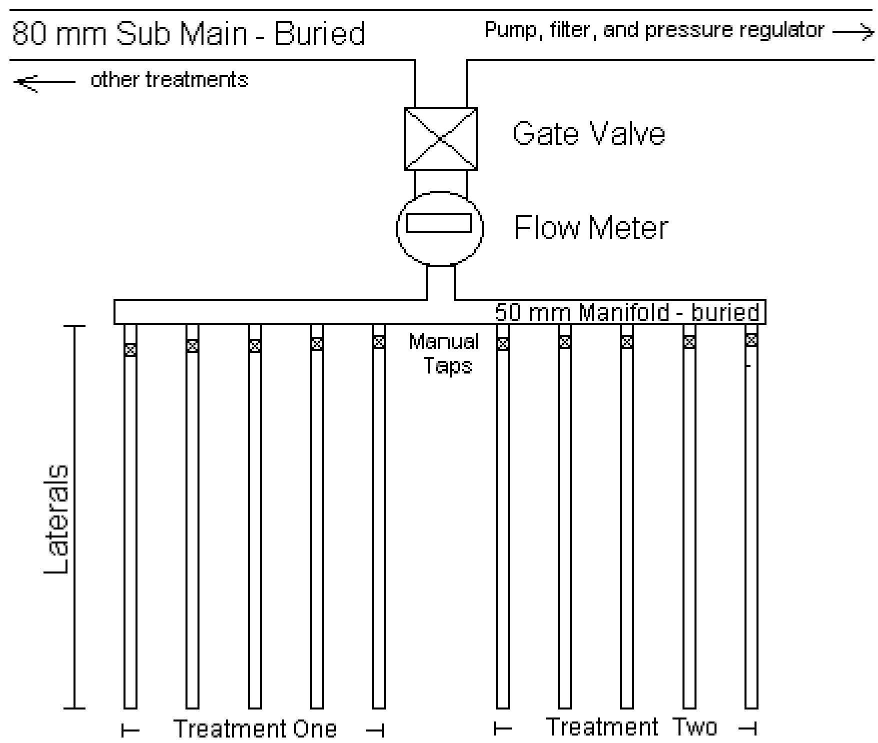


Figure 4.1. Submain, flowmeter, manifold, and lateral layout used in Irrigation System Experiment.

4.2.5 Soil Water Monitoring

A neutron probe soil moisture meter (NMM) (CPN Corporation, Martinez, California, USA) was used to monitor soil water content (SWC) throughout the trial. Aluminium access tubes (50 mm OD) were installed at a distance of 10 m, 100 m and 180 m from the supply in one bed per treatment of Block 1. At each of these positions tubes were placed 0.15 m, 0.3 m and 0.6 m from the centre of the row giving a total of 36 tubes (see Figure 4.2). The neutron probe was set to take readings, each with a duration of 32 seconds, at 0.1, 0.2, 0.3, 0.4, 0.6, 0.8, 1, and 1.2 m. Readings were taken before and after each irrigation throughout the season.

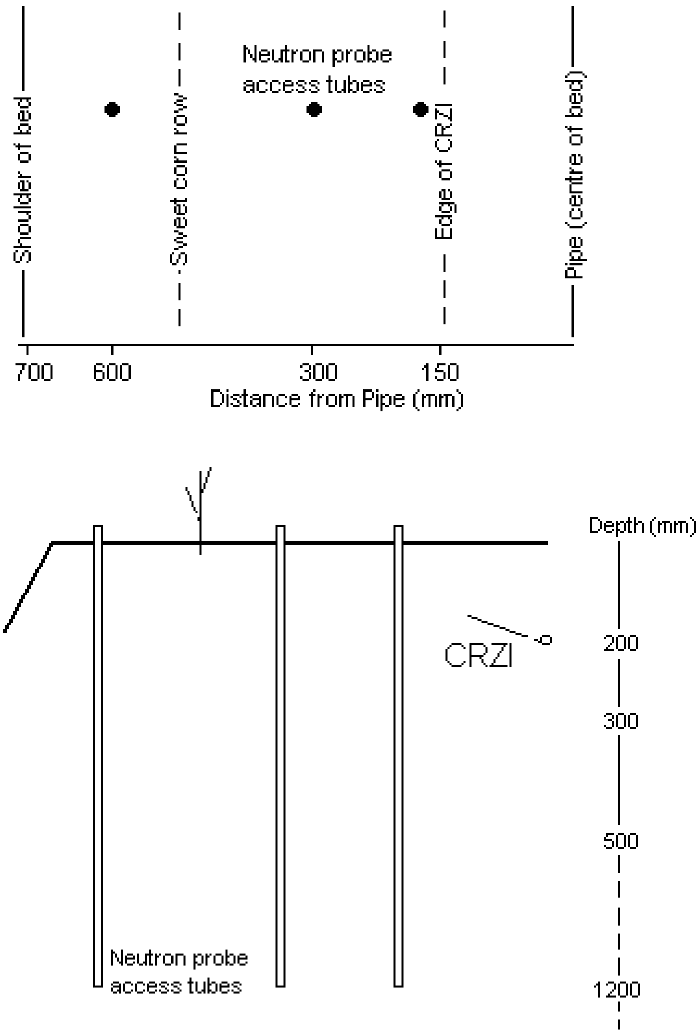


Figure 4.2. Plan (top) and side elevation (bottom) views of neutron probe installation in relation to bed, crop and pipe placement.

4.2.6 Crop Water Balance

A crop water balance was derived from soil water content, flow meter and weather data. Water inputs and outputs were balanced as such :

$$I + R = ETc + D \pm \Delta\theta \qquad \text{Equation 4.1}$$

where : I = irrigation (mm) ETc = crop evapotranspiration (mm).

R = rainfall (mm) D = Drainage (mm).

$\Delta\theta$ = Soil water content change (mm).

Drainage, being the only unknown, included the error in measurements associated with other components and unmeasured runoff, that was considered to be small. Rainfall and irrigation were measured with good confidence, however, ETc was estimated assuming both a healthy, uniform crop and an accurate method of ETo (potential ET) calculation. ETo was computed from weather data collected from the nearby CSIRO weather station.

Profile water content was calculated using SURFER (Golden Software, Golden, Colorado, USA) graphing software. Two dimensional contour plots were interpolated from the neutron probe data (Figure 4.3). The area of each contour interval was then multiplied by the water content. These figures were summed and divided by the total profile area to give a depth equivalent :

$$Profile\ Water\ Content\ Depth\,(cm) = \frac{\sum (\ Contour\,Volume_{1..n} * \theta\ v_{1..n})(cm^3)}{Surface\ Area\,(y*x)\,(cm^2)} \quad \text{Equation 4.2}$$

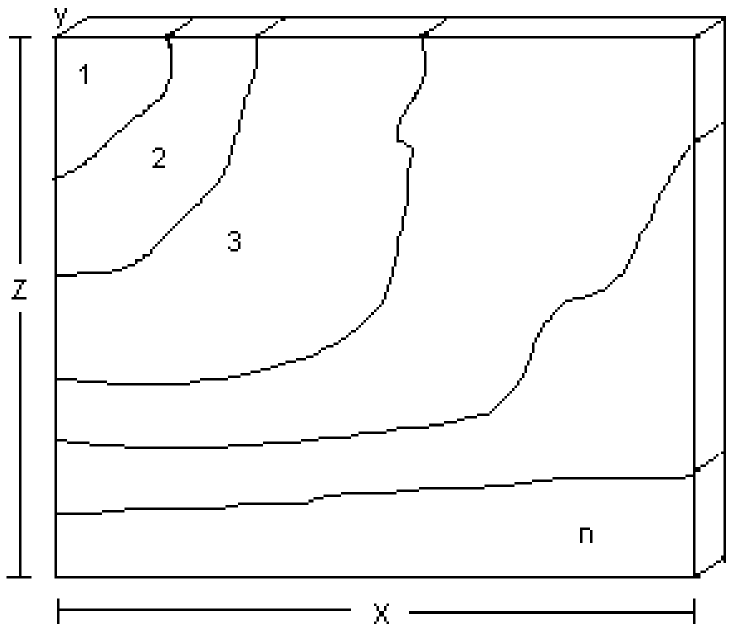


Figure 4.3. Generic example of SURFER 2-D soil water content plot.

4.2.7 Crop Monitoring

Measurement Positions

Given the large hole spacing used in the CRZI 'Perforated Pipe' product, the distribution uniformity between holes was of particular interest. To quantify this variation, establishment and yield measurements were taken in the areas both surrounding the hole and surrounding a point midway (1.5 m) between holes. One metre of crop bed (0.5 m each side) was measured at each point and equivalent points were measured in each treatment (Figure 3.4).

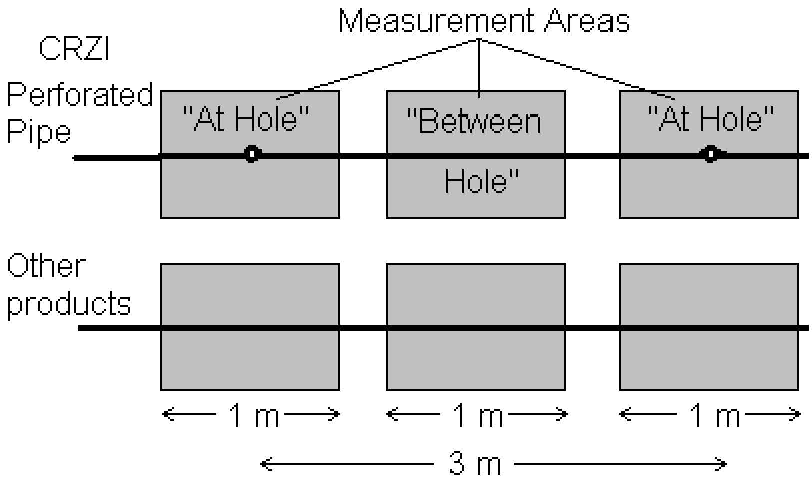


Figure 4.4. Crop sampling positions relative to CRZI 'Perforated Pipe'.

Establishment

Total established plants were counted after each of the two irrigation attempts - crop one on December 30 (10 DAS) and crop two on February 6 (20 DAS). Measurements were taken every 12 metres down the centre bed of each treatment. At each point readings corresponding to "AT HOLE" and "BETWEEN HOLE" positions in the CRZI 'Perforated Pipe' treatment were taken.

Suspected salt damage caused plant death in the lower portion of the SIP and CRZI Low Flow treatments in Block 2. In this confined area counts of both emergence and survival were recorded.

Harvest

A commercial harvest was carried out on 4th April 1997 (79 DAS) followed by a dry matter harvest on 14th May 1997 (118 DAS).

Yield measurements were taken relative to the 'At Hole' and 'Between Hole' positions in the CRZI 'Perforated Pipe' treatment. To quantify the effect of treatments on the yield uniformity along the irrigation pipes, samples were taken 1/3 (66 m) and 2/3 (133 m) from the supply end in one bed per treatment. In the CRZI 'Perforated Pipe' treatment plants 0.5 m either side of 3 consecutive holes were harvested. An equivalent 3 metres of bed length was harvested from all other treatments. The CRZI 'Perforated Pipe' 'Between Hole' position (0.5 m either side of the mid-point between holes) was also harvested in the same manner.

Only cobs were removed during the commercial harvest. These were weighed fresh and a sub-sample of 16 cobs was dried to derive a fresh/dry weight relationship.

The end of season dry weight harvest involved counting the number of plants in a six metre bed length and reaping a 10 plant sample, adjacent to the areas harvested in the commercial harvest. These samples were separated into corn kernel and cob core, plant stem and leaves, dried and weighed. The sample weights were multiplied by the number of plants to give an area weight equivalent to that used in the commercial harvest.

4.3 Results and Discussion

4.3.1 Visual Wetting Patterns

Water reached the surface from the drip tape in a series of small point sources which quickly joined and moved outwards to form the quite uniform wetting pattern seen in Figure 4.5b. Some free water was observed on the surface. The photograph also shows that had the seed been planted 0.1 m closer to the bed centre, a much improved establishment would have resulted.

The following observations were made and are discussed further in subsequent sections.

The SIP surface wetting pattern clearly shows no wetting below halfway (Figure 4.5a).

The major method of soil wetting with CRZI 'Perforated Pipe' was from the centre outwards and the emitter sites were clearly visible (Figure 4.6b).

The CRZI Low Flow produced a more diffuse pattern that emerged later than the drip tape. No free water was observed on the soil surface (Figure 4.6a).

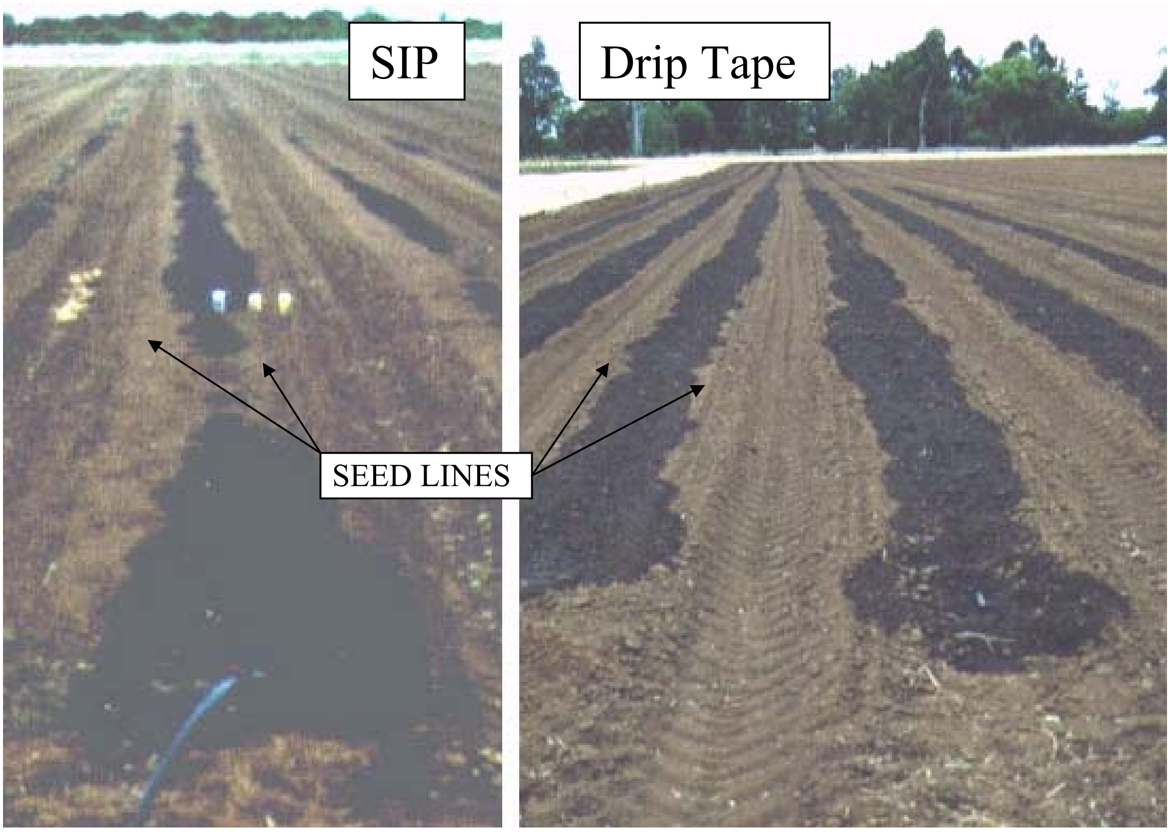


Figure 4.5. Photograph of (a) SIP and (b) Drip Tape surface wetting pattern and seed lines.

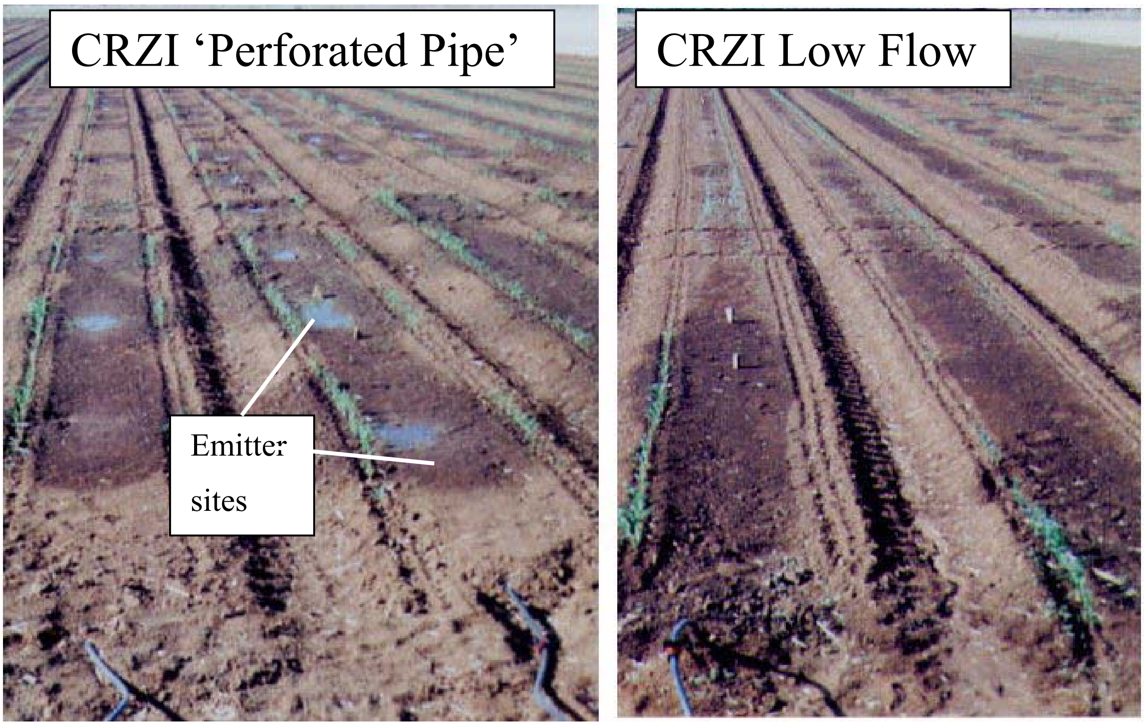


Figure 4.6. Photograph of (a) CRZI 'Perforated Pipe' and (b) CRZI Low Flow surface wetting pattern and seed lines.

4.3.2 Crop Establishment when Irrigated through Buried Systems – Crop 1

Poor and variable establishment resulted from irrigation by the buried products (Figure 4.7) as water failed to uniformly reach the seed. The extreme example is SIP with no germination beyond 90 m. All treatments produced similar plant establishment (mean 7.9 plants m^{-1}) except SIP with a significantly ($p<0.05$) reduced stand of 1.5 plants m^{-1} (Table 4.3).

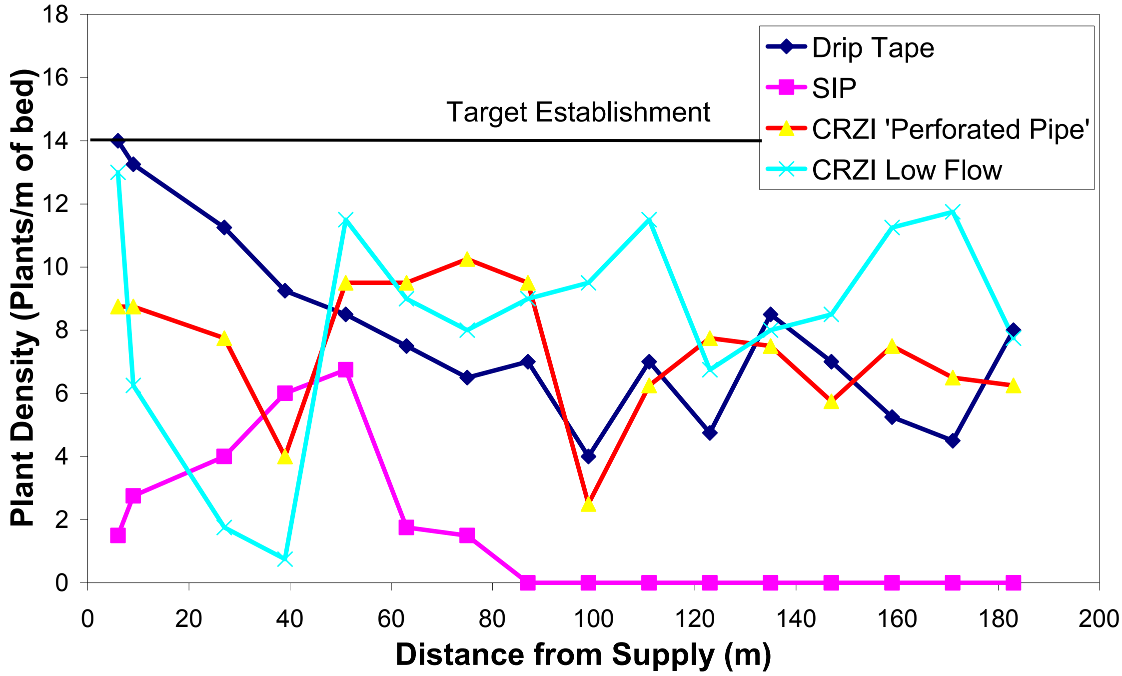


Figure 4.7. Sweet corn establishment - crop 1.

Table 4.3. Mean sweet corn establishment - crop 1.

	CRZI 'Perforated Pipe'	CRZI Low Flow	SIP	Drip Tape
Mean (Plants m^{-1})	7.4	8.4	1.5	7.9
LSD ($p<0.05$)	4.3			

4.3.3 Irrigation Application

The aim of the initial irrigation was to apply sufficient water to establish an acceptable crop of 14 plants per bed metre.

According to the 1996 NSW Agriculture Farm Budget Handbook (Anonymous, 1996) an 'average' sweet corn crop in the MIA requires approximately 800 mm of irrigation. However this figure is a conservative financial budgeting estimate and a figure of 500-600 mm may be a more acceptable approximation of plant water requirement (D. Smith, pers comm).

The major point to note from Figure 4.8 and Table 4.4 is the significant amounts of water applied while attempting crop establishment. The amounts varied from 36% (Drip Tape and CRZI 'Perforated Pipe') to 47% (CRZI 'Low Flow' and SIP) of estimated total crop requirement.

The treatments can be seen to split into two groups based on flow rate – CRZI 'Perforated Pipe'/ Drip Tape and CRZI Low Flow/SIP (Figure 4.8). As the wetting-up schedule was based on a 12 hour changeover time, the total amount of water applied depended on treatment flow rate and when the decision was made to cease irrigation. As there was no difference in mean crop establishment except SIP (Table 4.3) it can be seen that crop establishment was insensitive to the amount of water applied, in the range used in the trial. Unlike all other treatments, SIP provides no impediment to infiltration out of the pipe (de Vries *et al,* 1997). Thus, when surrounded by a loose, dry, soil, infiltration will be high and distribution uniformity will be low, as water will not reach the downstream end of the pipe. This can plainly be seen from the establishment pattern in Figure 4.7. The SIP distribution uniformity will be discussed further in Section 4.3.12.

The CRZI Low Flow exhibited a visually wider wetted area. The 0.3 m width of the product combined with the 0.3 m depth of installation produced a more diffuse wetted zone when compared to the more concentrated wetted area of the Drip Tape. Differences in wetting method are investigated in greater detail in Section 6.4.7.

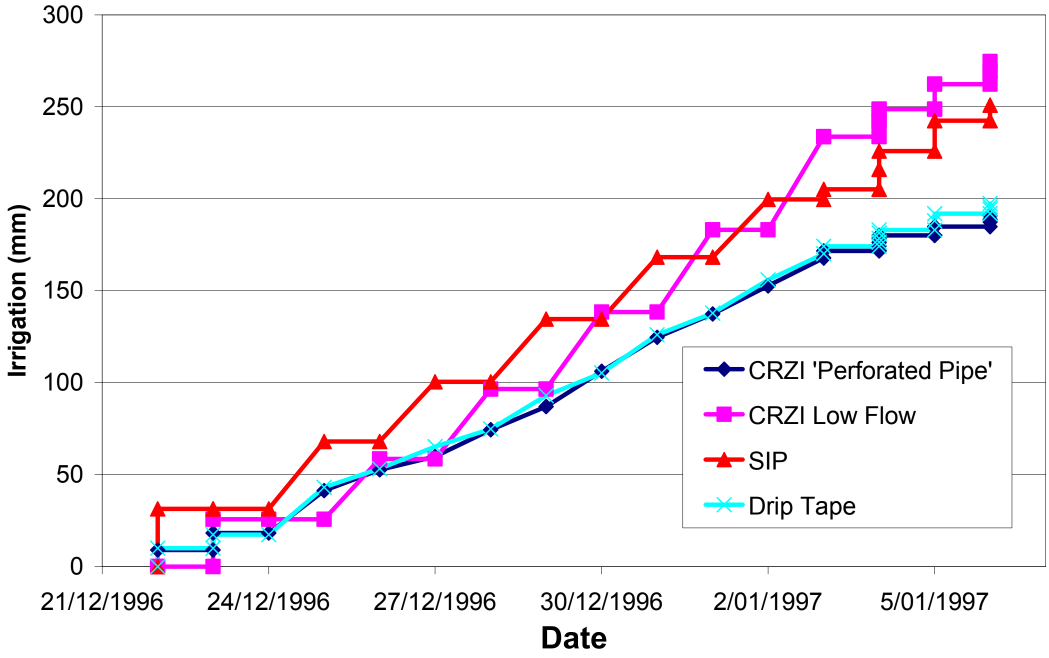


Figure 4.8. Irrigation application to sweet corn - crop 1.

Table 4.4. Pre-emergence irrigation – crop 1.

	CRZI ‘Perforated Pipe’	CRZI Low Flow	SIP	Drip Tape
Pre-emergence irrigation (mm)	191	275	251	197
Total time (hr)	131	143	149	150
Flow rate (L hr^{-1} m^{-1})	2.7	3.5	3.2	2.5

4.3.4 CRZI ‘Perforated Pipe’ Hole Separation Effect

The large hole spacing (3 m) in the CRZI ‘Perforated Pipe’ product produced a 50% reduction in establishment (significant at $p<0.05$) midway between the holes (Figure 4.9, Table 4.5). Visually an hourglass surface wetting pattern was produced (Figure 4.6a).

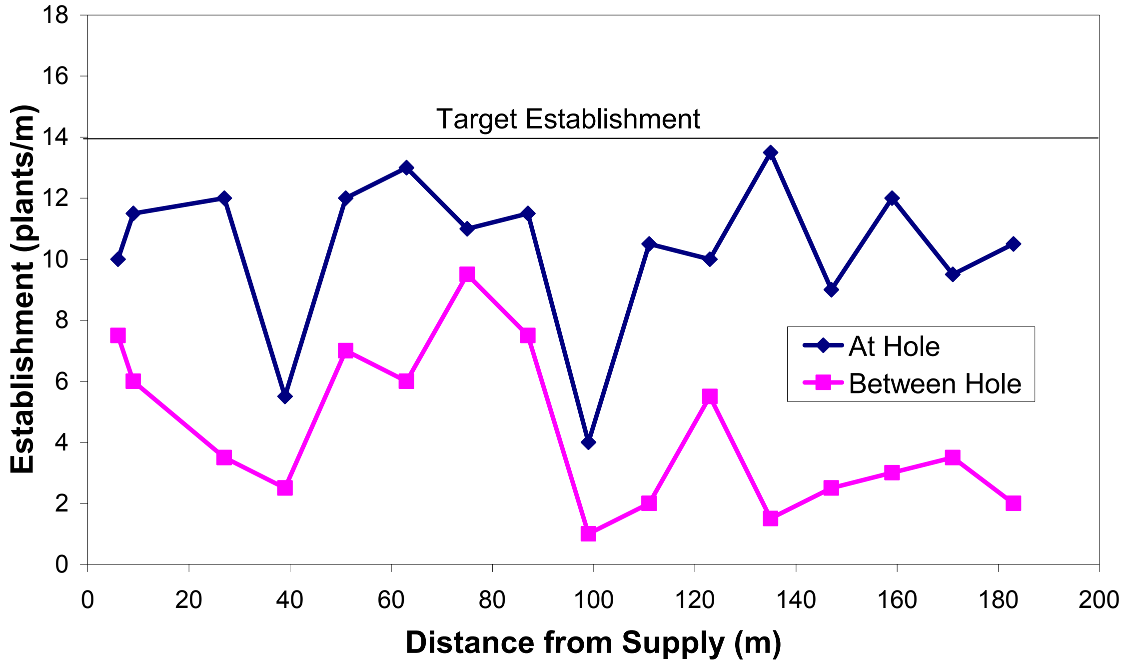


Figure 4.9. CRZI 'Perforated Pipe' - comparison of crop establishment in 'at hole' and 'between hole' positions.

Table 4.5. Effect of CRZI 'Perforated Pipe' hole position on crop establishment

	CRZI "Perorated Pipe (At Hole)	CRZI "Perforated Pipe (Between Hole)
Mean (plants m^{-1})	10.3	4.4
LSD ($p<0.05$)	5.9	

4.3.5 CRZI 'Perforated Pipe' Tunnelling

In reference to SDI, tunnelling occurs when water follows a preferential path from an emitter directly to the soil surface. Tunnelling is caused by pressurisation of the soil volume surrounding a buried emitter with a flow rate exceeding the rate at which water moves away through the soil. Eventually the pressure reaches a threshold, 'breakout' level dependent on soil condition, and a flow path to the surface forms (Zimmer *et al*, 1988).

Tunnelling was found only in the CRZI 'Perforated Pipe' treatment. From the surface, tunnelling is characterised by a volcano or 'caldera' formation where fine (silt/clay) particles were deposited. Slicing vertically through a tunnel revealed a column of sand linking the emitter to the caldera (Figure 4.10). The high energy input into the system (from the 15 L hr^{-1} emitters) appears to have caused the process of *illutriation* or dissociation and settling out of soil particles.

Tunnelling is seen as a disadvantage as it promotes preferential flow to the soil surface and not by capillarity through the soil matrix. This causes surface saturation and runoff to areas not intended for irrigation such as wheel tracks and inter-row zones. Having free water on the soil surface promotes both evaporative loss and weed growth.

The disruption of soil texture is irreversible and different cultivation methods have been unsuccessfully attempted to remediate tunnelled soil (Phene, pers comm).

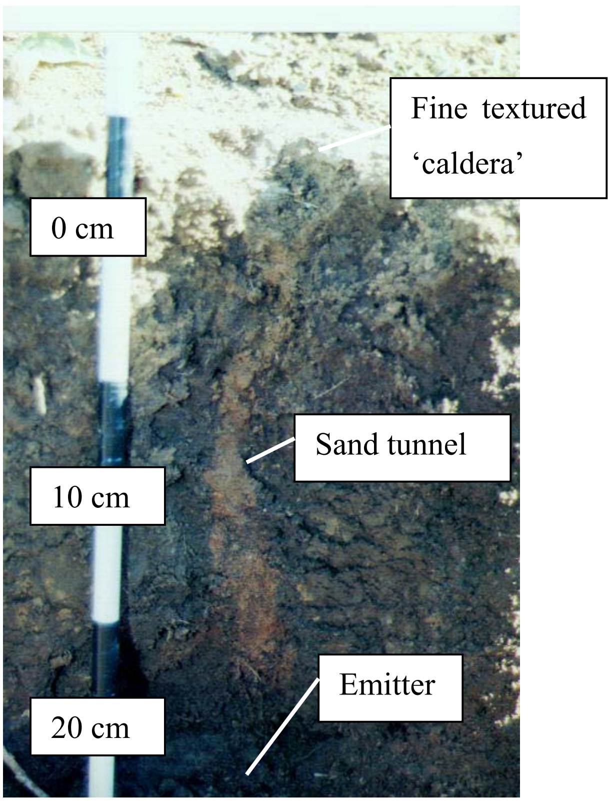


Figure 4.10. Vertical slice through a tunnel issuing from CRZI 'Perforated Pipe'.

(Note sand column leading to surface caldera.)

4.3.6 Crop Establishment through Furrow Irrigation – Crop 2

Furrow irrigation of the second crop attained far superior establishment, both in number and uniformity (Figure 4.11). Also evident is a reduced establishment in the lower part of the field common to all treatments. The 11% reduction (mean 13.6 to 12.1 plants m^{-1}), although not statistically significant, may have been caused by water standing in the furrow ends resulting in a degree of waterlogging.

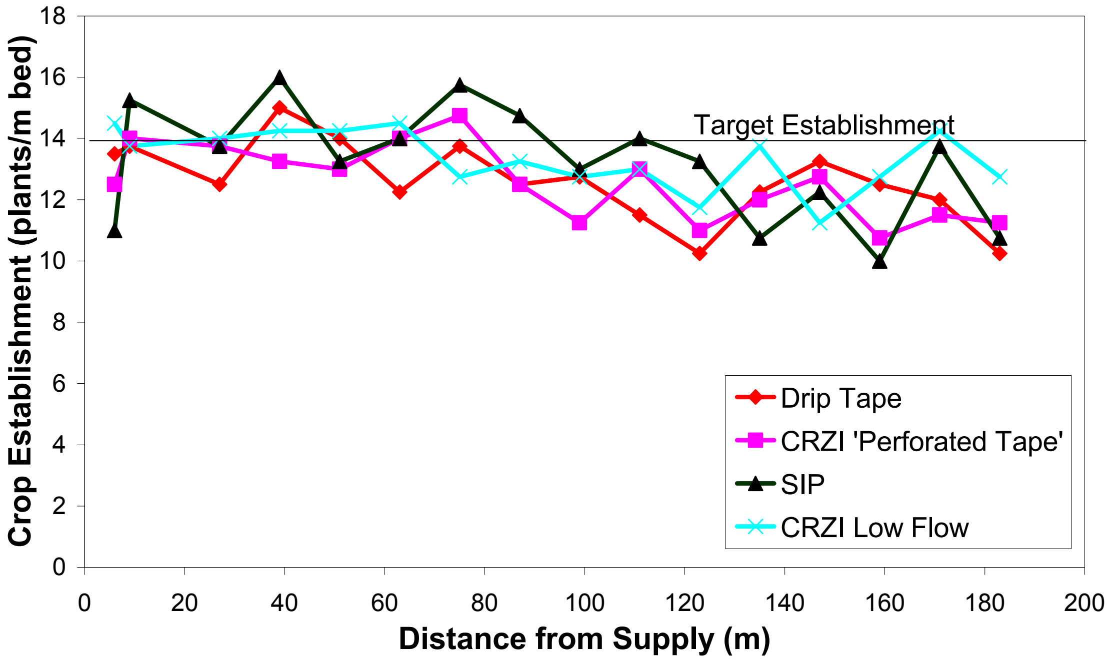


Figure 4.11. Sweet corn establishment with furrow irrigation - crop 2.

4.3.7 Water Application

Irrigation was applied to the second crop in three phases (Figure 4.12) which are discussed further below. Actual plant evapotranspiration (ETc) was calculated using 4 crop factors : 0.3 (0-20 DAS), 0.6 (21-39 DAS), 0.85 (40-75 DAS), 0.6 (76-92 DAS).

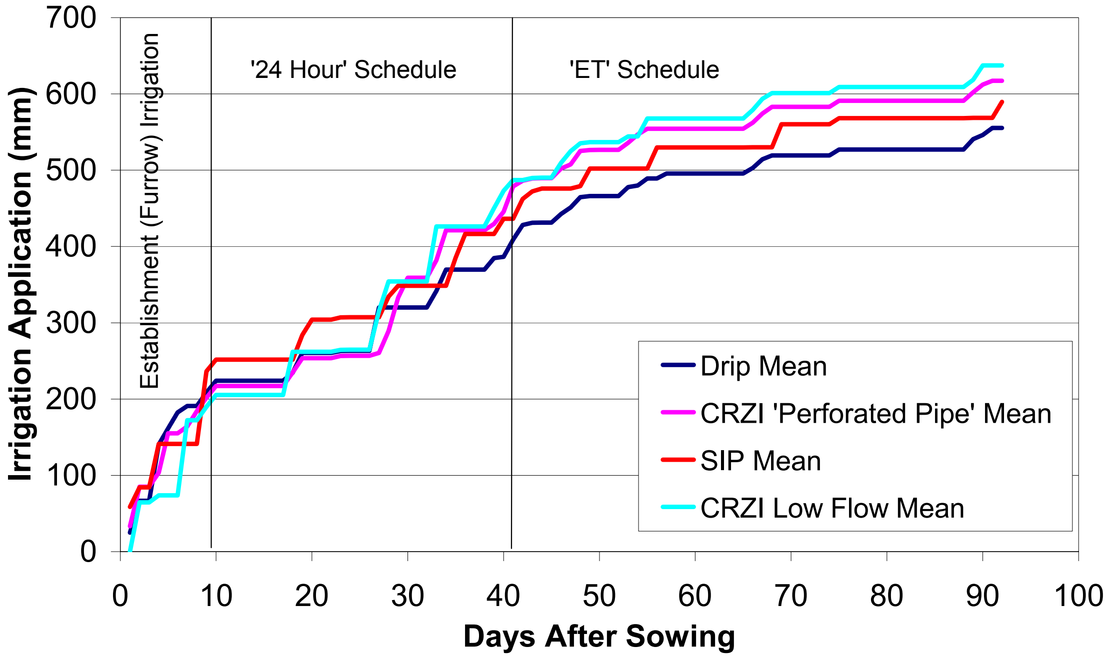


Figure 4.12. Irrigation and rainfall applied to sweet corn – mean of blocks 1 and 2.

Table 4.6. Mean irrigation and rainfall application depth (mm) - crop 2.

Irrigation Phase	ETc	CRZI 'Perforated Pipe'	CRZI Low Flow	SIP	Drip Tape
Establishment (Furrow Irrigation)	29	184 (+155)*	172 (+143)	141 (+112)	191 (+162)
'24 Hour' Schedule	142	259 (+117)	279 (+137)	259 (+117)	182 (+40)
'ET' Schedule	226	121 (-105)	133 (-93)	137 (-89)	129 (-97)
Total I or ETc	397	564	584	537	502
Rain		53	53	53	53
Total	397	617 (+220)	637 (+240)	590 (+193)	555 (+158)

*Bracketed figures indicate water deficit (-ve) or surplus (+ve).

Establishment (Furrow) Irrigation

Individual irrigation amounts for the season are presented in the Appendix (Figure 12.4).

Water was applied to the inter-bed furrows until sufficient lateral wetting was achieved to germinate the second crop. This ranged from 3 days and 141 mm (SIP) to 6 days and

191 mm (Drip Tape) and was immediately followed by 33 mm of rain. Any differences between the amounts that were required (Table 4.6) may be attributed to gradient, furrow condition, and soil consolidation in the bed.

The site was not intended for furrow irrigation. The steep gradient (0.25%) and consequent low application uniformity is the most likely reason for the large amount of water required to achieve sufficient infiltration for germination. Due to the furrow ends being blocked, no runoff occurred.

'24' Hour Schedule

Following the successful establishment phase a 'maintenance' schedule was adopted while instruments (36 neutron probe tubes and 70 tensiometers) were installed. Again, this resulted in over-irrigation (Table 4.6).

'ET' Schedule

From 41 DAS to harvest (92 DAS) irrigation application was matched to 0.75 * ETc. This decision was made because the over-irrigation which had occurred in the first 40 days meant there was a high probability of the experiment yielding no significant yield difference – there being no limiting factors. The result was an average application of 65% of ETc (including rain) during the 51 day period (Table 4.6). In addition, the intended irrigation amount was split into three applications per week.

The effect of the furrow water applied during the establishment phase (mean 143 mm) is demonstrated when compared with the average end of season surplus (200 mm). When sprinkler irrigation is used for establishment, good results are attained with approximately 30 mm (Hickey, pers comm). The use of sprinkler irrigation had potential to reduce the overall surplus by approximately 50%.

4.3.8 Yield Data

Commercial Yield

Yields ranged from a mean 16.9 t ha^{-1} for Drip Tape to 12.8 t ha^{-1} for SIP. Considering the late planting, yields compared well to the region average of 15-20 t ha^{-1}. Yields for all treatments were lower in the drainage end of the field (Table 4.7). This may have been due to a period of aeration stress following the furrow irrigation or salinity caused by an elevated water table. The lower end of the field is bounded by a drainage channel and is hence the lowest level in the area. Evidence to support these opinions are flowing tile drains (2 m depth) and a salt scald causing plant death in SIP Block 2 treatment (Figure 4.13).

Figure 4.13. Salt scald in sweet corn crop.

The irrigation treatment and harvest position interacted in their effect on yield (Table 4.7). The yield was similar at the two harvest positions for all treatments except SIP. Yield at the lower end of the SIP was 44% lower (8.8 *cv* 16.8 t ha^{-1}) than the SIP upper end and led to a significantly lower mean yield. This yield reduction would clearly have economic significance and points to a lack of distribution uniformity which will be discussed further.

The lack of statistical significance between the upper and lower yield measurements was further analysed. It was thought the low yield of the drainage end of the SIP treatment may have masked the effect through increasing the variability. A further ANOVA was performed with the SIP treatment removed but still no significance resulted.

Table 4.7. Freshweight yields (t ha^{-1}) from commercial sweet corn harvest (79 DAS).

	Supply End	Tail End	Mean
Drip Tape	18.2	15.7	16.9
SIP	16.8	8.8	12.8
CRZI 'Perforated Pipe'	17.4	15.0	15.7
CRZI Low Flow	16.2	15.1	16.6
Mean	17.4	13.7	15.5
LSD ($p<0.05$)	ns		1.7

End of Season Dry Matter Yield

Total dry matter production ranged from 12.7 t ha^{-1} for CRZI 'Perforated Pipe' (Supply End) to 10.7 t ha^{-1} for SIP (Tail End) (Figure 4.14). Significantly less kernels were produced with SIP in the Tail End of the field confirming the results from the commercial harvest (Table 4.7). No other differences were significant.

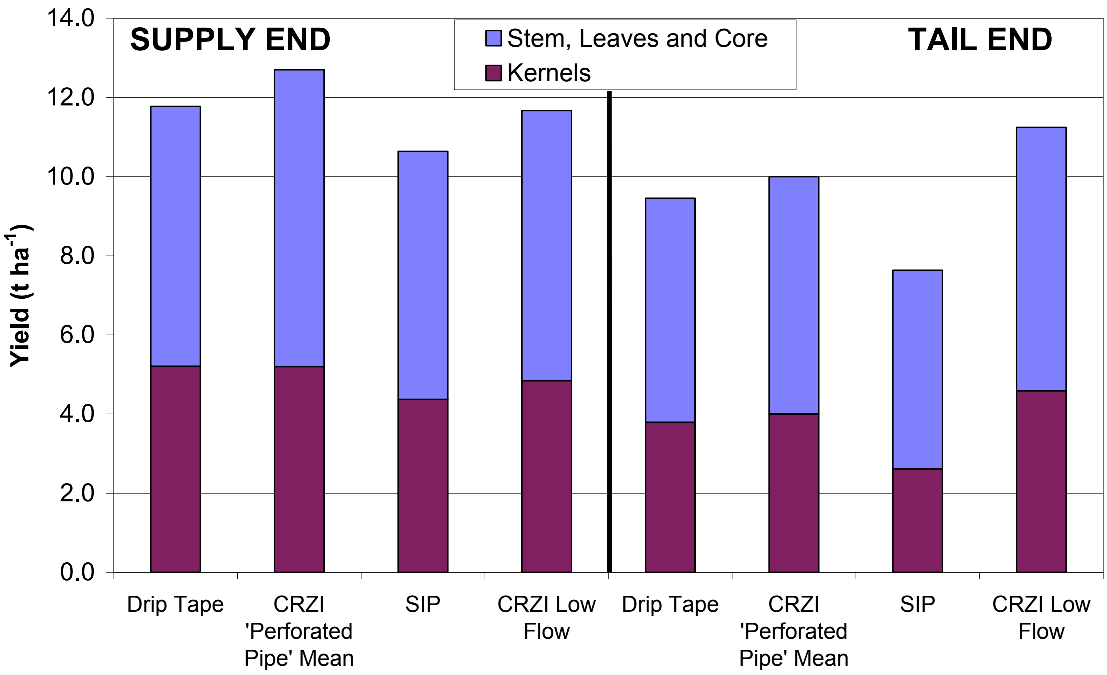


Figure 4.14. Sweet corn dry matter production. End of season (118 DAS) harvest.

Table 4.8. Sweet corn dry matter production (t ha^{-1}). End of season (118 DAS) harvest.

	Stem, Leaves and Core	Kernel	Total
Drip Tape	6.1	4.5	10.6
CRZI 'Perforated Pipe' (Mean)	6.7	4.6	11.3
SIP	5.6	3.5	9.1
CRZI Low Flow	6.7	4.7	11.4
LSD (p<0.05)	ns	0.6	ns

Effect of CRZI 'Perforated Pipe' Hole Spacing

While yield is lower between the holes, the wide hole spacing in CRZI 'Perforated Pipe' had no significant effect on crop production (Table 4.9). However, this may be an artifact of the furrow irrigation, as it has already been shown that a significantly lower establishment occurred between the holes when the CRZI 'Perforated Pipe' was used. The initial furrow irrigation may have resulted in a sufficiently developed root system able to adapt to the wetted zones emanating from the holes on either side. Also, leaf yellowing consistent with nitrogen deficiency was observed in plants in the 'Between Hole' position at the tail end of CRZI 'Perforated Pipe'. Again, this supports the lack of inter-emitter application uniformity.

Of significance ($p<0.05$) is the lower production in the tail end of the field. One possible reason for this is lower distribution uniformity of the CRZI 'Perforated Pipe' product. This will be discussed further in section 4.3.12.

Table 4.9. Effect of CRZI 'Perforated Pipe' 'At Hole' and 'Between Hole' positions on dry matter production (t ha^{-1}).

	Stem, Leaves and Core		Kernels	
	Supply End	Tail End	Supply End	Tail End
CRZI 'Perforated Pipe' (At Hole)	7.9	6.3	5.7	4.3
CRZI 'Perforated Pipe' (Between Holes)	7.0	5.7	4.6	3.7
Mean	7.5	6.0	5.1	4.0
LSD (p<0.05) (Between Supply and Tail end means)	0.3		ns	

4.3.9 Water Use Efficiency

The dry matter production and water use data were combined to give water use efficiency in yield per volume terms (Table 4.10). Water use efficiency ranged from 2.1 t/ML (Drip Tape) to 1.7 t/ML (SIP) with no significant difference existing between any of the treatments.

Table 4.10. Sweet corn experiment water use efficiency.

	Dry Matter Production (t/ha)	Mean Irrigation (ML)	WUE (t/ML)
Drip Tape	10.6	5.03	2.1
CRZI 'Perforated Pipe'	11.3	5.64	2.0
SIP	9.1	5.37	1.7
CRZI 'Low Flow'	11.5	5.85	2.0

4.3.10 Root Intrusion and Silt Deposition

Several lengths of CRZI Low Flow were removed from the field and washed to examine the degree of root intrusion.

Most roots were visible between the PE and geotextile. The major direction of intrusion seemed to be sideways rather than through the fabric, especially where the PE may have been protruding slightly outside the fabric (Figure 4.15). Only a small number of intrusions are needed to produce the masses seen in the photographs (Figure 4.16) because once in the PE/geotextile interface the root moved in only two-dimensions and was well supplied with water and nutrients. No evidence of emitter intrusion was found. This may be due to the nature of the drip tape product used. The Drip Tape emitter opening comprised a slit which remained closed when the line was not pressurised.

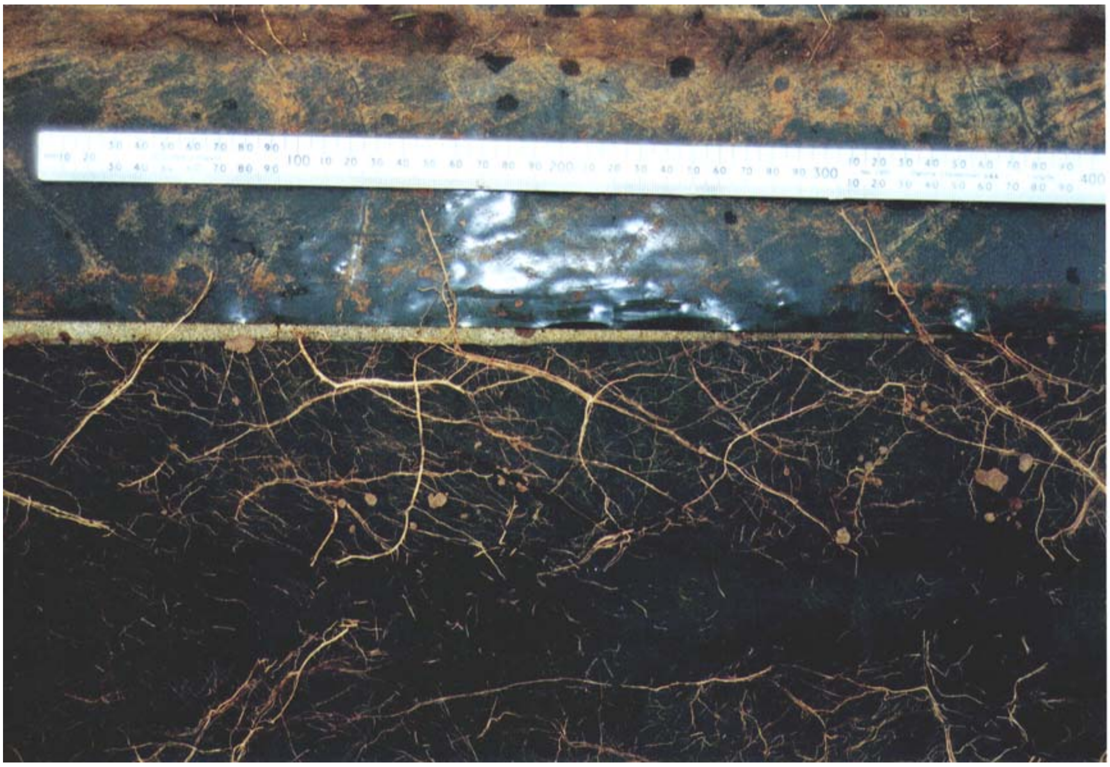


Figure 4.15. Photograph showing root growth on the geotextile/PE interface in CRZI Low Flow. CRZI Low Flow opened to show PE at top and geotextile at bottom of photograph

Figure 4.16. Sweet corn root mass in CRZI Low Flow.

4.3.11 Crop Water Balance

The major feature of the total crop water balance (Table 4.11) is the very high values attributed to drainage. These range from 52% of irrigation applied (CRZI 'Perforated Pipe') to 40% (Drip Tape). The data also show that irrigation amount, and hence irrigation management, is by far the major factor determining drainage.

Table 4.11. Total crop water balance.

Total Crop Water Balance (mm)				
	SIP	CRZI 'Perforated Pipe'	CRZI Low Flow	Drip Tape
Irrigation (I)	559	632	590	524
Crop Evapotranspiration (ETc)	388	388	388	388
Rainfall (R)	52	52	52	52
Change in Soil Water Content (SWC)	-25	-34	-41	-32
Drainage (D)	249	331	296	221

More detailed examination reveals the establishment phase (furrow) irrigation to be the primary contributor to the drainage (Table 4.12). Drainage during the establishment phase accounted for 98% of the total in the SIP and Drip Tape treatments and 58% in the two CRZI treatments.

Table 4.12. Crop water balances (mm) divided into establishment and growth phases.

	Establishment Water Balance				Growth Phase Water Balance			
	SIP	CRZI 'Perforated Pipe'	CRZI Low Flow	Drip Tape	SIP	CRZI 'Perforated Pipe'	CRZI Low Flow	Drip Tape
I	297	253	241	290	262	380	349	234
ETc	63	63	63	63	325	325	325	325
R	33	33	33	33	19	19	19	19
SWC	+21	+44	+37	+42	-46	-78	-78	-74
D	247	179	174	219	2	152	121	2

The SIP/Drip Tape treatments shows lower total drainage, but higher establishment-drainage and lower growth-phase-drainage than the two CRZI products. The two treatments in each combination (SIP/Drip Tape and CRZI 'Perforated Pipe'/CRZI Low Flow) share the same sub-main offtake (see Figure 3.5) and examination of the irrigation data reveals three large applications in the growth phase which would account for the differences. This demonstrates the major effect of control system inflexibility and lack of experience on this experiment. When this is taken into consideration, deep drainage for all treatments is likely to be similar.

4.3.12 Wetting Patterns

The following sections present individual wetting patterns for each treatment. The graphs (Figure 4.17, Figure 4.19, Figure 4.20, and Figure 4.21) show soil water content change between two neutron probe readings taken before and after irrigation. A period (before irrigation, 25Feb – after irrigation, 1 Mar) was selected where irrigation amounts were similar for each treatment. Separate water balances for the period are presented in Table 4.13. Also presented is a table showing changes in soil water storage for the four treatments at the 3 positions down the irrigation pipe (Table 4.14). This data was obtained by summing all the before/after irrigation soil water storage changes for the whole season, giving an indication of both water application and usage uniformity. The results are discussed below for each treatment.

Table 4.13. Water balances (mm) for the period 25 Feb-1 Mar based on changes in wetting pattern.

	I	ETc	R	ΔSWC	D	Days Between NMM Readings	No. Irrigations
SIP*	55	31	3	+15	12	5	3
Drip Tape	59	28	3	+30	4	4	2
CRZI Low Flow	62	20	0	+35	7	3	2
CRZI 'Perforated Pipe'	51	28	3	+10	16	4	1

*Balance for SIP is for the period (26Feb-3Mar).

Table 4.14. Mean profile soil water storage and cumulative change in soil water storage (Δθ) between all neutron probe data at three positions down the irrigation pipe.

	Mean Profile θ (mm)			Mean Profile Δθ (mm)		
	Supply	Middle	Tail	Supply	Middle	Tail
SIP	418	401	404	-47	-20	-9
Drip Tape	454	424	434	-59	-44	-46
CRZI 'Perforated Pipe'	432	376	402	-51	-28	-24
CRZI Low Flow	432	380	439	-30	-46	-46

SIP

The most notable feature of the SIP wetting patterns (Figure 4.17) is that, following irrigation, soil water content change decreased down the row, from +30 mm at the supply end to +3 mm at the tail end. This highlighted the poor distribution uniformity of this product. An extreme situation existed at the tail end of the SIP bed where a large area of *water depletion* existed following irrigation.

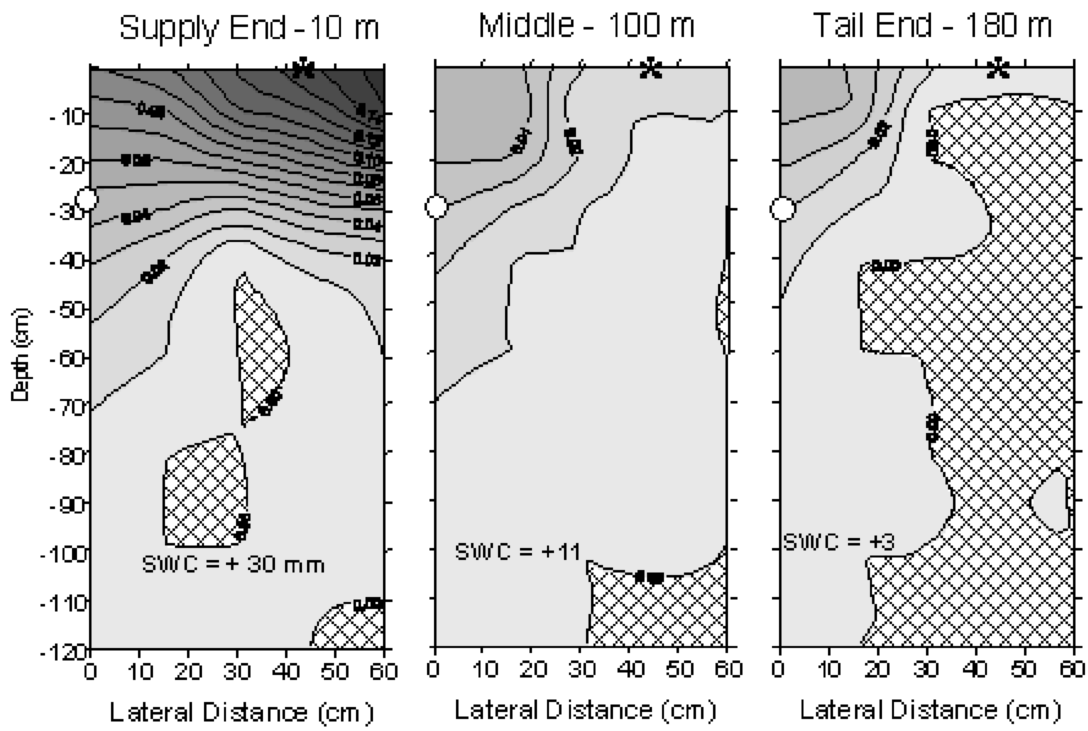


Figure 4.17. SIP - Lateral soil water content change (cm^3 cm^{-3}) at 3 interrow positions. Pipe position is indicated on Y-axis and asterisk shows plant position. Hatched area shows zone of water content decrease.

The wetting pattern example also agreed with the cumulative season SWC change (Table 4.14) which showed a decrease in SWC change down the row from –47 mm at the supply to –9 mm at the tail end. A reduction in total profile SWC at the tail end, could be expected but the smaller plants (producing far lower yield) at the tail end extract smaller amounts of water, maintaining the same whole profile SWC balance as at the supply end. It is also possible the neutron probe data is not showing the SWC peaks, as not every irrigation was followed immediately by a reading. As no readings were taken between irrigation end/start, it is also not possible to ascertain relative profile drainage rates. It is most likely, significant drainage occurred at the supply end. However, this cannot be determined from the neutron probe data due to the lack of readings and because the soil below 0.5 m remained close to saturation in all treatments, for the whole crop length.

To further demonstrate the cause of the yield decline, Figure 4.18 compares supply and tail end SWC for the whole season at a point most likely to show changes (top 0.1 m of soil, 0.3 m from bed centre). Clearly evident is the supply end SWC response to irrigation events which is absent at the tail end. The tail end can be seen to maintain a very dry surface layer close to the plant.

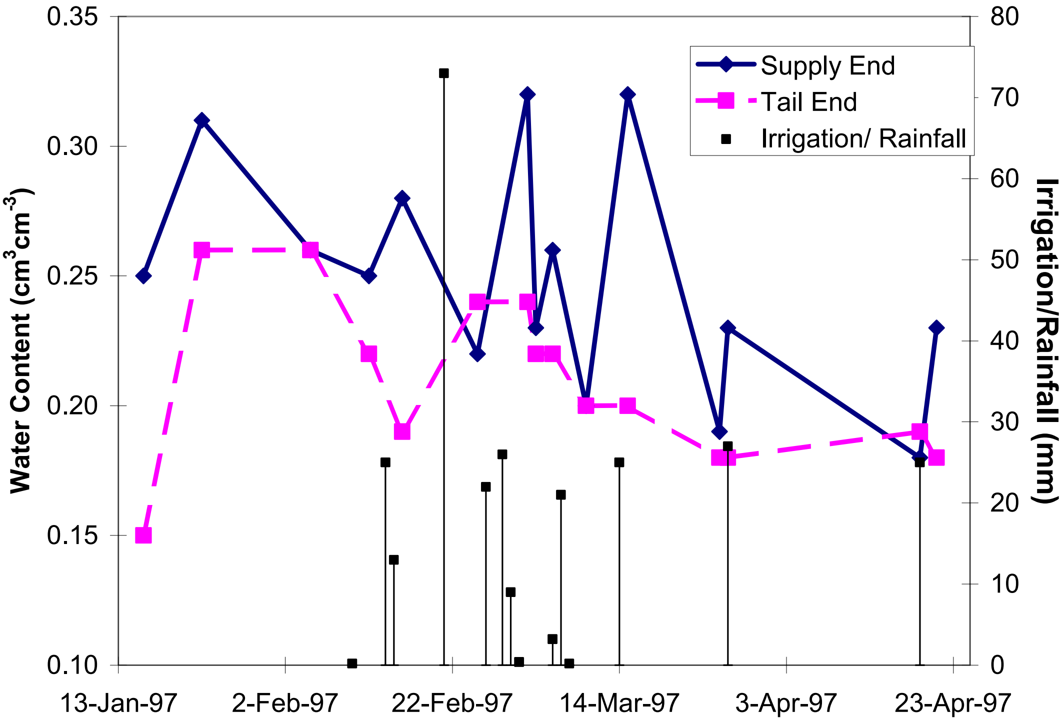


Figure 4.18. Comparison of SWC at supply and tail end of SIP. Top 0.1 m of soil at 0.3 m from bed centre.

Drip Tape

The Drip Tape exhibited very uniform application down the row length, ranging from 28 to 34 mm (Figure 4.19). Such performance is not surprising as the tape was designed to provide a distribution uniformity of 95%.

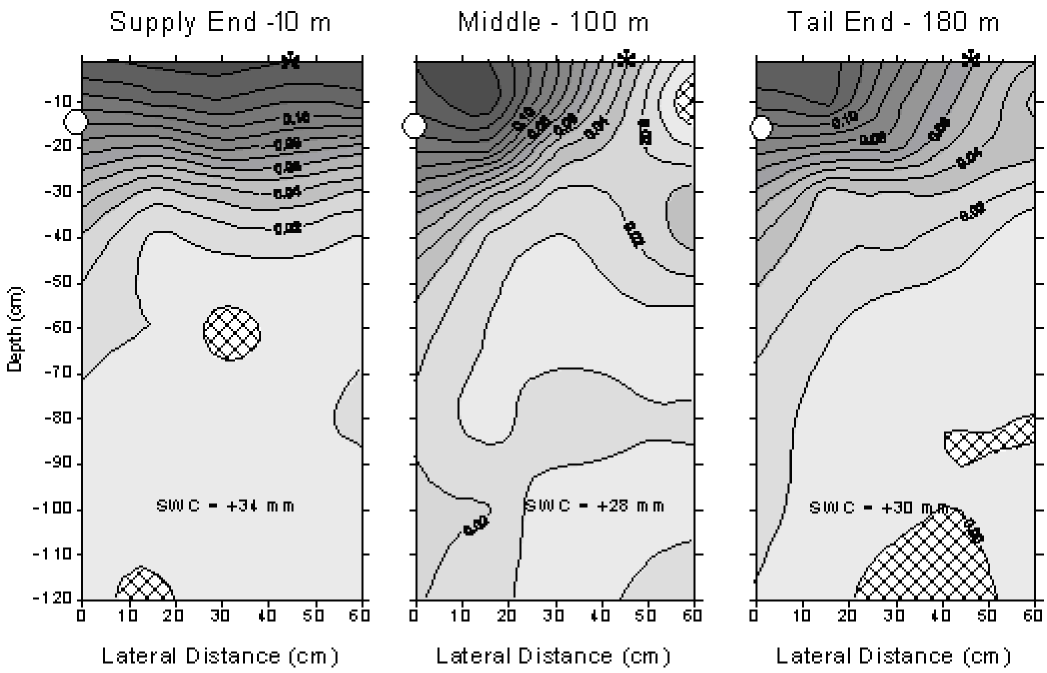


Figure 4.19. Drip Tape - Lateral soil water content change ($cm^3\ cm^{-3}$) at 3 inter-row positions. Pipe position is indicated on Y-axis and asterisk shows plant position. Hatched area shows zone of water content decrease.

CRZI Low Flow

Soil water content increased 16 – 30 mm reflecting the lower application amount (Figure 4.20). The narrower lateral distribution in the middle position is also evident in CRZI 'Perforated Pipe'. In fact, the middle position maintains the least profile SWC in all treatments and may indicate soil variability.

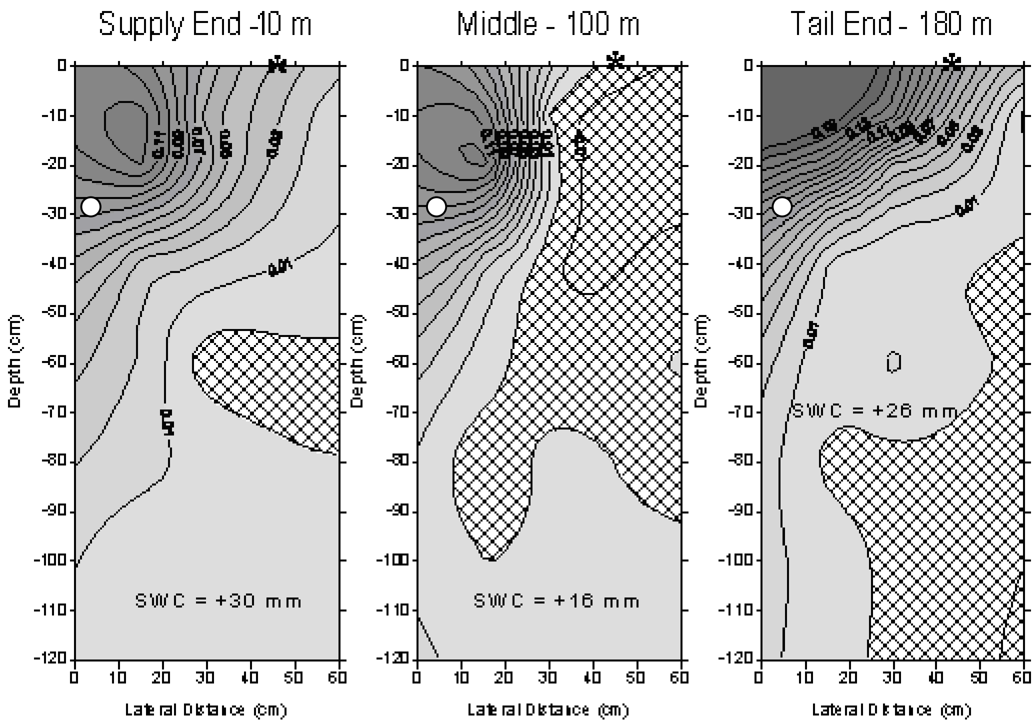


Figure 4.20. CRZI 'Low Flow' - Lateral soil water content change (cm^3 cm^{-3}) at 3 interrow positions. Pipe position is indicated on Y-axis and asterisk shows plant position. Hatched area shows zone of water content decrease.

CRZI 'Perforated Pipe'

A lack of uniformity is also evident in CRZI 'Perforated Pipe'. Water content change varies from a 22 mm increase at the supply end, to a 3 mm decrease at the middle position.

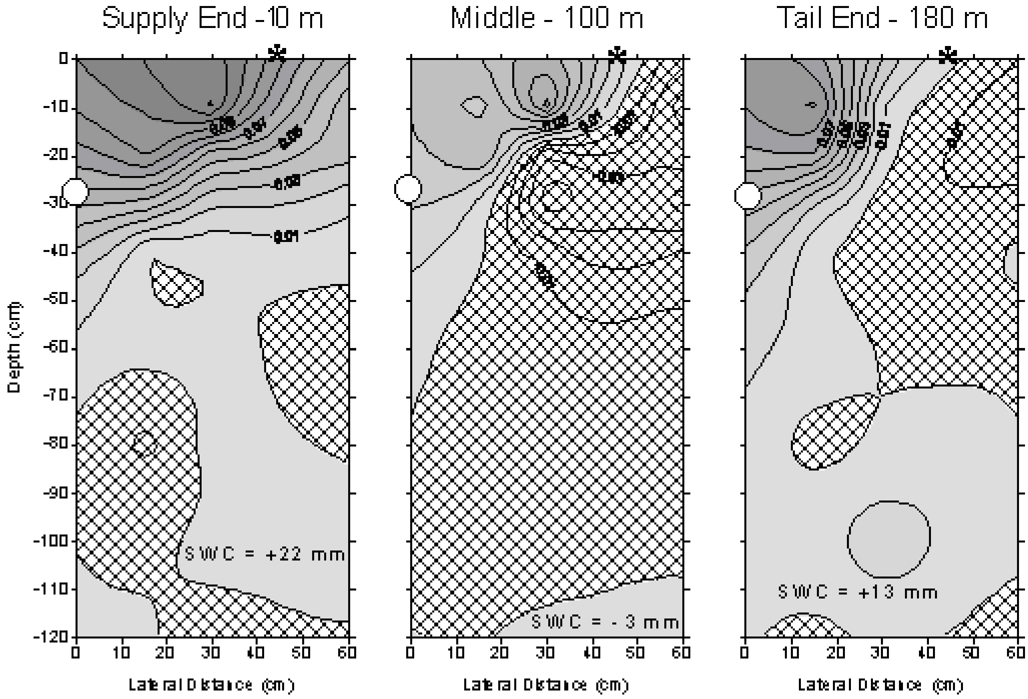


Figure 4.21. CRZI 'Perforated Pipe' - Lateral soil water content change (cm^3 cm^{-3}) at 3 interrow positions. Pipe position is indicated on Y-axis and asterisk shows plant position. Hatched area shows zone of water content decrease.

4.4 Conclusion

Uniformity

CRZI 'Perforated Pipe' exhibited problems with both distribution (downline) application uniformity and between emitters. When establishment was attempted using the system a 'sawtooth' establishment pattern resulted from at best, delayed emergence and at worst, no emergence. Wetting patterns indicated less water was applied at the tail end and was accompanied by a yield reduction.

Tunnelling is a major limitation of this product and is inherent with the design. The soil matrix is not strong enough to resist the disruption caused by the high pressure and flow rate of the water exiting the pipe.

CRZI Low Flow and Drip Tape have an acceptable uniformity which is not surprising as CRZI is using the same drip tape. The fact that no free water was observed on the surface above CRZI 'Low Flow' can be seen as an advantage, by lowering soil evaporative loss and maintaining good soil structure.

The poorest performer was SIP which suffered a 44% yield reduction in the tail end. The data clearly shows this was due to poor distribution uniformity. If it was considered worth pursuing, SIP would need to be designed similarly to other hydraulic systems where pipe diameters are matched to row length. The infiltration rate of the soil would be included in this design.

Root Intrusion

Large amounts of roots were found growing in the PE/geotextile interface from few actual intrusions. Such intrusion should not pose a problem with annual crops, as decomposition will occur following harvest, reducing organic matter accumulation between seasons. The same cannot be said for perennial crops eg. grape vines. Such crops have a permanent root superstructure, which gradually expands every season and may accumulate preferentially in the CRZI 'V'. Monitoring of these crops is required to ascertain the risks involved.

Crop Performance

Apart from SIP no significant difference in crop production or WUE was seen. Factors contributing to this situation were lack of control system flexibility and a lack of experience with this form of irrigation.

Irrigation water balances revealed a systematic difference between treatments sharing the same submain offtake. Several irrigations were obviously applied either at the wrong time or for the wrong length of time. The results of the Drip Tape have shown the potential for even yield, with minimal drainage loss if a more efficient establishment method was used.

The CRZI 'Perforated Pipe' concept was intended to be technologically simple, utilising low pressure and not requiring expensive filtering or control systems. The major outcome of this experiment was to show that it did not perform well. While achieving similar WUE the product showed high drainage rates and low distribution uniformity.

To fully exploit the potential of SDI products, requires a control system capable of applying set amounts of water at daily or greater frequencies. Such systems not only keep the soil at optimal water content but reduce the labour requirement and errors associated with manual operation that this trial has demonstrated.

Establishment

No treatment produced satisfactory crop establishment. However, when establishment was provided by another method (furrow) the crop grew normally.

In California, the establishment problem has been deemed too hard and bypassed by growers hiring spray rigs. With this method, an application of approximately 30 mm is sufficient for an acceptable crop stand. This practice is not used commonly in Australia and would therefore be limited to those enterprises where SDI had been installed in fields previously serviced with solid set or hand move sprinklers. However, these options are not economically viable for new installations.

Offering a solution to the establishment problem was seen as an important CRZI marketing advantage.

Summary from Conclusions

The results from this trial provided the following general conclusions:

1. Further WUE experimentation should concentrate on optimal irrigation control with crops more sensitive to soil water deficit.
2. Drip Tape was the only SDI product with high distribution uniformity and as such can be considered the ‘standard’ for comparison of the new CRZI configurations.
3. Crop establishment is a significant problem requiring further research to understand why and how to overcome this with other SDI configurations.

5 Water Use Efficiency Experiment

5.1 Introduction

Accurately evaluating the water use efficiency (WUE) of CRZI when compared with available products will show whether it has significant benefits. The previous Irrigation Systems experiment did not show such improvements.

The key to optimal CRZI operation is the management of water within the soil above the material 'V'. While the saturated zone is contained within the CRZI 'V' deep percolation is minimised. Due to soil water potential difference, water will be sorbed from the 'V'. However, once the saturated zone extends significantly beyond the impermeable membrane, water movement is subject to gravitation and hence downward movement dominates. Therefore, to minimise the risk of this drainage, the irrigation schedule must be arranged to only replenish water at a rate to contain the zone of saturation within the 'V' and an unsaturated zone not extending past the crop root zone.

The hypothesis to be tested in this trial is that if equal amounts of water are applied with CRZI and Drip Tape, more of the water will drain below the root zone in the Drip Tape treatment and being unavailable, the crop will suffer a yield decrease, or will require more frequent irrigation. Both of these will decrease WUE.

To test the hypothesis the crop and irrigation control system were changed.

After considering many crops, rock melon (*Cucumis melo*) was chosen as it was perceived to be more sensitive to water deficit stress than the previous sweet corn crop, suited the seasonal time available better, and considerable growing experience existed in the region. The cause of the variability of different plant species' response to water deficit stress is extremely complex. Water deficit stress changes the acquisition of carbon through photosynthesis and the partitioning of this carbon to the harvested organ (Hsiao, 1993). Leaf growth is particularly sensitive to water stress. The difference in water deficit stress response between rock melon and sweet corn may be explained through their determinacy. Indeterminate crops rely on canopy extension to provide nodes for potential fruiting sites. Any reduction in canopy will produce lower yields through lower fruit numbers (Jordon, 1983). Determinate crops such as sweet corn and cereal grains have their reproductive potential fixed soon after establishment and yield is lowered through length and rate of ear filling stage. Thus, with the assumption that for both crops water is not limited during the establishment phase, rock melon has greater potential for yield response to subsequent water stress through canopy reduction.

A more sophisticated method for controlling the irrigation schedule was developed to enable the application of accurate amounts of water in a flexible manner.

5.2 Objectives and Activitites

Objective : To compare water use efficiency of CRZI and Drip Tape using a rigorous schedule and control of irrigation water additions.

To accomplish these objectives the following activities were set :

1. Prepare new site.
2. Install new irrigation infrastructure including treatment laterals.
3. Construct irrigation control hardware.
4. Write irrigation control software.
5. Install soil water content/tension sensors.
6. Prepare real-time irrigation schedule based on feedback from sensors.
7. Identify and measure relevant crop parameters, water applied and soil water status.
8. Manage crop to best-practice standards.
9. Harvest produce to calculate WUE.

5.3 Methods

5.3.1 Treatments

Prior to treatment installation the field was deep ripped to 0.25-0.3 m (16Sept97) and fertilised with urea (100 kg N ha^{-1}). Two further shallower cultivations were performed to allow furrowing and bed forming operations. Treatments were then inserted into the beds using the same equipment described in the Irrigation System experiment. Rows were 1.8 m wide and 40m in length of which 30 m was plastic mulch covered (Figure 5.1).

Figure 5.1. Water Use Efficiency experiment site layout.

Seven combinations of product (CRZI and Drip Tape), depth (0, 0.2 and 0.3 m), and flow rate were installed (Table 5.1). A randomised complete block design was chosen with 6 replicates giving a total of 42 rows (Appendix, Figure 12.10)

Table 5.1. WUE experiment treatments. The various CRZI prototypes are detailed in Section 3.4.

Treatment #	Description	Depth (m)	Flow Rate (L h^{-1})	Irrigation Schedule Control
1	Deep CRZI Low Flow	0.3	1	Sensors #1
2	Shallow CRZI Low Flow	0.2	1	Same as 1
3	Deep CRZI High Flow	0.3	4	Same as 1
4	Shallow CRZI High Flow	0.2	4	Same as 1
5	Surface Drip Tape	0	1.1	Same as 1
6	Drip Tape	0.2	1.1	Same as 1
7	Drip Tape (own schedule)	0.2	1.1	Sensors #2

* Sensors #1/2 refer to instruments used to design irrigation scheduling treatments.

Two irrigation control treatments were selected to balance specific irrigation scheduling requirements of the CRZI and Drip Tape products. Here 'control' refers to maintaining the SWC/tension measurement instruments in the control treatment between pre-determined thresholds. The instruments and scheduling process are discussed further in section 5.3.2. The resulting irrigation schedule was then imposed on the other treatments connected with that control (Table 5.1). Therefore, the irrigation schedule used in treatment 1 was also used for treatments 2-6. These treatments enabled comparison between CRZI and Drip Tape using a CRZI-customised irrigation schedule. To balance this, a separate treatment (7) was included where Drip Tape was controlled by its own instruments.

Due to the poor sweet corn establishment results in the previous trial, a shallower depth of 0.2 m was used but a 0.3 m depth was also included as this was still the most practical for permanent bed systems. Both high and low flow rate (CRZI 'Low Flow' and 'High Flow') configurations were included.

The maximum practical depth for Drip Tape was 0.2 m and this was compared with a surface treatment (5). Surface Drip Tape is the most common form used, where tape is retrieved at the end of the season.

Additional Treatments

Two additional melon rows were used in a separate experiment operated by personnel from CSIRO Land Water, Canberra. This experiment trialed a new wetting front detector called 'FullStop' (Stirzaker and Hutchinson, 1999). These rows were operated from separate solenoids automatically controlled by the 'FullStop' instruments. The FullStop contains a switch whose contact is broken when a wetting front enters the instrument. As the solenoid was placed in series with the FullStop, irrigation was stopped as the wetting front arrived at the depth of instrument installation. The FullStops were placed at a depth of 0.4 m just lateral to the Drip Tape. To account for soil wetting variability, four FullStops were installed and irrigation was set to occur when 3 of the 4 had tripped. The schedule was set to repeat daily.

The researchers installed a weather station and a Time Delay Reflectometry SWC monitoring system with 16 probes, two of which were made available to the WUE experiment.

Plastic Mulching

After consideration of the following points, plastic mulch was used to cover the bed tops. It is also standard practice amongst commercial growers.

1. Possible large shift in water balance.

Fifty percent of a crop's evapotranspiration can come from soil surface evaporation depending on soil water content of surface, crop coverage, and weather conditions (Ritchie and Johnson, 1990). Plastic mulch will negate this loss, resulting in a sharp lowering of supplementary water requirement. This will mean the irrigation interval may be lengthened.

2. Enhancement of lateral capillary movement.

The soil water content will show less change through the upper soil profile and this will aid the maintenance of higher hydraulic conductivity, given a similar hydraulic gradient.

3. Lack of visual appraisal of wetting patterns.

As the beds would be covered, there would be no way of viewing the wetting patterns.

4. Possible lowering of the probability of detecting treatment differences.

If the soil water content is kept more uniform for a longer period of time, effect of water stress on yield may be lowered. However, the longer interval between irrigations may even out this effect.

An unmulched length of 10 m was added to the bottom of each bed to view wetting patterns and observe the effect on plant growth, where irrigation was supplied at the "mulch covered" plant requirement.

5.3.2 Irrigation Control System

Irrigation Hardware Installation

A new site was surveyed adjacent to the sweet corn block (see Appendix Figure 12.1). The choice of treatments required the provision of four separately metered manifolds from the sub-main and, given the randomised complete block design, were required to extend across the whole width of the site. Each manifold was controlled by a manual gate valve and a solenoid valve.

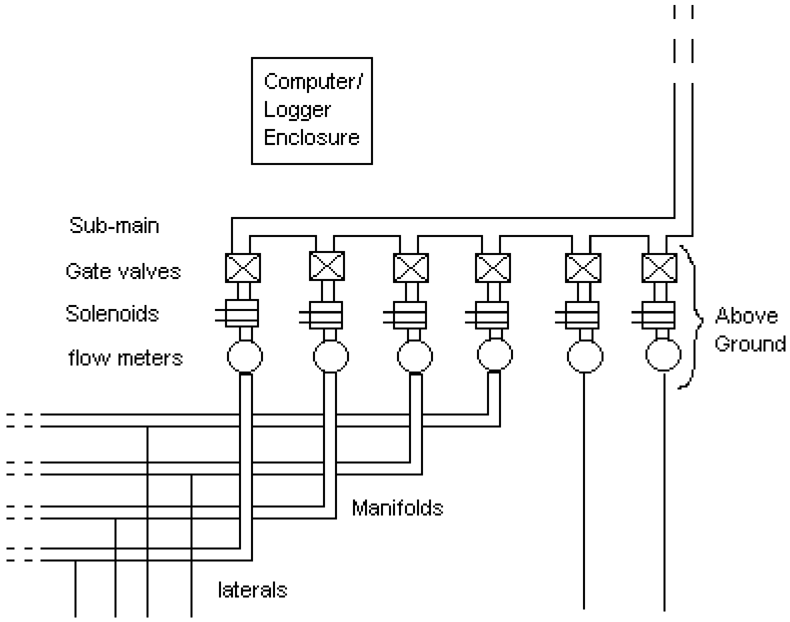


Figure 5.2. Arrangement of sub-main, valves, flow meters, manifolds and laterals in WUE trial.

Irrigation Schedule

One of the conclusions of the Irrigation System experiment stated that the irrigation control system was not flexible enough to allow optimal management of the buried drip irrigation products. It has also been stated that schedule design for CRZI should be based on managing the water contained in the soil above the CRZI 'V'.

The volume of the 'V' was calculated to be in the region of $7x10^{-3}$ m^3m^{-1} (7 L m^{-1}). Assuming a soil bulk density of 1340 kg m^{-3} and allowing 8% for 'blind pores', leaves an effective porosity of approximately 3 L m^{-1}. Using this information the time taken to increase the soil water content in the 'V' by 5% is approximately 2.6 minutes for CRZI High Flow, and 4.2 minutes for CRZI Low Flow. Assuming 1.8 m row spacing, 0.2 mm of water is applied in this time. To supply a peak plant water use of 10 mm/day would require 50 such 'pulses' throughout the day or every 30 minutes. Now there is a serious practical limitation on the minimum pulse time. This is the 'system fill time', or the time required for the whole irrigation system to reach operating pressure. The higher the fill time/operating time ratio, the lower will be the distribution uniformity. It is recommended this ratio should not exceed 5% (Claude Phene, pers comm).

It was therefore accepted that through practical constraints, the aim of managing the water inside the 'V' could only be partially met.

The irrigation schedule was monitored by tensiometers (the placement of which is described in the following section). Each morning, tensiometers in two control treatments were read and an irrigation depth estimated to maintain the soil matric potential in the range of –20 to –30 kPa. Being managed daily, this allowed small adjustments to be made to the irrigation application.

Control Software

The ultimate aim of the control system was to provide automatic irrigation through a sensor (dual probe heat pulse) feedback loop. Installation of instruments at the same positions in each treatment and applying the same re-irrigation rules through a processor, was the best independent method for supplying each treatment with exactly the amount of water it required. Unfortunately, due to failure of the heat pulse sensors, the feedback loop was not utilised and the backup sensors (tensiometers) had to be used to develop the schedule.

After reading the tensiometers, a daily irrigation depth was input into the computer. The software would then calculate the required volume and through applying a mean flow rate for each treatment, the time the solenoids should be kept on. The software then split the total time into pulses to apply the calculated volume, at a rate of 1 mm per hour (approximately ½ hour on/off).

Solenoid control was provided from the parallel port of a 386 PC. Software (QuickBASIC) was written to provide the following functions :

1. Operate solenoids.
2. Display current solenoid status and date/time of last solenoid event.
3. Display current flow meter reading and daily application totals.
4. Interrogate logger and display soil water content data.
5. Display irrigation set points.
6. In *automatic* mode, compare mean SWC with set point and turn on/off solenoid if SWC is below/above set point.

7. Allow automatic irrigation pulsing with input depth and frequency parameters.
8. Record and backup all data.

A flow chart of the irrigation control algorithm and sample input screen, are presented in the Appendix, (Figure 12.5 and Figure 12.6).

5.3.3 Instrumentation

A good knowledge of the soil water status was paramount to ensure precise irrigation scheduling. To achieve this, both SWC and matric potential were measured during this trial.

Heat Pulse Sensors.
Dual-probe heat pulse sensors were used to measure SWC. The main calculations will be discussed below.

An energy balance approach was used by Tarara and Ham (1997) to calculate SWC from soil heat capacity through the following equation (de Vries, 1963) :

$$\rho c = 1.92X_m + 2.5X_o + 4.18\theta_v \qquad \text{Equation 5.1}$$

where : ρc is soil heat capacity and X_m, X_o and θ_v are the mineral, organic and water fractions of the soil.

Solving for θ_v :

$$\theta_v = (\rho c - 1.92X_m - 2.5X_o)/4.18 \qquad \text{Equation 5.2}$$

For an instantaneous heat pulse, the solution for volumetric heat capacity (Campbell *et al*, 1991) is :

$$\rho c = \frac{q\,t_h}{e\pi r^2 \Delta T_m} \qquad \text{Equation 5.3}$$

where : ρc = soil volumetric heat capacity (J m^{-3} $^{o}C^{-1}$)

q = heat input (W m^{-1}) r = probe spacing (mm)

t_h = heat pulse duration (s) ΔT_m = max temperature change at sensing probe (^{o}C)

For a heat pulse duration of 8 seconds and probe spacing of 6 mm, Equation 5.3 simplifies to :

$$\rho c = \frac{26022q}{\Delta T_m}$$ Equation 5.4

The probe uses a simple 3-wire resistance bridge, consisting of the heater resistance and a reference resistor (1 KΩ) in series. Heat input per unit probe length (q) is then calculated using Ohm's law :

$$q = I^2 R_h/L$$ Equation 5.5

where R_h/L is resistance of the heater per unit length (Ω m^{-1}).

The heating current (I) is calculated from the voltage (E_r) across the probe reference resistor (R_r) :

$$I = E_r/R_r$$ Equation 5.6

Thus, the following parameters were measured prior to commencement and remained constant throughout the trial. They are presented in the Appendix (Figure 12.8).

1. Reference resistance (R_r) – voltmeter (1KΩ).
2. Heater resistance (R_h) – voltmeter.
3. Probe length (L) – controlled by supplier (30 mm).
4. Soil mineral fraction (X_m) - measured from soil bulk density samples taken at installation site of each probe.
5. Soil organic fraction (X_o) – measured from same samples using permanganate digestion.

The following variables were logged at every reading time :

1. Maximum temperature change at sensing probe (ΔT_m).
2. Mean voltage across the probe reference resistor (E_r).

Sensor control and logging was performed by a Campbell 21X data logger (Campbell Scientific Australia, Townsville, Queensland) and a flow chart of this operation is included in the Appendix (Figure 12.7). Each sensor was connected to the logger via a wire pair, to power the heater and a copper constantan thermocouple wire, to measure temperature. A total of twelve sensors were used, six in each of the two control treatments. One shallow and one deep sensor were buried in each of 3 rows per treatment. The rule used to site the shallow sensor was ’50 mm above and lateral to the closest saturated zone’ (Figure 5.3). The deep sensor was placed directly beneath the pipe at a depth of 0.4 m. Readings were taken half hourly as this was the minimum interval for the number of probes used (each probe taking 1.5 minutes to read).

Sensors were installed horizontally into the undisturbed side of a small trench dug beside the pipes. Soil was removed in layers and when replaced was repacked to a similar bulk density.

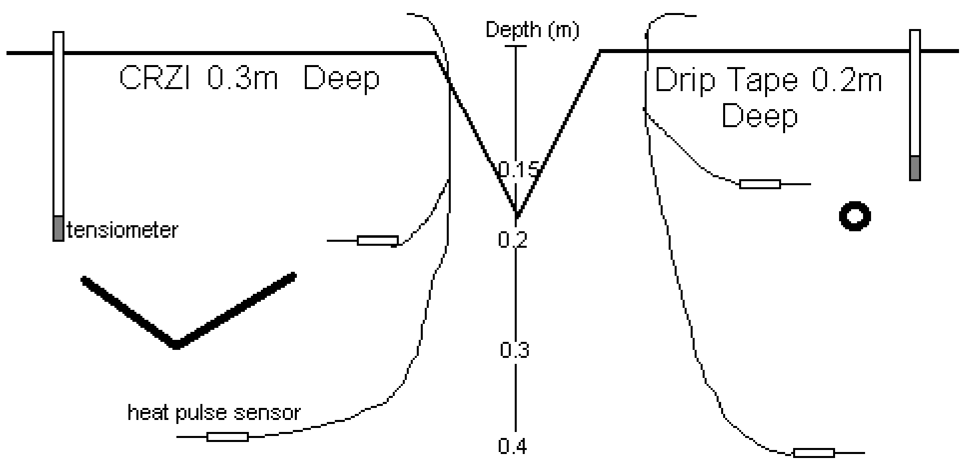


Figure 5.3. Installation position of tensiometers and heat-pulse sensors.

Only four of the original twelve sensors were still functioning at the end of the season. A faulty heater was invariably the cause of failure. Although not fully investigated, the diagnosis was thought to be a short between the thermochrome wire and the probe (hypodermic needle) inside which the wire was coiled.

Tensiometers

One tensiometer was installed in every row as a backup when the heat pulse sensors began failing. These were placed in an equivalent position to the shallow heat pulse sensor. Readings were taken at approximately 9am every day.

Time Delay Reflectometry (TDR)

A portable Trase TDR was also used to measure surface SWC during the wetting up phase. Measurements were taken following equivalent application depths (23 mm) and 15 hours of redistribution. A single 0.1 m TDR probe was inserted vertically in the bed centre and again at 0.3 m off-centre of each replicate.

5.3.4 Crop

Rock melon (*Cucumis melo* cv Hyline) seeds were planted every 0.4 m giving a total of 100 seeds per row. Wetting up of the beds prior to seeding began on 8 December 1997. The irrigation schedule adopted added 1 mm hr^{-1} with redistribution time varying with the measured treatment flow rate (Table 5.2).

Table 5.2. Irrigation schedule for wetting up of beds prior to sowing.

Manifold	Flow Rate ($L\ hr^{-1}\ m^{-1}$)	mm hr^{-1}	Time for 1 mm (min)
CRZI Low Flow (Treatments 3 + 4)	3.3	1.8	33
CRZI High Flow (1 + 2)	5.8	3.14	19
Drip Tape (5+6)	3.75	2	30
Drip Tape (7)	4	2.2	27

Seeds were planted into holes cut into the plastic mulch. Planting took place on 17 December 1997. An emergence count on 23 December (7 DAS) indicated low plant numbers. Reasons for this were surface crusting, causing the epicotyl to rupture, and insect damage. A second seeding was carried out on 23-24 December, followed by an application of Lorsban (chlorpyrifos) at the rate of 30 ml per plant, using a concentration of 70 ml Lorsban per 100 L of water.

A downy mildew outbreak necessitated spraying with Ridomil (mancozeb/metalaxyl) at the rate of 2.5 kg ha^{-1} on 13 January 1998 (28 DAS). Calixin (tridemorph) at the rate of 120 ml ha^{-1}, was used to treat Powdery mildew at the same time.

First flowering occurred on 15 January 1998 (30 DAS). Petiole nitrate samples were taken weekly from 21 January 1998 (50 DAS). For each sample, petioles were removed from the first fully open leaf, near the growing tip of 10 plants. The petioles were crushed and the juice sample analysed using a Horiba hand held spectrophotometer. The crop was fertigated with calcium nitrate at the rates of 20, 10, and 10 kg N ha^{-1} at 51, 63, and 66 DAS.

First harvest occurred on 2 March 1998 (76 DAS) and continued every second day until 27 March (100 DAS) when the arbitrary threshold of less than one bin (300 kg) was picked in one day from the 0.3 ha site. Fruit was harvested from a 20 m plot in the centre of each row. The weight of each fruit was recorded.

Establishment

In addition to plant emergence counts, a further two sets of data were collected during this period. Weed growth in the unmulched row ends was recorded 20DAS as a measure of the soil surface area sufficiently wet to allow germination. Soil water content was also measured at two points in the bed, to determine quantitatively the extent of water distribution.

Parallel Crop Experiment

The trial was synchronised with a NSW Agriculture demonstration comparing the WUE of furrow and SDI irrigated melons. The 1 ha demonstration was performed on the property of the largest rock melon grower in the MIA, 5 kilometres from CSIRO. The soil was similar to that found at CSIRO, and identical crop variety and planting configurations were used. The objective of the NSW Agriculture trial was to showcase the environmental and economic advantages of changing to a more controlled irrigation system. Simultaneous operation of the two trials presented a great opportunity to compare a ‘micro-managed’ crop (CSIRO) with a more commercially managed crop (NSW Agriculture) given similar climatic conditions.

5.4 Results and Discussion

5.4.1 Crop Performance

Plant Emergence Counts

Overall initial emergence was poor, especially in the unmulched row ends (Table 5.3). A second seeding increased emergence in the mulched area to an acceptable level but despite a large increase, emergence in the unmulched area was still poor.

In the mulched section of the field initial emergence (counted 7 DAS) ranged from 68% for Deep CRZI Low Flow to 48% for surface Drip Tape. These treatments were also the only two to show a significant difference in emergence (Table 5.3).

The unmulched section showed a consistent pattern, where all CRZI treatments had significantly greater emergence than the Drip Tape treatments. These ranged from 45% for the two CRZI Low Flow treatments, to 3% for Surface Drip Tape (Table 5.3).

The second sowing achieved a mean emergence of 90% in the mulched area, with no significant difference between treatments. In the unmulched area, a range from 61% (Shallow CRZI Low Flow) to 28% (Surface Drip Tape) was observed, with CRZI still producing greater emergence than Drip Tape.

The second planting showed far greater success, due to seeds being placed into wetter soil.

Table 5.3. Crop establishment. Percentage of seeds planted.

	First Sowing		Second Sowing.	
Treatments	Mulched (%)	Unmulched (%)	Mulched (%)	Unmulched (%)
Surface Drip Tape	48	3	86	28
Shallow Drip Tape	65	14	90	41
Shallow Drip Tape (own schedule)	54	15	88	33
Deep CRZI Low Flow	68	45	93	55
Deep CRZI High Flow	62	43	82	51
Shallow CRZI High Flow	66	33	92	45
Shallow CRZI Low Flow	55	45	92	61
LSD (p<0.05)	19	15	ns	19

The main reasons for plant fatality were insects and surface crusting. In the second sowing insects were treated with insecticide. Emergence was worse in the unmulched area, due to the surface drying to a harder and drier crust. The treatments which saturated the soil surface (all Drip Tape treatments), exacerbated the problem. As CRZI relies more on capillary upflow, the wetting of the surface is controlled more by the soil and hence is slower and less disruptive to the surface soil structure. As the plastic mulch inhibited drying of the surface, the crust was of lower strength, and thus did not present as much of a limit to emergence.

Weed Growth

Weed production in the unmulched row ends, as measured 10 DAS, ranged from 0.49 kg m^2 for Shallow Drip Tape, to 0.13 kg m^2 for Deep CRZI High Flow (Table 5.4). Shallow Drip Tape produced significantly more weeds than all CRZI treatments, except Shallow CRZI Low Flow. Surface Drip Tape produced significantly more weeds than the two CRZI High Flow treatments.

Figure 5.4. Weed growth on melon beds, (left) Shallow Drip Tape, (right) Deep CRZI Low Flow.

It must be pointed out that these results occurred in the absence of rain. In the event of rain, more even weed growth would be expected. The results also rely on the assumption that weed seed is uniformly distributed in the soil.

Table 5.4. Weed dry matter production in unmulched row ends.

Treatment	kg m^2
Surface Drip Tape	0.45
Shallow Drip Tape	0.49
Shallow Drip Tape (own schedule)	0.35
Deep CRZI Low Flow	0.21
Deep CRZI High Flow	0.13
Shallow CRZI High Flow	0.17
Shallow CRZI Low Flow	0.41
LSD ($p<0.05$)	0.27

Surface SWC Variation

In the bed centre position volumetric SWC varied from 32.8% (Surface Drip Tape) to 22.5% (Deep CRZI Low Flow) (Table 5.5). Installation depth was the major factor affecting surface wetting with the Shallow CRZI installations being significantly wetter (average 5.6%) than the Deep installations. Although still evident, this effect is lessened at 0.3 m from the bed centre with the only significant difference being between Surface Drip Tape and Deep CRZI.

Table 5.5 .Volumetric SWC of beds following 23 mm irrigation during wetting up phase (10DAS).

	Bed Centre (%)	0.3 m from Bed Centre (%)
Surface Drip Tape	32.8	24.9
Shallow Drip Tape	27.9	23.6
Shallow Drip Tape (own schedule)	27.8	23.0
Deep CRZI Low Flow	22.5	18.2
Deep CRZI High Flow	22.3	18.1
Shallow CRZI High Flow	28.2	22.5
Shallow CRZI Low Flow	27.8	22.3
LSD ($p<0.05$)	4.8	5.6

The data supports the observation from the Irrigation System experiment that Drip Tape has a concentrated wetting pattern immediately above the pipe and wets out from the centre, whereas CRZI has a more diffuse pattern, which emerges at the surface in a more even manner.

This may mean less water is required by the Drip Tape for the purposes of attaining adequate SWC for crop establishment (assuming the system is installed under the crop row). However, the greater volume of soil wetted by the CRZI is available for the plant after germination, with the polyethylene membrane reducing water moving below the irrigation source.

The combination of the three data sets of emergence counts, weed bioassay, and SWC measurement shows that CRZI has attained equivalent emergence, with significantly less surface wetting and significantly less weed growth in the absence of rain.

Water Added During Emergence

Irrigation was applied in 3 periods of 3 days each before and after sowing. As the seed was planted just below the soil surface, visual inspection was used to decide when soil was sufficiently wet. The irrigation requirement for crop establishment varied from 65 mm (Drip Tape) to 84 mm (CRZI High Flow) (Table 5.6). This range represents only 50% of that used to establish the Sweet Corn in the Irrigation System experiment. This is because melon seed was planted in the centre of the bed. However, this amount is still markedly above the estimated 30 mm required were sprinkler irrigation employed. Again, CRZI was seen to require more water to wet the bed centre to an adequate level.

Once more, the point is made that moving water upward is the greatest challenge for SDI systems, especially at crop establishment stage.

Table 5.6. Irrigation application during emergence (mm).

	Period			
Manifold	8-11Dec	16-19Dec	28Dec-2Jan	Total (mm)
CRZI Low Flow (Treatments 3+4)	23	26	29	78
CRZI High Flow (1 + 2)	25	27	32	84
Drip Tape (5+6)	23	28	14	65
Drip Tape, own schedule (7)	26	26	14	66

Fertigation

The target petiole nitrate threshold for a good melon crop is 2000 ppm (Kelly and Salvestrin, 1996). The petiole nitrate contents were as high as 7000 ppm when the first reading was taken, but declined sharply after the first appearance of fruit, indicating increasing sink strength of the fruit (Figure 5.5). Although not analysed further, nitrate levels appear higher in the shallow treatments especially after the first fertigation.

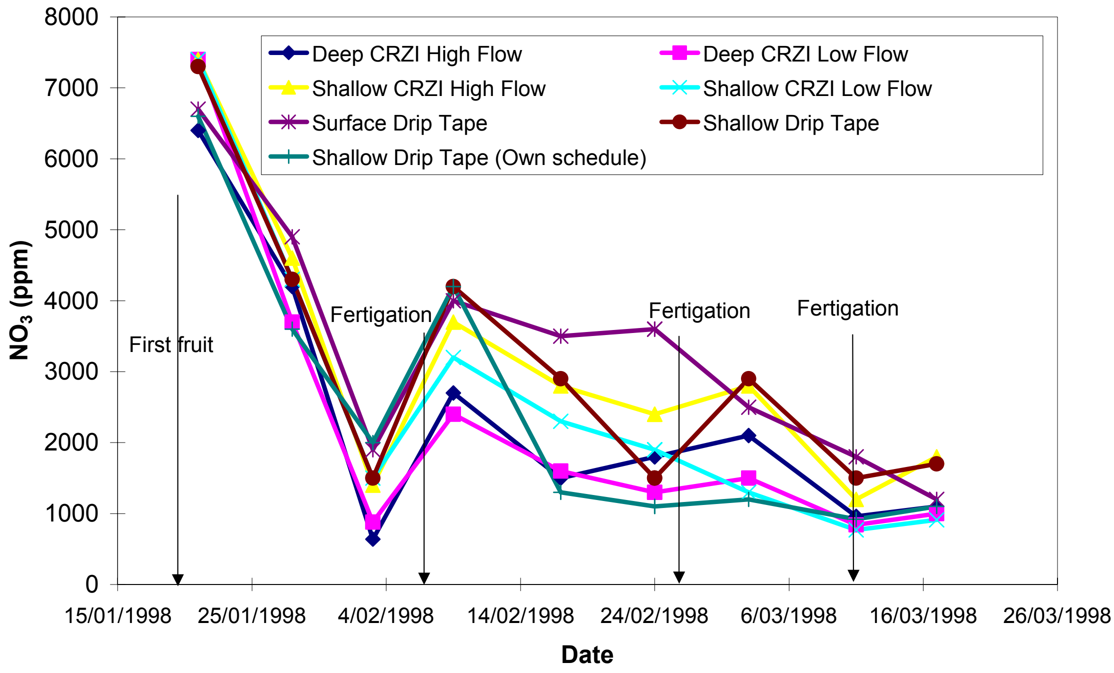


Figure 5.5. Petiole nitrate levels per treatment.

Quantity of Irrigation Water Applied

A total of 69 mm rain fell during the trial. Rain has not been considered in any calculations, due to the plastic mulch diverting it from the beds and into the furrows. It was thought unlikely that the rainfall had contributed significantly to the crop water use.

Irrigation scheduled with reference to the tensiometers irrigation application varied from 374 mm for the Drip Tape control, to 287 mm for Drip Tape under control of CRZI schedule (Table 5.7). The 6 treatments under control of the CRZI (#2) schedule should have all received similar applications. This is true for the Drip Tape (#3) but an undetected slow leak in the CRZI High Flow (#4) resulted in an excess of approximately 50 mm being applied.

Table 5.7. Irrigation application and Estimated ETc.

Solenoid/Treatment	Initial Wetting (mm)	Growth Phase (mm)	Total (mm)
1. Drip Tape own schedule	66	308	374
2. Deep and Shallow CRZI Low Flow Control	69	221	290
3. Surface and Shallow Drip Tape	64	223	287
4. Deep and Shallow CRZI High Flow	52	272	324
Estimated Crop Water Use (ET_c)	35	295	430

The estimated crop water use, ETc in Figure 5.6 was calculated using the following crop factors taken from (Meyer, 1996) : 0.2 (1-10DAS), 0.4 (11-24DAS), 0.65 (25-85DAS), 0.4 (86-100DAS). The excess water applied for emergence was sufficient to meet plant requirements for a further 3 weeks. Irrigation recommenced again on 22 January 1998. In the growth phase, it can be seen that the Drip Tape control is being supplied with water at the same rate as the estimated use. All CRZI treatments received a deficit when compared with the estimated crop use. This difference has important implications for yield and is discussed further in the next section.

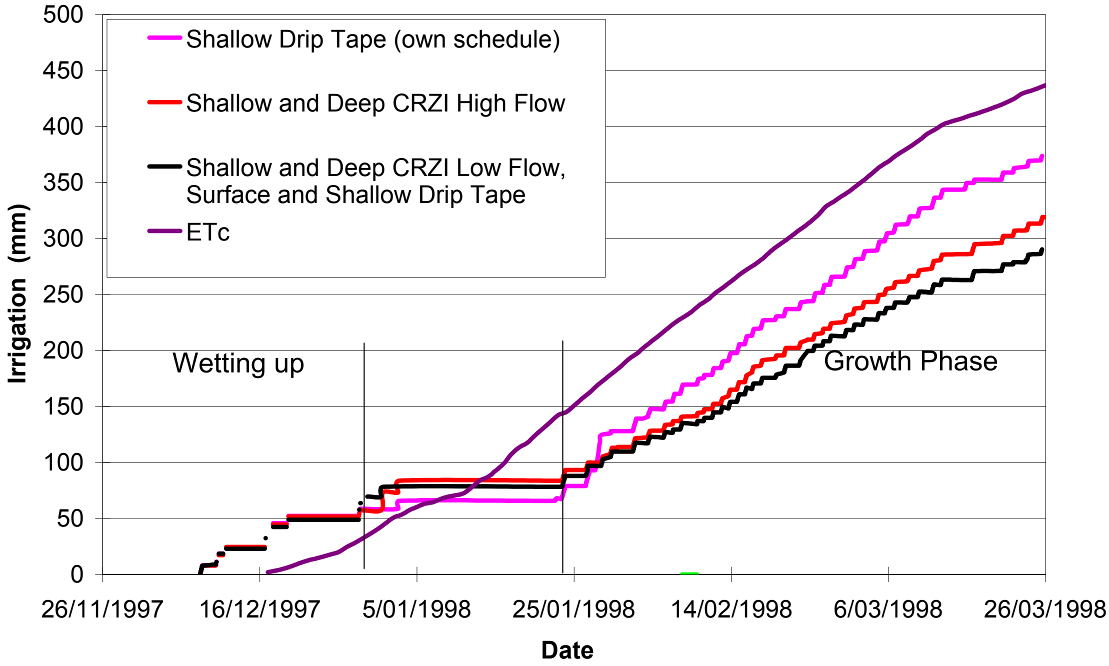


Figure 5.6. Cumulative irrigation and estimated crop water use.

Yield and WUE

The greater amount of water applied to Drip Tape (own schedule) produced the highest yield of 44.2 t ha^{-1} (Table 5.8). The four CRZI treatments were the next highest with Surface and Shallow Drip Tape being the lowest yielding treatments with 32.3 and 34.9t ha^{-1}, respectively. All yields were in excess of the region average of 25-30 t ha^{-1}.

The Shallow CRZI Low Flow had a significantly higher WUE than Surface Drip Tape (Table 5.8). However, if the wetting-up volume is ignored, both the Shallow and Deep CRZI Low Flow treatments exhibited a significantly higher WUE than the self-scheduled Drip Tape. The extra water required by the latter treatment did not produce a proportional increase in yield.

Table 5.8. Rock melon yield and water use efficiency.

Treatments	Yield ($t\ ha^{-1}$)	WUE (inc. wetting up) ($kg\ kL^{-1}$)	WUE (not inc. wetting up) ($kg\ kL^{-1}$)
Surface Drip Tape	32.3	11.2	14.5
Shallow Drip Tape	34.9	12.2	15.6
Shallow Drip Tape (own schedule)	44.2	11.8	14.4
Deep CRZI Low Flow	36.3	12.5	16.4
Deep CRZI High Flow	38.9	12.0	14.3
Shallow CRZI High Flow	40.6	12.5	14.9
Shallow CRZI Low Flow	38.1	13.1	17.2
LSD ($p<0.05$)	4.6	1.5	1.9

The total quantity of water applied to the various treatments accounted for 83% of the variation in yield (Figure 5.7). The first impression is that the lower total water applied to CRZI was insufficient to avoid some yield reducing stress. However, as following sections explain, the opposite may be true – yield decrease may have been due to aeration or waterlogging stress. This is also evidence that Drip Tape allowed a greater proportion of water to drain past the root zone ie. a portion of the extra 80 mm applied to the Drip Tape treatment went to enhance yield and a portion drained past the root zone.

The FullStop treatment has been included for further comparison. The FullStop controlled a 0.2 m deep Drip Tape product.

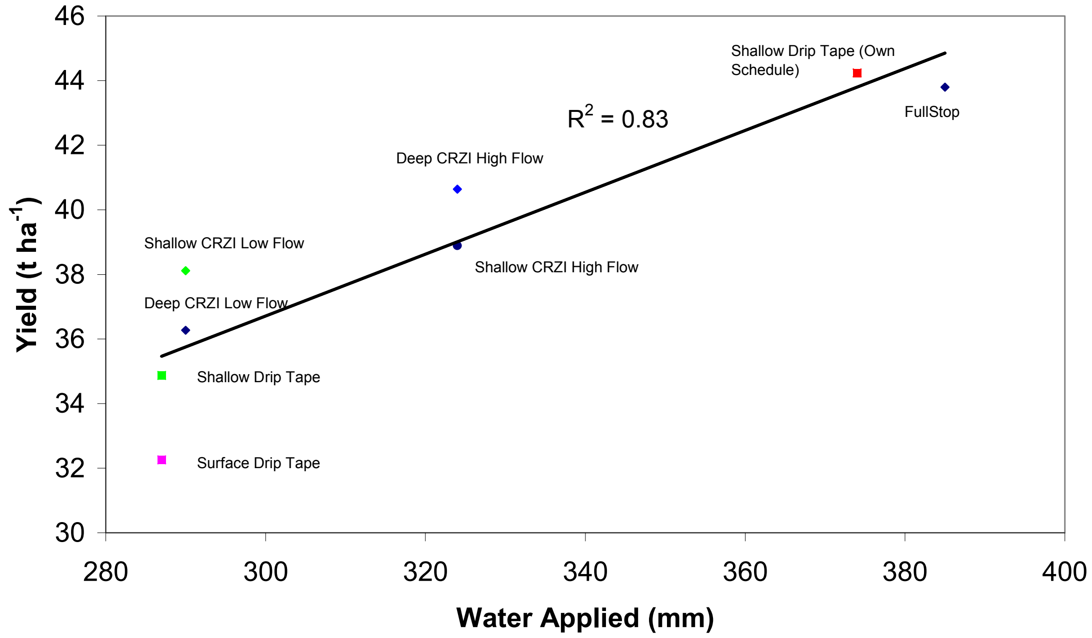


Figure 5.7. Yield as a function of irrigation amount.

A general crop yield response to water application follows 3 stages (Feddes *et al*, 1978) (Figure 5.8). These are water deficit stress stage (A-B), a plateau where water is not limiting (B-C), and a yield decreasing stage where aeration stress occurs (C-). The experiment aimed to produce maximum yield on all treatments (point B) but the results indicate there was further potential for increased yield (Figure 5.7). Whether yields were depressed through aeration or deficit stress will be discussed further.

Point B represents maximum WUE. In practice, it is very difficult to attain this standard and due to the risk of yield reduction, producers generally apply water in excess of that required. The financial penalty of over-irrigating is minimal, due to the large disparity in water price, plus cost of application and irrigated crop return. Comparison of the two Shallow Drip Tapes in Figure 5.7 shows that at \$350/t rockmelons and \$20/ML water the self-scheduled control has increased gross income by \$700/ha for the cost of \$20/ha water.

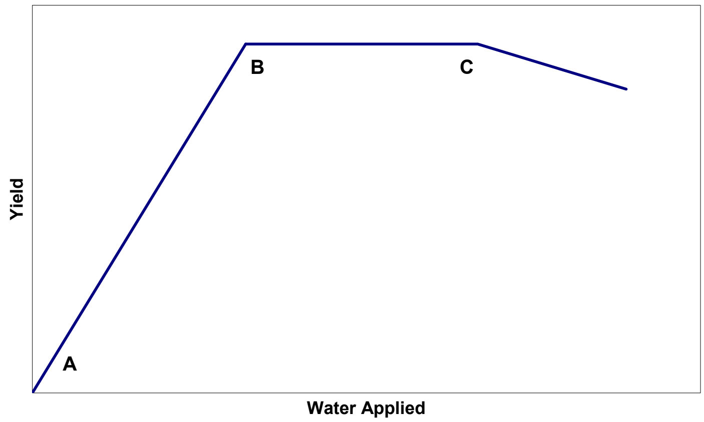


Figure 5.8. Generic yield response to applied water (Feddes *et al*, 1978).

5.4.2 Tensiometer Scheduling Performance

Irrigation scheduling was performed with reference to six tensiometers in the CRZI Low Flow and Drip Tape treatments (one per replicate).

To present this data 3 soil matric potential brackets were selected relative to their implication for plant stress (Taylor and Ashcroft, 1972 ; Hanks and Ashcroft, 1980):

1. WET : matric potential > -10 kPa = Too wet, no irrigation required
2. GOOD : -10 kPa ≥ matric potential ≥ –39 kPa = No irrigation required
3. DRY : matric potential < -40 kPa = Too dry, irrigation required

The following graphs (Figure 5.9 and Figure 5.10) show the number of tensiometer readings in each bracket for a given day. For instance, both control treatments commenced with 6 WET tensiometer readings. In the CRZI, these progressively dried until 23/1/98 when all tensiometer readings were below -40 kPa.

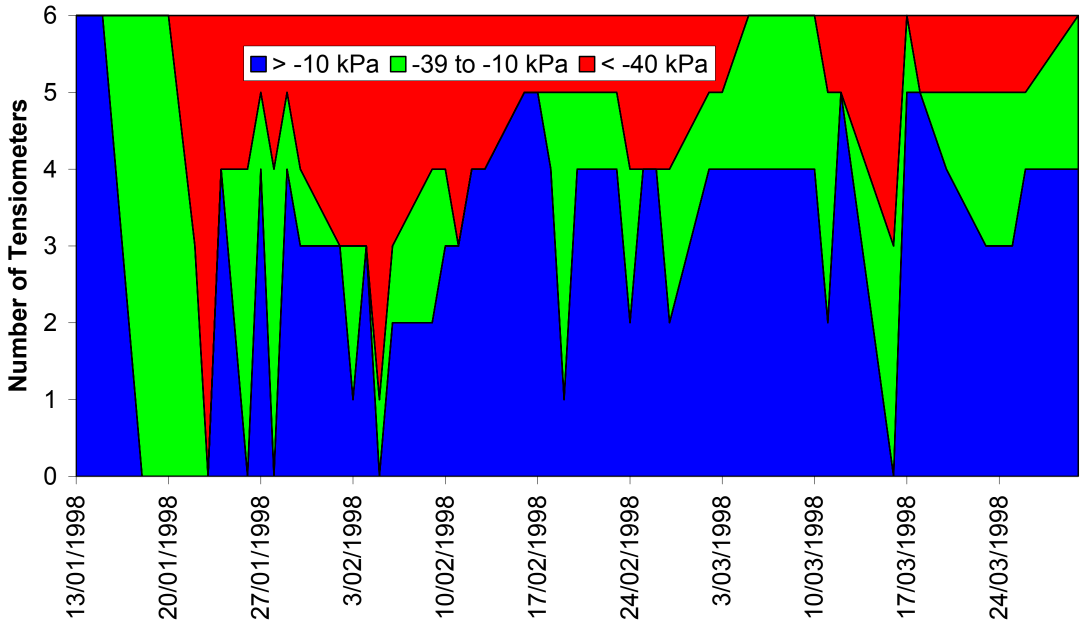


Figure 5.9. CRZI Control - number of tensiometer readings in each tension bracket at 9AM.

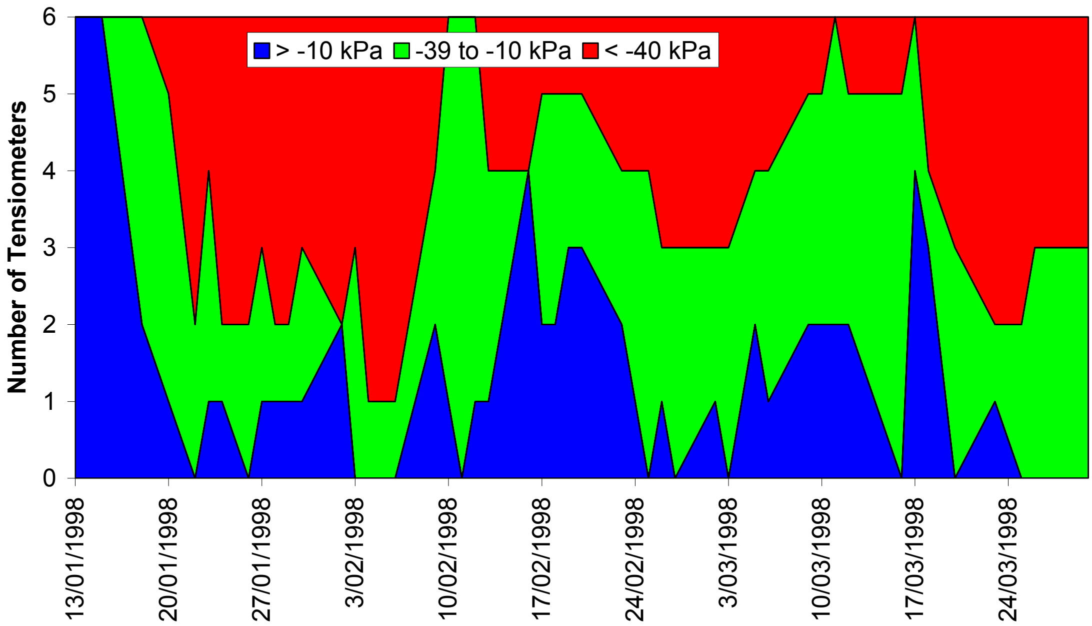


Figure 5.10. Drip Tape Control - number of tensiometer readings in each tension bracket at 9AM.

Qualitatively the graphs show CRZI maintained a greater number of WET readings and less DRY readings than the Drip Tape. Tensiometers in the Drip Tape spent more time in the GOOD range. Considering the values (Table 5.9), it can be seen the CRZI readings are WET twice as often as those in the Drip Tape (51% *vs.* 23%). In fact, CRZI readings spent 75% of the time above –40 kPa compared with 63% for Drip Tape. It should be noted that all CRZI/Drip Tape soil matric potential differences are highly significant.

This result has been attained while applying less water and indicates that CRZI has a positive effect in holding water in the root zone.

Table 5.9. Percentage of tensiometer readings in each bracket for whole season.

Soil Matric Potential Bracket	Drip Tape (%)	CRZI (%)	Sig. Different ($p<0.01$)
WET (> -10 kPa)	23	51	✔
GOOD (-39 to -10 kPa)	40	24	✔
DRY (< -40 kPa)	37	25	✔

The two previous figures (Figure 5.9 and Figure 5.10) demonstrate the problem a producer faces with spatial variability when scheduling a whole field. While the aim was to maintain all tensiometer readings in the ‘GOOD’ range, one can see that out of 77 days, the aim was met for 2 days in the CRZI (19-20 Jan) and one day in the Drip Tape (11 Feb). Variation in soil, installation, blocked drippers, and plant condition can all contribute to the range of values measured and makes the problem of dealing with spatial non-homogeneity very difficult. The most common solution would be to irrigate to keep the driest tensiometer in the right range, thus causing over-irrigation in other parts of the field but not risking yield decline.

5.4.3 The Paradox

The three sets of data (yield, water use and root zone matric potential) present a contradiction.

CRZI has maintained a wetter rootzone with a smaller irrigation volume than Drip Tape. This difference supports the hypothesis that CRZI has a positive effect in keeping the wetted zone higher in the soil profile, offering protection against drainage loss.

However, has the greater moisture availability produced a greater yield? The answer is no. Drip Tape with its own schedule produced higher yield than all other treatments.

The best explanation is a combination of deep percolation loss from Drip Tape and aeration stress in the CRZI treatments.

The WUE of Drip Tape was lower than CRZI due to deep percolation losses beneath the plant root zone. That is, a proportion of the extra water applied to the Drip Tape treatment contributed to extra yield, while the remainder was not able to be used by the crop.

Few references to aeration stress thresholds are available in the literature. Thresholds for 5 crops (cucurbits not included) presented by Wesseling (1991) indicate matric potentials above –3kPa may cause yield loss. Further analysis of the tensiometer data revealed CRZI was wetter than –3kPa for significantly ($p<0.01$) more days than Drip Tape (15% *vs* 3%). Although not measured, CRZI could be expected to present a significant barrier to root zone development, given that rock melon is a tap-rooted plant and the crop was planted directly above the bed centre. Soil structure may also affect aeration problems, as oxygen diffusion depends on pore connectivity (Hopmans, pers comm). Massive soils, like the soil in the experiment, possess few macro-pores to aid in diffusion. Thus, the yield decease may have been caused by two inter-related factors. Firstly, the soil in the CRZI 'V' was wetter than –10 kPa, and there may have been a significantly greater proportion of the root system in the 'V'.

Further evidence of the optimal management of the Drip Tape (own schedule) treatment is presented in Figure 5.11, which compares the cumulative irrigation amount for the two tensiometer scheduled treatments, with the FullStop scheduled treatment. The Drip Tape and FullStop treatments have attained very similar irrigation amounts through totally independent methods. In fact, the FullStop was automatically scheduled ie. when the sensor detected the soil was full it closed the solenoid, and all data was remotely retrieved from Canberra. This supports the opinion that the FullStop irrigated the crop with the 'right' amount and may even indicate these treatments were watered at the point of maximum WUE (B in Figure 5.8).

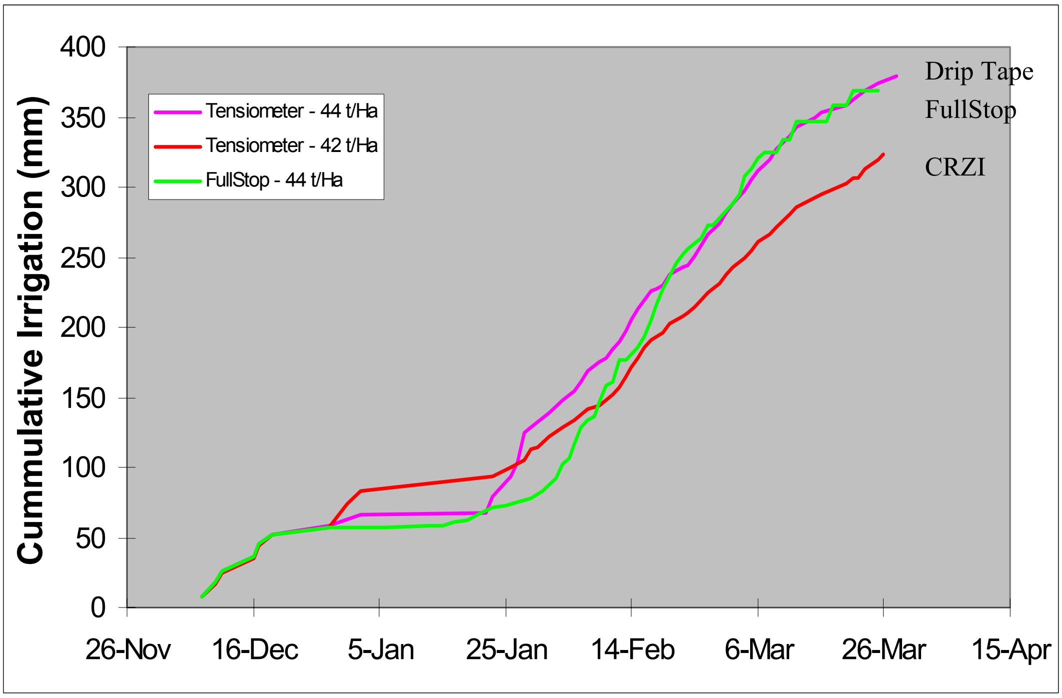


Figure 5.11. Cumulative irrigation of the treatments scheduled with tensiometer and FullStop. The yield of the crop is shown in the legend.

Comparison between Parallel Crops

The mean WUE in this experiment and NSW Agriculture WUE (Hickey, pers comm.) for SDI were both more than twice the furrow irrigation WUE (Figure 5.12). This difference was achieved through both maintaining a more even soil water content with less water and extension of the window for crop harvest. Furrow irrigators must cease irrigation prior to harvest to ensure dry ground for the harvest machinery. There is a harvest period of about 2 weeks where plants rely on soil stored water before fruit quality becomes unacceptable. Conversely, SDI is capable of watering the crop while harvesting proceeds, thus maintaining plant and fruit quality.

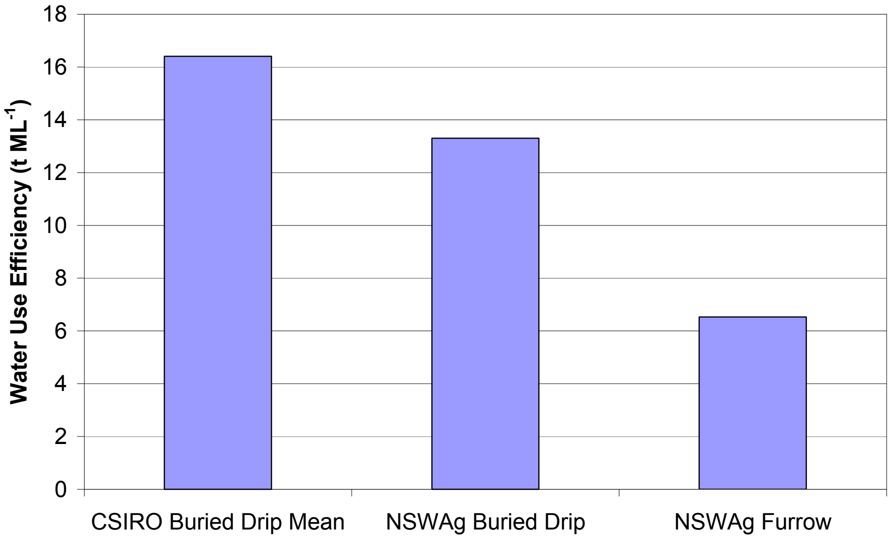


Figure 5.12. CSIRO and NSW Agriculture SDI/furrow irrigation comparison.

For this particular season and soil type, the comparison clearly demonstrates the advantages of SDI, particularly where water availability is a limiting factor. The grower has seen this advantage and has since converted 150 ha from furrow to SDI.

The difference between this WUE experiment and NSW Agriculture SDI results may be attributed to the difference in management levels. This crop was both small (0.3 ha), well supplied with monitoring equipment and was the sole research activity enabling stricter management and rapid reaction to changing conditions. This is not always possible with commercial operations where optimisation must be carried out at a larger scale to satisfy a mean crop requirement.

5.5 Conclusions

The WUE experiment added more focus to both the control of irrigation and the products being tested.

The WUE trial produced some very interesting conclusions during both the establishment and growth phases :

1. Identification of different wetting methods between CRZI and Drip Tape

Water distribution away from CRZI relies more on soil-controlled capillarity, thus producing a slow and diffuse wetting front which helps maintain a stable soil structure.

In contrast, Drip Tape produced a rapid, concentrated wetting front, which quickly saturates the soil surface and seemed to exacerbate the surface sealing problem.

Consequences of this difference have been significantly higher crop establishment and lower weed growth by CRZI.

2. *Establishment required more water for CRZI*

The larger soil volume influenced by CRZI means a greater volume of water is required for crop establishment than Drip Tape. However, both methods are well in excess of estimated requirements for sprinkler establishment.

3. *CRZI produced significantly greater WUE after establishment*

Despite producing the highest yield, the greater amount of water applied to the Drip Tape (own schedule) did not produce a proportional increase in yield. It was hypothesised that this difference was due to two factors. Firstly, a greater percentage of water applied to the Drip Tape (than CRZI) percolated below the crop root zone and was unusable by the crop. Secondly, higher root zone water potential may have caused aeration stress in the CRZI treatments.

4. *Subsurface Drip Irrigation more than doubled the WUE of furrow irrigation (for this season and soil type)*

6 Crop Establishment Experiment

6.1 Introduction

The literature review has stated that crop establishment is such a challenge for SDI, that growers rely on second irrigation systems such as portable sprinklers to perform this critical function. Hence there is economic and practical advantage in being able to efficiently establish and grow the crop using one system. Again, it is hypothesised that the CRZI concept of producing a wide, more diffuse wetted area with protection against drainage loss is well suited to enhance crop establishment.

6.2 Aims

i) To measure differences in the extent of wetting patterns between several SDI configurations and installation depths.
ii) To evaluate subsequent success in crop establishment.

6.3 Methods

6.3.1 Site Preparation

The treatments were installed in the northern end of the field used for the Irrigation System experiment (see Appendix Figure 12.1). Prior to installation of the drip products, the field was deep cultivated (0.3 m) in two directions and shallow cultivated (0.15 m) with a rotary hoe. Following installation, a further two passes were performed with a vertically tyned rotary cultivator, to break up some of the larger clods to form a seed bed.

6.3.2 Experimental Design

A Randomised Complete Block Design was used with six blocks and six treatments (Table 6.1). Plots were split in the centre and a surface applied gypsum treatment was randomly assigned to half of the subplots. These treatments enabled comparison of soil wetting and crop establishment using conventional drip tape and CRZI at depths of 0.2 m and 0.3 m. Two additional treatments were included. These were CRZI with high flow rate without a top PE layer, and CRZI at low flow rate with in-solution gypsum. The plots were 30 m in length and 2 m wide, with a drip line in the centre. The in-solution gypsum was supplied by an Ag Solution Master®† injection machine. A saturated solution (28 meq/L or 560 ppm Ca) was prepared by adding 3 kg superfine gypsum (21% Ca) to the 1100 L water tank. Surface gypsum was applied at the rate of 15 kg per subplot, giving an equivalent rate of 5 t ha^{-1} for the 30 m^2 area. The gypsum was incorporated into the surface by raking.

Table 6.1. Treatments for Establishment experiment.

	Treatment Name	**Emitter**			
		Discharge ($L\ hr^{-1}$)	Spacing (m)	Specific Discharge Rate ($L\ hr^{-1}\ m^{-1}$)	Depth (m)
1	Shallow Drip Tape	1	0.2	5	0.2
2	Shallow CRZI	1	0.2	5	0.2
3	Deep Drip Tape	1	0.2	5	0.3
4	Deep CRZI	1	0.2	5	0.3
5	Deep CRZI + in solution gypsum	1	0.2	5	0.3
6	Deep High Flow CRZI	4	0.5	8	0.3

6.3.3 Crop management and irrigation schedule

English spinach (*Spinacia oleracea cv* Polka) seed was sown in the plots at a depth of ~0.02 m with 0.02 m between seeds and 0.125 m between rows, giving a population of 400 seeds m^{-2}. Seed rows were perpendicular to the drip lines, to enable determination of the effect of wetting on the lateral extent of crop establishment.

Water was first applied to the trial on 28 Feb 1998. The trial was only irrigated during the daytime, to enable observation of daytime wetting patterns and overnight redistribution wetting patterns. Irrigation was stopped once either the wetting pattern ceased, moving laterally, or the wetting patterns merged with adjacent rows. This varied from 6 days for the Shallow Drip Tape and Deep CRZI High Flow to 9 days for the Deep CRZI.

6.3.4 Measurement of wetting and crop establishment

Measurements of surface wetted width, water content, and crop establishment were confined to the area between the wheel tracks formed during sowing. Fourteen sampling units, 1m in width, were available for gravimetric sampling (4) and measurement of surface wetted width (10) (Figure 6.1).

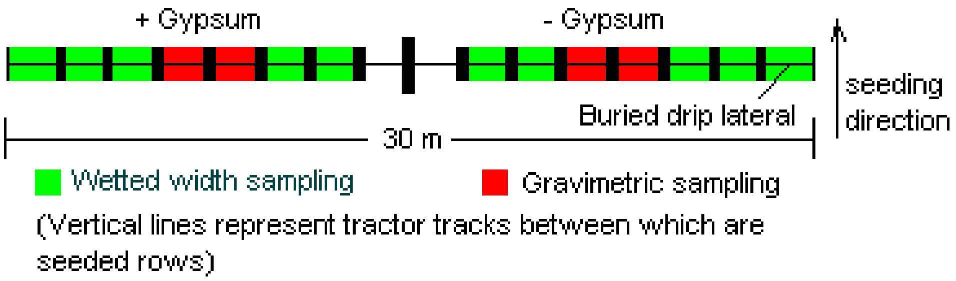


Figure 6.1. Measurement unit layout for lateral.

The width of the surface wetting pattern was measured through visual inspection of soil colour change at 20 permanent positions in each row, twice per day. This gave 1440 data points per day. The data collected within a plot were averaged to give a mean surface wetted width (W) for each plot. At the same time, applied water depth (I) was determined from reading the flowmeter for each treatment. This enabled a *surface wetting efficiency* (E_{sw}) to be calculated, where :

$$E_{sw} = \frac{W}{I}$$

6.3.5 Profile Wetting Patterns

The wetting patterns for soil profiles were measured gravimetrically for four treatments (Shallow CRZI and Deep CRZI and Shallow Drip Tape and Deep Drip Tape).

Three soil cores were taken from each treatment at distances of 0, 0.2, and 0.4 m from the row centre. The cores were taken to a depth of 0.5 m and separated into 0.1 m increments. Sampling was carried out at three times : prior to and at two and four days after irrigation commenced. All treatments had received approximately 40 and 100 mm irrigation respectively, at the later measurement times.

6.3.6 Crop Establishment

Crop establishment was measured 17 days after irrigation first commenced, which was 8 days after irrigation had ceased on the last treatment. A 2 m x 1 m quadrat with 0.1 m gradations was placed at two positions in each sampling unit. The number of seedlings in the quadrat was then counted.

6.3.7 Statistical analysis

Subsamples were averaged to give a single measurement for each parameter per plot. ANOVA was used to test for statistical significance between the treatments.

6.4 Results and Discussion

6.4.1 Installation depth

Measurement of installation depth for the drip lines showed that the Deep Drip Tape had the largest discrepancy with the intended depth (Table 6.2). The remaining treatments were slightly shallower than the desired depth (Table 6.2). The two main causes of variation were i). soil settling and changes caused by surface levelling operations after installation, and ii) a high clay layer at about 0.25-0.35 m depth which limited deep cultivation and operation of tape installation machinery.

Table 6.2. Design depths of drip line for each irrigation treatment.

Treatment	Design Depth (m)	Measured Depth (m)*
Shallow Drip Tape	0.2	0.19
Shallow CRZI	0.2	0.18
Deep Drip Tape	0.3	0.24
Deep CRZI	0.3	0.28
Deep CRZI + In-solution Gypsum)	0.3	0.27
Deep High Flow CRZI	0.3	0.27

* Measured depths are means for six rows.

6.4.2 Wetted Width

The development of the surface wetted area with irrigation was almost identical for Shallow Drip Tape and Deep Drip Tape (*Figure 6.2*). This can be partly attributed to the installation of the Deep treatment at 0.24 m rather than the target depth of 0.3 m. The Shallow CRZI and Deep High Flow CRZI were slightly slower to wet the surface. The Deep CRZI was the slowest of all treatments but in-solution gypsum substantially improved surface wetting.

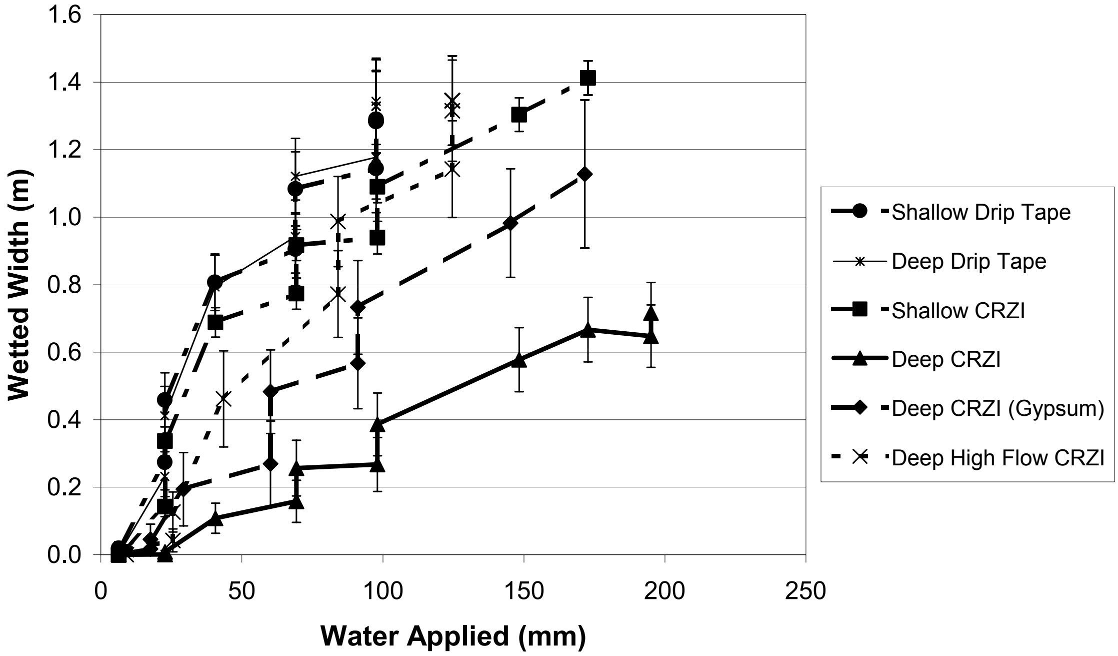


Figure 6.2. Effects of SDI treatments on wetting of the soil surface. Error bars indicate ±1 standard error.

6.4.3 Surface Wetting Efficiency

For statistical analysis of treatment effect on wetted width, the width attained after 100 mm water application was determined and Surface Wetting Efficiency calculated for each plot (Table 6.3). The Shallow and Deep Drip Tape treatments were the most efficient (13), followed by Deep High Flow CRZI and Shallow CRZI (11). Efficiency was significantly reduced ($p<0.05$) by the two Deep CRZI treatments. However, the Deep CRZI with in-solution gypsum was significantly ($p<0.05$) more efficient (7) than Deep CRZI (4).

Table 6.3. Statistical comparison of Surface Wetting Efficiency (E_{sw}).

Treatment	Wetted width after 100 mm irrigation (m)	E_{sw}*
Shallow Drip Tape	1.3	13
Shallow CRZI	1.1	11
Deep Drip Tape	1.3	13
Deep CRZI	0.4	4
Deep CRZI + In-solution Gypsum)	0.7	7
Deep High Flow CRZI	1.1	11
LSD ($p<0.05$)		3

* E_{sw} calculated as wetted width(m)/irrigation depth(m).

These data highlight the high water usage required when attempting crop establishment with SDI. For instance, in the Irrigation System experiment, roughly 125 mm irrigation water was required for the wetting pattern to reach the seed in a bed situation, with 2 rows of crop 0.6 m either side of the buried drip. This may represent 25-40% of the total crop water requirement for the whole season. In contrast, it is estimated a sprinkler system could achieve the same results with approximately 30 mm (eg. Mailhol *et al*, 2001).

The higher flow rate of the Deep High Flow CRZI appeared to compensate for the extra depth of installation. This version was designed with a flow rate significantly higher than the soil hydraulic conductivity to promote water flow along the geotextile and therefore aid lateral wetting between emitters. This flow rate was high enough to produce a pressurised zone through the geotextile and act more like a *point source*, as occurred with the Drip Tape. Free water was observed on the soil surface of this treatment.

6.4.4 Effect of In-Solution Gypsum

When comparing the Deep CRZI and Deep CRZI + in-solution gypsum treatments, dissolved gypsum was of significant benefit in increasing the proportion of water reaching the soil surface and increasing the wetted width (Figure 6.2, Table 6.3). In this study, the EC of the irrigation water was 0.13 dS m^{-1} and so a beneficial effect on the soil hydraulic properties would be anticipated.

6.4.5 Effect of Surface Applied Gypsum

Gypsum placed in the irrigation water has already shown significant benefit in increasing the surface wetted width. In contrast, surface applied gypsum has shown no significant effect on the surface wetted width (Table 6.4).

Table 6.4. Effect of surface applied gypsum on surface wetted width (m) after 100 mm irrigation.

Treatments	+ Surface Gypsum	- Surface Gypsum
Shallow Drip Tape	1.37	1.21
Shallow CRZI	1.10	1.08
Deep Drip Tape	1.35	1.33
Deep CRZI	0.39	0.38
Deep CRZI + In-solution Gypsum)	0.71	0.75
Deep High Flow CRZI	1.17	1.12
LSD ($p<0.05$)	ns	

The use of surface gypsum for SDI may be described as impractical, in that no benefit is possible until water reaches the surface and causes dissolution. Some advantage may be possible from those products that produce free water on the soil surface, thus allowing some gypsum dissolution but no such effect was apparent from this trial. Products designed to minimise surface wetting (ie CRZI) have little potential benefit from surface applied gypsum. However, the longer term benefits to soil structure of slow dissolution of surface applied gypsum, are recognised.

6.4.6 Day/Night Surface Wetting Pattern Comparison

It was observed that wetting patterns continued to advance at night, despite the irrigation system being off. This was caused by redistribution of water after irrigation had ceased, and was probably enhanced by low evaporation rates at night, as investigated by Philip (1997).

The wetting front velocity (WFV) for day and night for each plot was calculated as the change in width (mm) per hour (Table 6.5). In general, the treatments had a greater effect on the daytime velocity (5-21 mm hr^{-1}) than night-time velocity (6-13 mm hr^{-1}). This was attributed to small scale runoff of the free water which pooled on the soil surface from all Drip Tape treatments and the Deep High Flow CRZI treatment. At night, the WFV advanced at approximately the Hanwood Loam saturated hydraulic conductivity (K_s) value of ~10 mm hr^{-1} (Hornbuckle and Christen, 1999). The proximity of the saturated zone to the surface will affect the hydraulic conductivity that drives this velocity. Thus, Deep CRZI experienced significantly lower wetting front velocities than all other treatments. Adding gypsum to the irrigation water was again of significant benefit.

Table 6.5. Comparison of day and night surface wetting front velocity (WFV) among irrigation treatments.

Irrigation Treatments	Day WFV (mm hr^{-1})	Night WFV (mm hr^{-1})	Mean
Shallow Drip Tape	12	11	11
Shallow CRZI	10	9	9
Deep Drip Tape	16	11	14
Deep CRZI	5	6	5
Deep High Flow CRZI	21	13	17
Deep CRZI + in solution Gypsum	9	13	11
LSD ($p<0.05$)	5		

6.4.7 Wetting Method

Free water was observed on the soil surface during irrigation for all Drip Tape treatments. Water appeared to reach the surface via the soil disturbed during installation of the drip line, rather than through visible tunnelling, and moved across the soil surface before infiltrating back into the soil, at some distance from where it emerged. Wetting of the surface was slower for CRZI and created a uniform strip the same width as the product, but with no visible surface saturation. Surface flow may be seen as an advantage, in that it results in higher wetting efficiency. However, it leaves the process highly dependent on the condition of the soil surface, which can potentially be a major limitation for surface applied systems as saturation may exacerbate surface sealing problems (Schwankl *et al,* 1990).

Analysis suggests differences between CRZI and Drip Tape in patterns of soil wetting relate to fluxes of water at the drip emitter. Assuming the area around a single drip emitter where water is first applied equals 3.14×10^{-4} m^2 (disc with diameter 0.02m), a 1 L hr^{-1} flow rate results in a depth equivalent application rate of 3200 mm hr^{-1}. Use of Shallow or Deep CRZI increases the application area to 300×10^{-4} m^2 (0.15 m wide geotextile with a 0.2 m emitter spacing). This results in an application rate of 33 mm hr^{-1}, which approximates the Hanwood Loam K_s of ~10 mm hr^{-1} far more closely than the Drip Tape application rate. The mean CRZI application rate is similar to the soil's infiltration rate and explains why its wetting method is by capillarity, rather than mass flow. In contrast, the enormous fluxes at the Drip Tape emitter quickly saturates the soil surface, particularly when first installed (Figure 6.3).

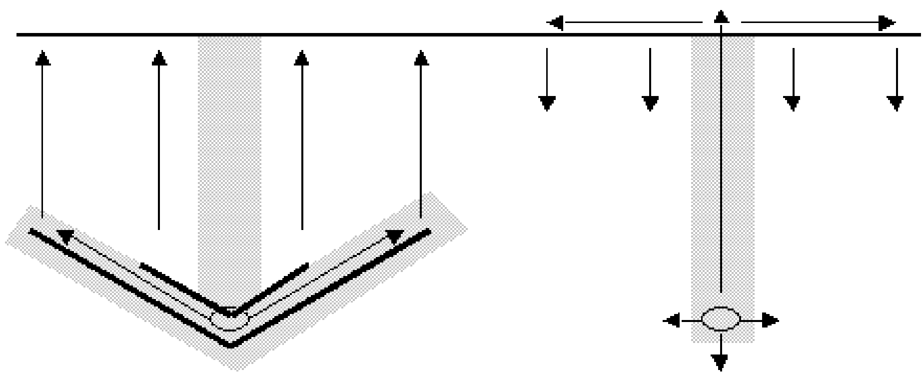


Figure 6.3. Different wetting methods of CRZI (left) and Drip Tape (right). Shading denotes area of soil disturbed during installation.

In the current trial, the surface was left with 'micro furrows' perpendicular to the pipe, after the seeding operation. These aided the overland lateral spread, just as seeding parallel to the rows may have impeded lateral spread and produced very different outcomes. Evidence of this difference in wetting method can be seen by contrasting the 'bulging' wetted edge produced by the Drip Tape, with the extremely uniform edge of the Shallow CRZI (Figure 6.4).

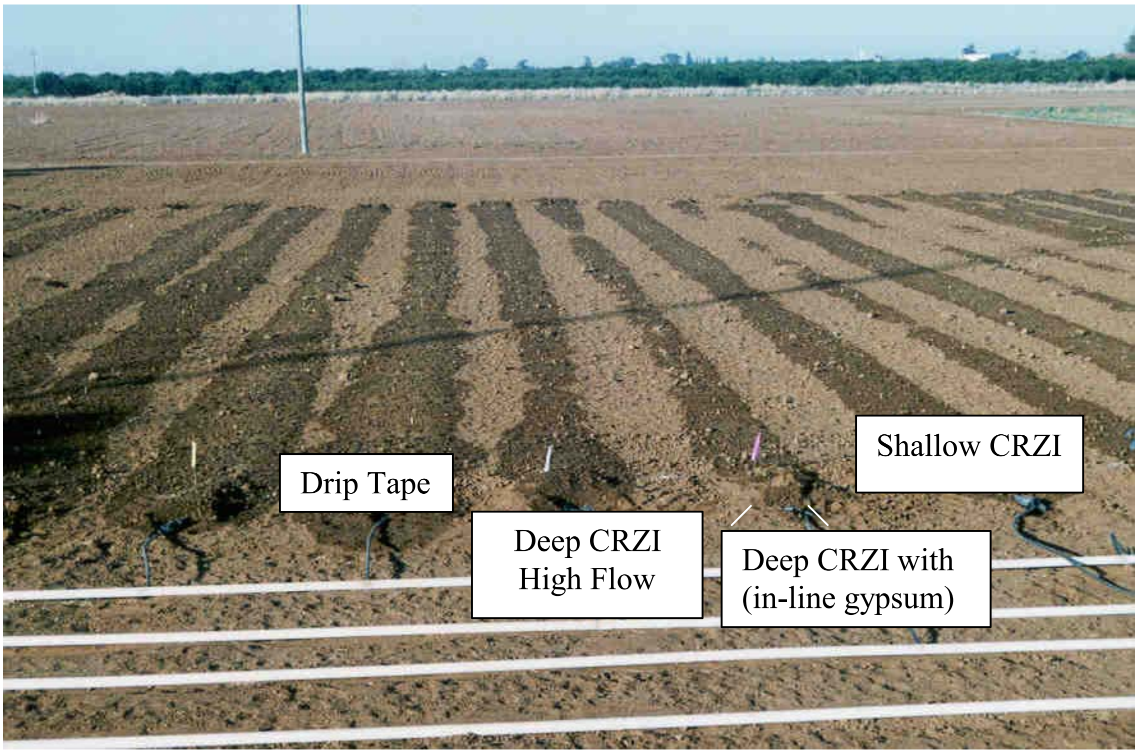


Figure 6.4. Field view of surface wetting pattern variation.

6.4.8 Profile Wetting Patterns

The final soil sampling was carried out 4 days after irrigation commenced, when all treatments had received approximately 100 mm. Volumetric soil water contents, are presented at two positions: (1) the surface (0-0.1 m) in the centre of the bed (Surface), and (2) the 0.2-0.3 m deep layer, 0.2 m lateral to the bed centre (Deep) (Table 6.6). The data show significantly lower wetting of the surface in the Deep CRZI treatment, consistent with the slow advance of the wetting front. In contrast, in the 0.2-0.3 m layer, 0.2 m from the bed centre, the Deep CRZI had the highest soil water content (Table 6.6). This is the layer immediately adjacent to the edge of the CRZI dripline. Even with high water availability at 0.2-0.3 m, therefore, there was insufficient capillarity to bring water to the surface. This is further evidence that 0.3 m is too deep for SDI on this soil, unless gypsum is used in the irrigation water. However, deep percolation may be increased under this treatment.

Table 6.6. Effect of irrigation treatments on volumetric soil water content (cm^3cm^{-3}) after 100 mm irrigation.

Treatment	Surface [1]	Deep[2]
Shallow Drip Tape	0.30	0.29
Shallow CRZI	0.29	0.33
Deep Drip Tape	0.33	0.32
Deep CRZI	0.22	0.36
LSD (P=0.05)	0.06	ns

[1] 0-0.1 m depth and above drip line, [2] 0.2-0.3 m depth and 0.2 m from drip line

The graphing package (SURFER™) was used to interpolate SWC data and produce vertical 2-D contour maps perpendicular to the pipe. In general, CRZI and Drip Tape treatments exhibited similar final wetting patterns. With reference to the previous section I conclude that this occurred through very different processes. However, due to the limited temporal information gained from gravimetric sampling, these differences were not captured. The graphs showing water content change relative to the initial soil water content, are presented in the Appendices (Figure 12.11 to Figure 12.14)

6.4.9 Crop Establishment

The mean maximum establishment for all treatments was 60% (range from 54 to 66%), indicating that 40% of seed was either non-viable or was in poor contact with soil. It is assumed this accounted for a similar proportion of seed in each treatment. As seed was sown uniformly, any variability in establishment was thus attributed to the amount of water available from the soil immediately surrounding the seed. A field view of the establishment results are shown in Figure 6.5.

Figure 6.5. The establishment trial with gypsum injection machine in the background (l) and uniform crop establishment produced by Shallow CRZI (r).

The band where 30% or more of the plants established (ie 50% of maximum emergence) was taken as the threshold below which establishment was unsatisfactory. Maximum establishment width for this criteria then varied from 0.25 m for Deep CRZI to 0.55 m for Shallow CRZI (Table 6.7) although differences were not significant ($p<0.05$).

Table 6.7. Plant establishment of seed sown in 0.1 m increments at distance (m) from row centre.

Treatment	Position (m from irrigation line)									
	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95
Shallow Drip Tape	58	58	57	56	39	19	11	9	2	0
Shallow CRZI	41	44	46	51	53	41	20	5	0	0
Deep Drip Tape	60	60	59	53	51	27	13	5	3	0
Deep CRZI	54	47	43	25	7	0	0	0	0	0
Deep CRZI + gypsum	65	62	60	49	35	17	13	8	3	0
Deep High Flow CRZI	59	58	60	55	45	21	9	3	0	0
LSD ($p<0.05$)	39	35	36	56	78	63	30	16	7	

Regression of width to 30% seedling establishment to wetted width accounted for 88% of variation (Figure 6.6). The results indicated that satisfactory establishment occurred over a width equal to 36% of the maximum wetted width. Wetted width may exceed establishment width because soil colour change occurs well below saturation and seed may be unable to imbibe water at this water content.

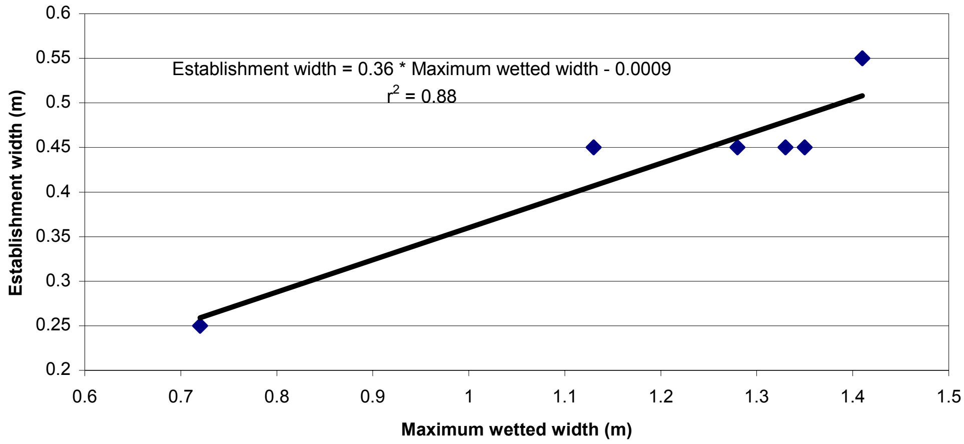


Figure 6.6. Regression of establishment and maximum wetted width for SDI treatments.

6.4.10 Recommendations for Crop Establishment

For crops requiring complete ground cover (eg pasture/lucerne) a dripline row spacing of no greater than 1 m is recommended for these soil conditions. For row crops (usually on beds) seed should be planted no greater than 0.4 m from the bed centre. Installation depth should be no deeper than 0.2 m. Given the positive effect of in-solution gypsum, its use is highly recommended. To maximise capillary flow the soil should be of a relatively fine tilth and consolidated after cultivation (eg. with a roller) to remove voids. Press wheels may be used to improve the soil-seed contact. These recommendations are only applicable for the sandy loam soil on which the trial was undertaken.

Irrigation system design that allows for crop establishment will invariably cost more. If designing a system for uniform crop coverage eg pasture/lucerne, then lateral spacing may be varied. A decrease in spacing from 1.2 or 1.5 m to 1 m, will mean an increase in drip tape density from 1700 to 3300 m ha^{-1}, respectively. The greater density will also mean that, at the same pump operating rate, more irrigation shifts will be required. For row crops, spacing is often not variable, due to its linkage to other equipment such as tractor and harvester width. This leaves depth of installation and number of laterals per row, as the main methods to decrease the seed to water-source-distance. Research in cotton has shown comparable yield between treatments, with drip tape below every row and every second row spacing (Figure 6.7) (Camp *et al*, 1997). Excellent establishment results are assured with every-row spacing, but an extra system cost of 30% is estimated.

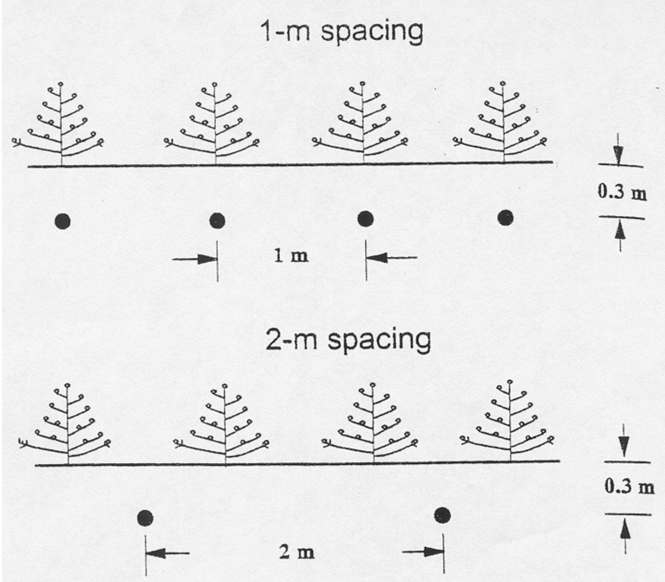


Figure 6.7. Subsurface drip spacing (Camp *et al*, 1997).

If the decision is made to use a second irrigation system for establishment, the most important consideration is choosing a system which will provide rapid coverage of the area and ensure the smallest establishment spread. Even a two day difference in first/last establishment can have a big effect on harvest uniformity of short duration crops. The advantage of using the drip system is, with a good design, all parts of the field receive very similar water amounts (±~5%). The data also shows that the surface wetting efficiency of SDI reduces with time, as the gravitation component dominates the capillary component of soil water movement. Therefore, one option to reduce the total amount of water, ensure satisfactory establishment and keep the SDI system cost low, is to use a combination of SDI and sprinklers. The SDI system can be turned on before seeding takes place. After seeding the sprinkler system can be moved quickly over the field to compliment the subsurface wetting. On the negative side, sprinkler systems require high pressure and cannot use drip system submains as hydrants. This means they must be supplied by separate, portable pipes. In California, such systems are commonly hired for the short establishment period.

6.4.11 Comparison of CRZI and Drip Tape

The combination of materials used in CRZI was designed to complement conventional Drip Tape and produce a wider lateral wetting pattern, while reducing deep drainage and surface tunnelling. However, this trial has shown that Drip Tape has produced the most efficient wetting of the soil surface. Soil type and condition have played a major role in this result. Evidence to support this is :

i) The trial found Drip Tape relied more on soil surface for overland water movement.

ii) There was a disturbed strip of soil immediately above the tape where installation occurred, that allowed preferential flow to the surface.

iii) Presence of perpendicular micro-furrows from seeding operation assisted overland lateral water movement.

iv) Presence of an impermeable B-horizon at 0.3-0.4 m that acted like the PE barrier on the CRZI treatments.

v) The medium texture (30% clay, 60% sand) promotes good capillary movement (Hanson *et al,* 1997).

vi) The soil is massive with no cracking to produce capillary barriers.

Optimal performance of CRZI would be expected in coarse textured soils prone to deep drainage and where drip irrigation has acknowledged problems with lateral wetting. The impermeable PE layer of CRZI is able to maintain a small saturated zone in all soils, irrespective of texture.

Due to the large pore size of coarser soils, the capillary force is weaker. The inverse of the 'α' term of the van Genuchten soil moisture retention equation (van Genuchten, 1980) is often referred to as the air entry value, or bubbling pressure and gives an indication of capillary length (van Genuchten *et al*, 1991). Variation in this term can demonstrate the change in capillary force with texture (Table 6.8). The combination of low capillary length/high K_s values makes sand highly susceptible to drainage. Conversely, clay has high potential for capillary movement but is limited by very low K_s values. Medium textured soils, such as the sandy clay loam used in the trial, are favoured as they have a compromise of capillary force and K_s.

Using this information it can be argued that CRZI will have the most benefit in light textured soils, where the polyethylene barrier both artificially increases the capillary length and reduces K_s in the zone above the barrier. Conversely, the product could be expected to have a lesser effect compared with conventional SDI in the sandy loam soil on which all experimentation has been performed.

Table 6.8. Variation of inverse of ‘α’ term with texture (Carsel and Parrish, 1988).

Texture	1/α (mm)	K_s (mm hr^{-1})
Sand	70	300.0
Loamy Sand	80	147.0
Sandy Loam	130	44.0
Loam	280	10.0
Silt	630	3.0
Silt Loam	500	5.0
Sand Clay Loam	170	13.0
Clay Loam	530	3.0
Silty Clay Loam	1000	0.7
Sand Clay	370	1.2
Silty Clay	2000	0.2
Clay	1250	2.0

6.5 Conclusions

Crop establishment with SDI can be difficult. The physics of soil water flow are such that in only the initial period of water application does upward movement through capillarity dominate downward gravitational flow. Thus, in requiring water to flow relatively large distances both upward and laterally to seeds, inevitably leads to inefficient water use when compared to a system such as sprinkler irrigation. This problem is exacerbated as the soil becomes both coarser textured and more structured. Further, prediction of soil wetting with SDI during crop establishment is extremely uncertain because of the many variables involved and therefore there is a strong need, until the processes are better understood, for site specific recommendations.

The hypothesis that CRZI had potential to offer better establishment than conventional Drip Tape was not found, as Drip Tape produced the highest Surface Wetting Efficiency. However, the trial did demonstrate differences in wetting method between the products. Drip Tape relied on free water moving to and across the soil surface, a potentially problematic effect that SDI seeks to avoid. Irrespective of soil type, CRZI is able to maintain a small saturated zone in the profile at the installation depth, which can move laterally and upwards through capillarity.

In general, the best establishment was achieved by treatments that support a 'top-down' method of wetting the soil surface (ie. Drip Tape). The CRZI treatments which matched the Drip Tape performance were i) shallow (<=0.2 m), ii).used in-solution gypsum, here applied only with Deep (30cm) CRZI, and iii). a high flow rate.

Even the most efficient SDI treatments still require far more water than sprinkler irrigation to obtain acceptable establishment.

Due to its high point-source application rate, water from Drip Tape moves quickly to and over the soil surface. In contrast, the area-source application of CRZI enables a 100 times lower rate, allowing the soil's capillarity to distribute water in a more diffuse manner. Drip Tape's reliance on the soil surface is seen as a disadvantage, as it is subject to surface variability and the sudden wetting from free water may even cause sealing problems. Had the trial been carried out on coarser textured soil, far different results would be expected where the Drip Tape would not have the drainage protection of the CRZI. Irrespective of soil type, CRZI is able to maintain a small saturated zone high in the profile.

The concept of Surface Wetting Efficiency was developed to compare the proportion of water moving upward from buried sources and being available for crop establishment. A new technique was then developed which used a crop as a bioassay to relate the water distribution to subsequent actual establishment width and density. The technique has the advantage of directly addressing the question at hand, without relying on assumptions made about secondary measurements eg soil water content or soil colour change. The establishment threshold is graphically indicated. In employing the technique, consideration must be made of the effect of sowing direction. In this trial one third of the row length available to measurement was lost to tractor tyre width. The ‘microfurrows’ formed during sowing may also affect surface water distribution. Rolling the soil after sowing may reduce the effect.

Even the most efficient treatments still require far more water than sprinkler irrigation (~150 mm vs ~30 mm) to obtain acceptable establishment. In the absence of rain, a combination of sprinkler/SDI irrigation may then be the most efficient method for gaining rapid and uniform crop establishment.

7 Tunnelling – Vineyard Trial

A vineyard was constructed in Nov/Dec 1996 as part of the CRZI research. While many parameters were measured including yield, pruning weight, colour, sugar content, anthocyanin content, and irrigation applied these will not be presented due to the following :

1. Newly planted grapevines are not well suited to short term trials, as full production is not reached until 3-5 years. This factor lessens the probability of obtaining significant results eg. yield difference, in the short term.

2. The site was too steep for efficient furrow or SIP irrigation management. The SIP treatment was changed to surface drip in the second season.

3. The CRZI treatments were changed after the first season. The change was made by installing the second product in the opposite side of the grapevine row. Although not measured, such a repositioning of the wetted zone would cause disruption to the root structure.

4. Large differences became apparent between results from the two blocks. Yield and pruning weight were both reduced in the west block. A soil problem was suspected but not tested.

There were however several findings which are very relevant and worthy of discussion. During the third season, tunnelling was observed in the subsurface drip product in the vineyard and this was further investigated.

7.1 Methods

The vineyard was located in the same field as other experiments (Appendix, Figure 12.1). Soil type is described in General Methods.

The vineyard consisted of 2 identical blocks of grafted Shiraz scion on Ramsay rootstock vines. Each block comprised 22 rows, with 50 m length and 3.33 m row spacing, giving a total vineyard area of 0.7ha. Vines were planted with a 1.8 m spacing in the row. Four irrigation treatments were used, i) Subsurface Drip (Netafim Dripline 2000, 0.6 m emitter spacing, 2.4 L/hr flow rate) ii). Furrow, iii). SIP, iv). CRZI 'Perforated Pipe'. Each treatment was made up of 5 rows consisting of 3 measurement rows and 2 buffers. All buried treatments were inserted approximately 0.4 m deep and 0.4 m lateral to the vine rows. In year 2 (1998) the CRZI 'Perforated Pipe' was replaced with CRZI High Flow.

7.1.1 Measurements

Tunnelling

In the third season a count of emitters with surface tunnels per row was made for the Subsurface Drip and CRZI High Flow treatments.

Soil Water Distribution

Variation in soil water distribution between CRZI and Subsurface Drip was measured by gravimetric soil sampling. Soil cores 35 mm in diameter were taken to 0.5 m depth at distances of 0, 0.2, 0.4 and 0.6 m perpendicular to the crop row and divided into 0.1 m intervals. These cores were taken when the soil was relatively dry and repeated after a large application of water (approximately 20 mm). Soil water content and bulk density were measured for each increment. Three replicates were taken from a row in each treatment and these were averaged. Using the SURFER graphing package, it was possible to plot the change in profile volumetric water content after an irrigation.

7.2 Results and Discussion

7.2.1 Tunnelling

Tunnel formation, as observed in this experiment, was consistent with that described in the literature and previously in the “Irrigation System Experiment”. Tunnel openings were surrounded by fine clay particles, and the tunnel itself was filled with sand. The tunnels were very similar in shape to those formed in the Irrigation System experiment (Figure 4.10). After formation, water continued to follow this preferred path to the surface and appeared within minutes of irrigation starting.

Tunnels were found in both the CRZI High Flow and the Subsurface Drip treatments. As a percentage of total emitters, Subsurface Drip (43%) exhibited significantly ($p<0.05$) greater tunnelling than CRZI High Flow (5%) (Table 7.1).

Table 7.1. Tunnel variation between sub-surface irrigation treatments.

	Subsurface Drip	CRZI High Flow
Mean tunnels per 50 m row	36.0	5.5
Total emitters	83	100
%	43.2	5.5
LSD ($p<0.05$)	32	

Further weight is added to this result when considering the CRZI emitter flow rate (3.5 L hr^{-1}) is 30% greater than the Subsurface Drip flow rate (2.4 L/hr). This is further evidence of the difference in ‘wetting method’, as introduced in the ‘Crop Establishment’ chapter. If using the same application per unit area calculations, CRZI High Flow has an area application rate of 6.7 mm hr^{-1}, while the Subsurface Drip has an application rate of 7680 mm hr^{-1}.

Soil Water Distribution

There was minimal increase in water content between the Drip Tube and vine row (Figure 7.1). The zone of greatest water increase was not centred around the source but in the surface/inter-row sector. A trench was dug perpendicularly to the drip tube and visual inspection provides good agreement with the data (Figure 7.2).

In contrast, the CRZI wetting pattern is centred above the product and is quite symmetrical (Figure 7.1). The implication here is that CRZI is wetting the root zone at a depth of 0.3-0.4 m, whereas water emitted from the Subsurface Drip is effectively bypassing the root zone and the vines must utilise water that reenters the soil from the surface.

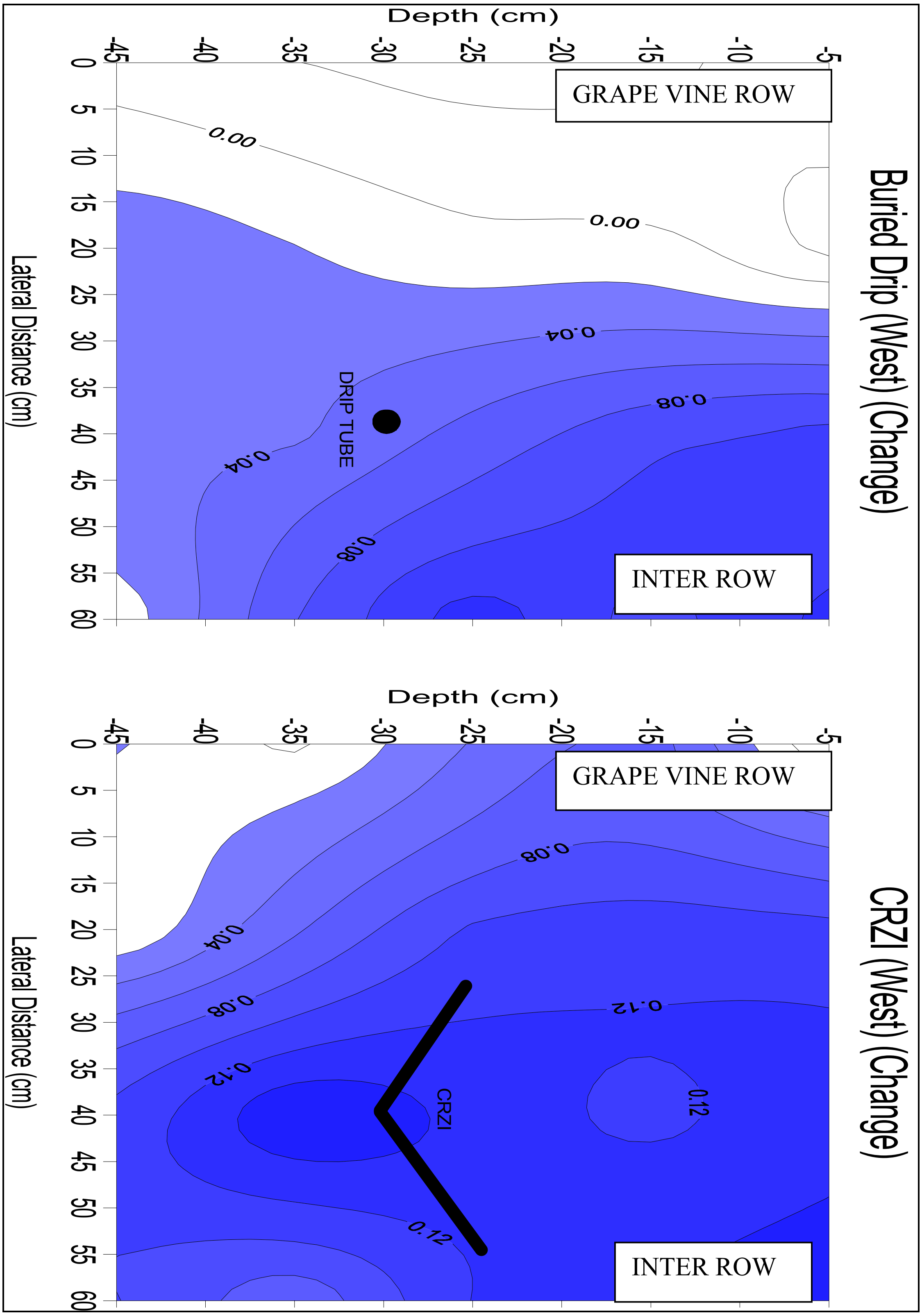


Figure 7.1. Wetting patterns for CRZI and Subsurface Drip showing soil water content increase (m^3/m^3) after a 20 mm irrigation.

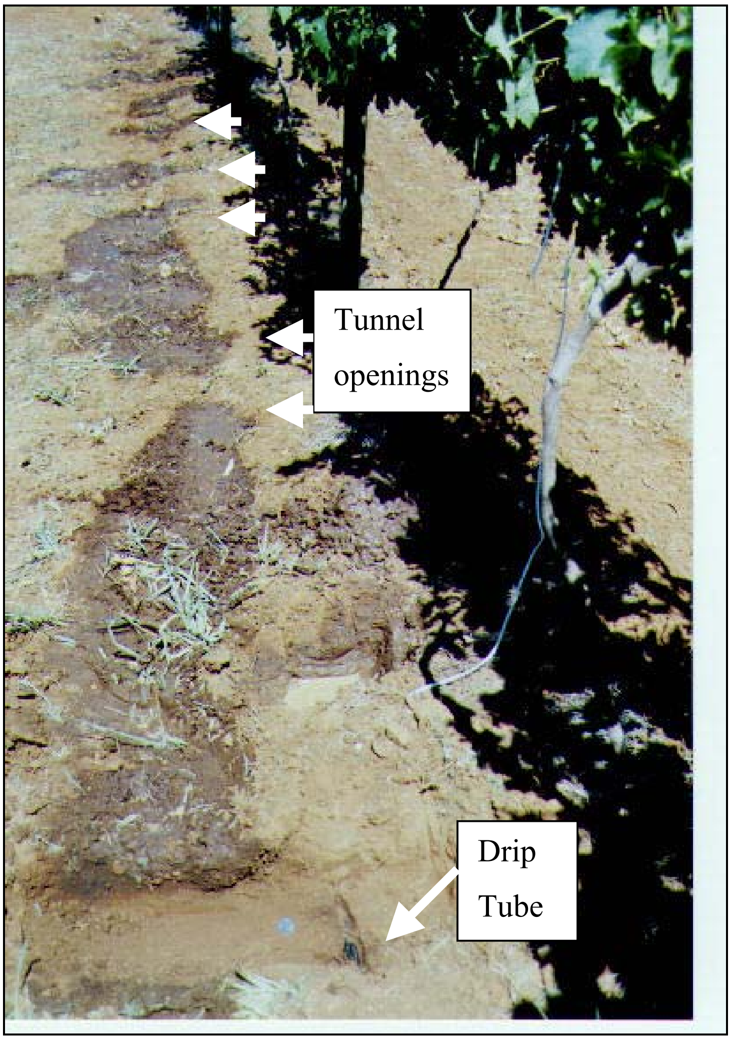


Figure 7.2. Photo showing the tunnel openings and flow of water away from vines irrigated with Subsurface Drip.

CRZI has shown significant benefit over Subsurface Drip tube in avoiding tunnelling and the trial has provided further evidence for the wetting method difference concept, introduced in the Establishment trial.

Tunnel formation in any subsurface drip irrigation installation negates many of the intended advantages of the system. This is graphically illustrated by Figure 7.2. Water in the inter-row limits trafficability, causes unintended weed growth and increases potential for evaporative loss. Perhaps most importantly, tunnelling directs water away from its intended target – the root zone. All of these factors were reasons why, in the initial design phase, SDI was chosen over other systems.

Remediation of this problem is unlikely. Cultivation of the zone to redistribute the sand tunnels has not stopped subsequent re-tunnelling in other trials (Phene pers comms). Also this trial is a good example of how long the problem can take to become apparent (third season with Subsurface Drip treatment). Therefore, careful maintenance commencing from the first irrigation is paramount to avoiding this problem. The core of the problem is a pressure build-up, caused by the application rate being greater than soil infiltration rate. The two strategies to be followed are, to decrease the application rate and maintain good soil conditions to resist dispersion. Application rate decrease can be accomplished by pulsing irrigation, to allow for redistribution to occur between events. Pulsing involves little disruption to irrigation management, as most controllers can be programmed to perform the task automatically. Maintenance of high organic matter contents and addition of in-solution gypsum to the irrigation water, are methods for maintaining good soil structure around the emitter.

7.3 Conclusions

Tunnelling is a major problem for SDI in that it diminishes many of the advantages of the system on which the original choice was made.

Through its ability to provide a much larger surface area over which to distribute water application, CRZI has shown significant benefit over conventional SDI in avoiding tunnelling.

The trial has also shown that tunnelling may take several seasons to become apparent, thus giving the impression that no problem exists.

As remediation appears difficult, tunnel avoidance strategies should be incorporated into the regular SDI maintenance schedule. These include irrigation pulsing to lower mean application rates and application of in-solution gypsum and maintenance of high organic matter to ensure good soil structure.

8 Extension of Problem Analysis

The four field trials discussed previously have followed an evolution from examining a broad range of products over a whole season, to a narrow product range over one stage of crop development.

To this point, there has been limited investigation of the specific management requirements for optimal operation of the CRZI. For example, no trial was performed using just one CRZI type and concentrating on varying irrigation scheduling regimes.

The experiments indicate the importance of managing the amount of water contained in the soil zone immediately surrounding the CRZI. This is critical in maximising the upwards and lateral to downwards water movement ratio, in keeping the saturated zone as high as possible in the profile, in minimising downward water movement and in achieving a wide wetting pattern. Limited time and resources have also precluded repeating the trials in other soil types. To further investigate these issues, computer-based modelling was undertaken using HYDRUS-2D.

8.1 Objectives

i) Compare the soil wetting patterns of CRZI and Drip Tape in soil types other those that used in the field experiments.
ii) To consider the effect of irrigation pulsing and flow rate on the wetting distribution.

8.2 HYDRUS-2D

The chosen tool used was the HYDRUS-2D (International Groundwater Modeling Center, Golden, Colorado, USA) unsaturated water movement simulation package (see Section 1.5.1).

In the pre-field trial phase, HYDRUS-2D was used to gain initial estimates of how the product may act under various situations (Kirby *et al*, 1996; Kirby and Knight, 1996).

The reports compared the effect on the flow regime of using a geotextile membrane, with and without the impermeable bottom polyethylene layer, in sand, silty clay and loam soils. Also tested, were configurations of different shapes and angles including use of a 'wing' at the outer edge of the product to increase the saturated volume.

The simulations were carried out when the CRZI concept was using low-pressure application. The fundamental comparison was to show the effect the membrane and soil type had on water flux. For this reason a small constant pressure head (10cm) was used to describe the source. Put simply, the question to be answered was "if supplied at a small head, how can the soil/membrane combination modify i) the amount of water the domain will accept and ii) the spatial distribution of that water ?".

The findings of this work can be summarised thus :

1. The presence of a geotextile membrane in contact with the irrigation source increased the volume of water infiltrated into the CRZI/soil system in a given time.
2. Placing an impermeable layer beneath the geotextile decreases the overall infiltration volume but increases the proportion of upward flow.
3. It would theoretically be possible to operate the system in a steady state, where the infiltration rate matched the sink strength (evapotranspiration) without excessive drainage.
4. Use of the membrane wing in coarse textured soils increased the volume of wetted soil before overflowing and percolation occurring.

The analyses performed for the previous study assumed the irrigation product used a *constant pressure head* eg. 2 m. The products used in the trial are all constant *flux* irrigation sources eg. 2 Lhr^{-1}. This major limitation with the previous study forms the basis for this chapter.

Flow induced by a constant head is affected by the hydraulic potential difference between the water in the pipe and the water in the soil. As the soil becomes wetter, the hydraulic potential increases, and the potential difference between the soil and the pipe decreases, and hence the flow from the pipe decreases. Also, using a constant pressure head delivery system means flow rate could not be used to modify the wetted area shape, as utilised by Zur (1996).

8.3 Methods

8.3.1 Treatments

Soil Types and Irrigation Systems

Three soil types (Sand, Hanwood Loam and Clay) provide the primary treatments. The methods for describing the soils in the model are outlined below.

Irrigation Management

A standard irrigation schedule was designed to apply 12 litres to the modelled domain in a 24-hour period. This volume converts to an irrigation depth equivalent of 12 mm (1 emitter m^{-2}) and meets the conservative design criteria of peak summer ET_0 in this region.

To compare with continuous application, two pulsing strategies were imposed on three flow rates (Table 8.1). Also, for each treatment, four different initial profile matric potential conditions were imposed (10, 20, 30, 40 kPa). Due to the single day schedule, it was not possible to perform the Pulsed (¼) strategy with the 1 L hr^{-1} flow rate. Therefore, a total of 96 simulations were performed.

Table 8.1. Irrigation pulsing and flow rate details.

	Elapsed Time (hours)		
Flow Rate (L hr^{-1})	Continuous	Pulsed (½) 30 minutes on 30 minutes off	Pulsed (¼) 15 minutes on 45 minutes off
8	1.5	3	6
5	2.4	4.8	9.6
1	12	24	-

8.3.2 Finite Element Mesh (FEM) Definition

The FEM decided on subdivided the 1m x 1m domain into 2217 elements with 1184 nodes. A higher density of nodes was used for the more dynamic area near the CRZI

(Figure 8.1). The impermeable PE layer was represented by an extension of the outer boundary. The geotextile layer was represented by a zone of dense nodes above the PE.

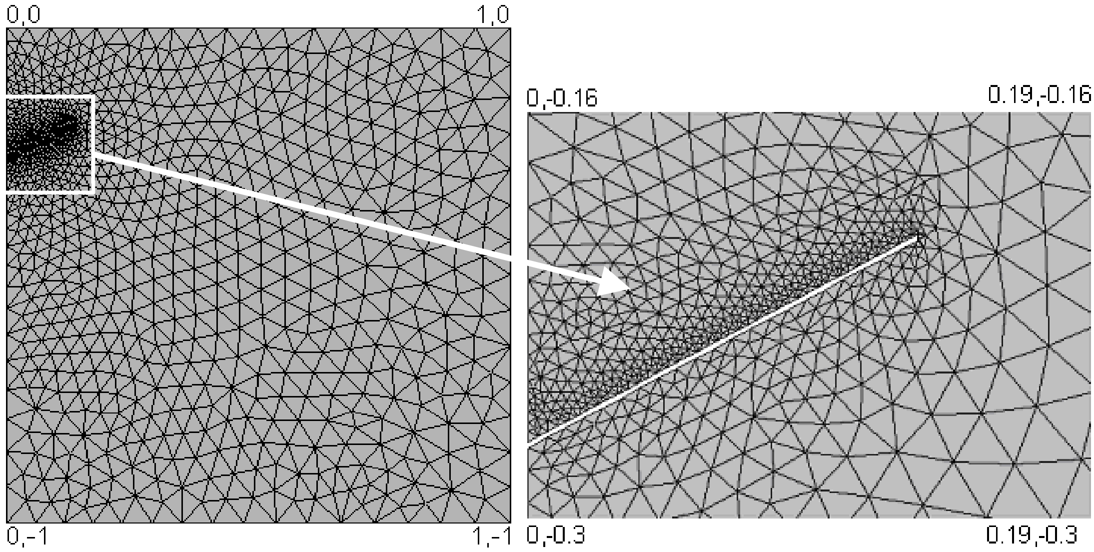


Figure 8.1. Finite Element Mesh used to simulate CRZI.

Whole domain (l), detail of CRZI (r). Coordinate units are metres.

8.3.3 Material Definition

Three soils were used for the primary material representing a sand, clay, and loam. The hydraulic characteristics for the sand and clay were taken from the HYDRUS-2D database, which uses data collected by Carsel and Parrish (1988). For the loam, the measured hydraulic characteristics for Hanwood Loam were used.

A second material was defined to describe the geotextile. Relative to the domain depth this material is very thin (1-2 mm). To simplify the mesh design, the method used by Kirby *et al* (1996) was adopted, where the geotextile thickness was increased ten-fold and the waterholding capacity decreased by the same amount.

The hydraulic properties used to describe these materials are discussed below.

Soil Hydraulic Properties

The RETC (RETention Curve) hydraulic properties optimisation software (van Genuchten et al, 1991) was used to derive van Genuchten (VG) unsaturated water flow equation parameters for the Hanwood loam soil water retention data presented in the General Methods (section 3.2.3). The saturated volumetric water content for each sample was calculated from the bulk density (Equation 8.1) and included in the model as a fixed parameter.

$$\theta_s = 1 - \frac{\rho_b}{\rho_s} \qquad \text{Equation 8.1}$$

where : θ_s = saturated volumetric water content

ρ_b = soil bulk density (kg m^{-3})

ρ_s = density of soil mineral material (2680 kg m^{-3})

Geotextile Hydraulic Properties

Without prior specific knowledge of the geotextile fabric Kirby *et al* (1996) used a 'very high' estimated saturated hydraulic conductivity (K_s) value of 10^3 mm hr^{-1}. Subsequent measurement by Miller (2000) derived a K_s value two orders of magnitude higher (10^5 mm hr^{-1}). It can be seen that the difference between these values is small when compared with the soil K_s (5-10 mm hr^{-1}). Hence, the soil acts as a limiting boundary condition, with only minimal variation in flow distribution expected, whichever geotextile conductivity value is used.

For the van Genuchten α and n parameters, values for a 'sand' were selected from Carsel and Parrish (1988). A large saturated volumetric water content of 0.75 cm^3cm^{-3} was chosen and this was input to the model as 0.075 to account for the increase in simulated material thickness.

Hydraulic parameters for the soils and geotextile are presented in Table 8.2.

Table 8.2. Optimised hydraulic parameters used in HYDRUS-2D model.

	Hydraulic parameters				
	θ_r (cm^3cm^{-3})	θ_s (cm^3cm^{-3})	α (cm^{-1})	n	K_s (mm hr^{-1})
Sand	0.045	0.43	0.145	2.68	300
Clay	0.068	0.38	0.008	1.09	2
Hanwood Loam 0-0.3 m	0.08	0.39	0.076	1.14	9
0.3-0.6 m	0.12	0.43	0.015	1.31	2
0.6-1.0 m	0.14	0.39	0.047	1.63	8
Geotextile	0.01	0.075	0.145	2.68	10^5

8.3.4 Boundary Conditions

No fluxes were allowed across the top (surface) and sides of the domain. A free drainage boundary condition was placed at the bottom of the domain. Free drainage is simulated in terms of a unit vertical hydraulic gradient.

For the CRZI domain, the drip emitter was simulated by placing a Flux boundary condition across nodes on the upper surface of the PE. For the Drip Tape domain, the flux nodes were placed on the side of the boundary at the prescribed depth. It was necessary to use at least three nodes, as the program was unstable using just one. Depending on the scenario being tested, both *variable* (for pulsed irrigation), and *constant* (for continuous irrigation) fluxes were used.

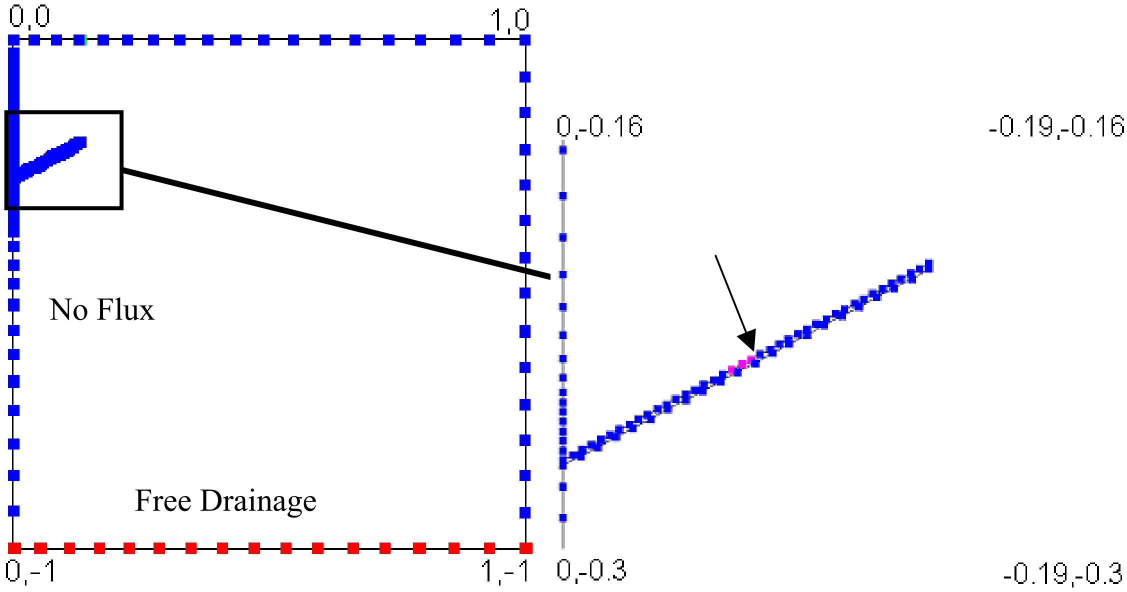


Figure 8.2. Boundary conditions.

Whole domain (l) and detail of CRZI (r). Coordinates in metres.

8.3.5 Measurement Parameters

After completion of the model, runs the measurements describing the shape of the wetted zone were extracted. These were the maximum radius, the maximum surface radius, and the maximum depth of the wetted zone (Figure 8.3).

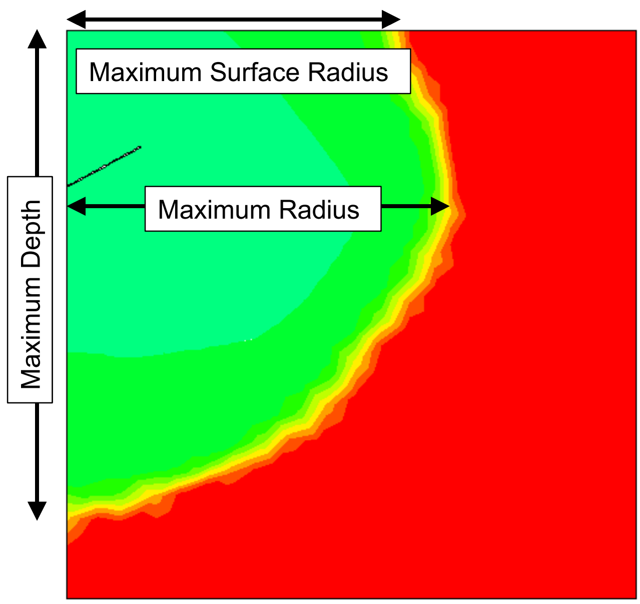


Figure 8.3. Measurements taken from HYDRUS-2D used to analyse changes in wetted volume.

8.4 Results and Discussion

8.4.1 Effect of Irrigation Pulsing

The following graphs present the mean difference between pulsed and continuous application for all simulations. That is, the plotted data is the Continuous result subtracted from the Pulsed result, for the same combination of soil type and flow rate. Both pulsed strategies gave very similar results and so only the Pulsed (½) data is presented. The clay simulations became unstable when using flow rates in excess of 1 Lhr^{-1}. This is due to the low hydraulic conductivity causing pressurisation of the zone surrounding the emitter. HYDRUS, like other numerical models, is subject to instability when hydraulic gradients become too high. In reality, this may point to the situation where the soil cannot contain the pressure build-up and tunnelling (as mentioned in sections 4.3.5 and 7) occurs – a process not modelled by HYDRUS.

The results demonstrate in most cases, that pulsing restricts the wetted volume. That is, a decrease in both the maximum wetted radius (by 0.01-0.03 m) and depth of the wetting pattern (by 0.06-0.07 m). Little difference was seen between trends in these two parameters in the loam and clay soils (Figure 8.4). Note that the low hydraulic conductivity of the clay produced model instability at flow rates greater than 1 L hr^{-1}. The loam also shows that the wetted volume increases with increasing flow rate. No difference in wetted zone dimensions is evident between the CRZI and Drip Tape products in these soils.

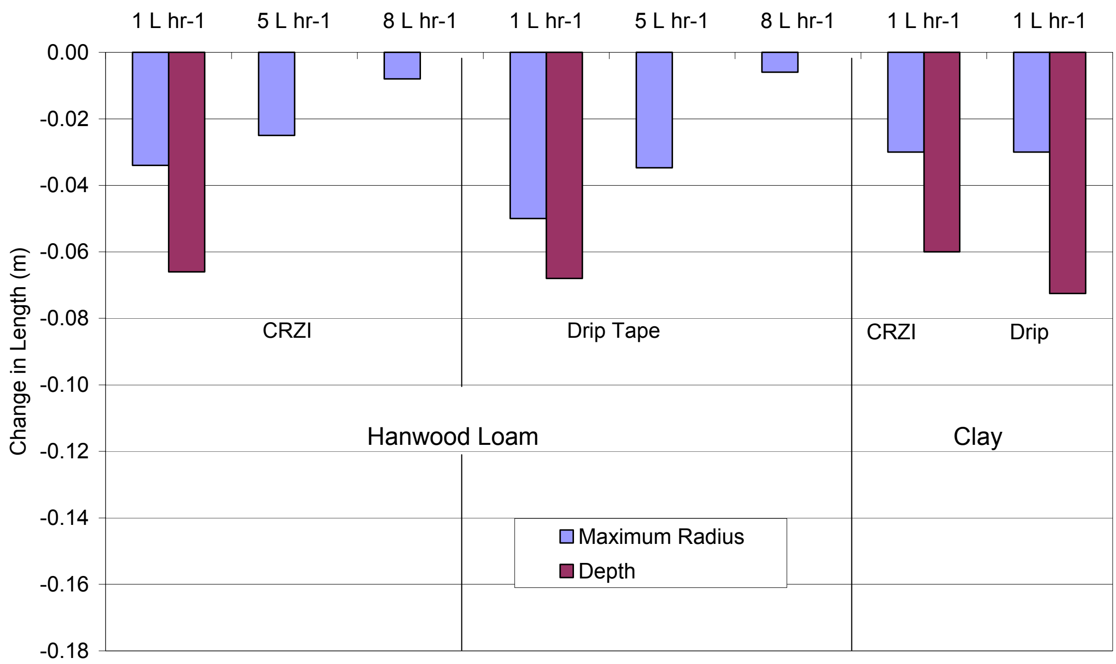


Figure 8.4. Mean difference (Pulsed – Continuous) in wetting pattern parameters between Pulsed and Continuous irrigation application. Clay and Loam.

Pulsing had a far greater effect on both parameters in the sand (Figure 8.5). When pulsed, the maximum radius was reduced by 0.01 to 0.05 m and depth by 0.02 to 0.16 m. As with the loam, the effect of pulsing on wetting pattern parameters decreased with increasing flow rate. At 1 L Hr^{-1}, pulsing produced a reduction in wetted zone depth for CRZI 0.04 m less than Drip Tape. This may indicate that the geotextile into which the water first flows, may buffer or dampen the pulsing effect at low flow rate.

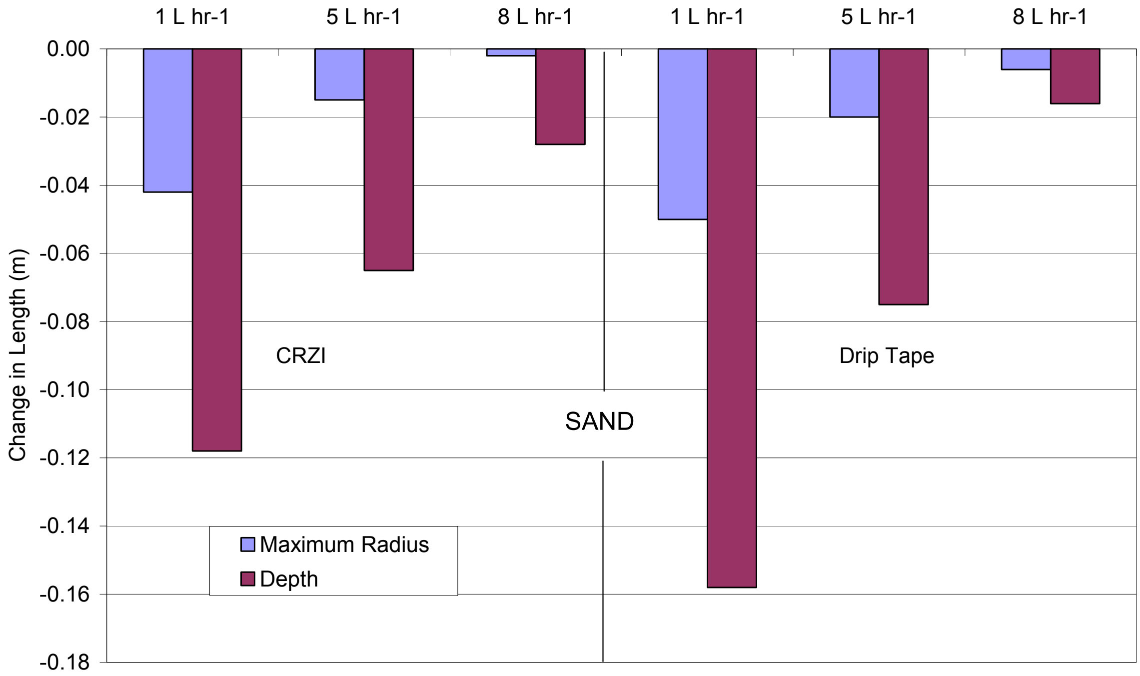
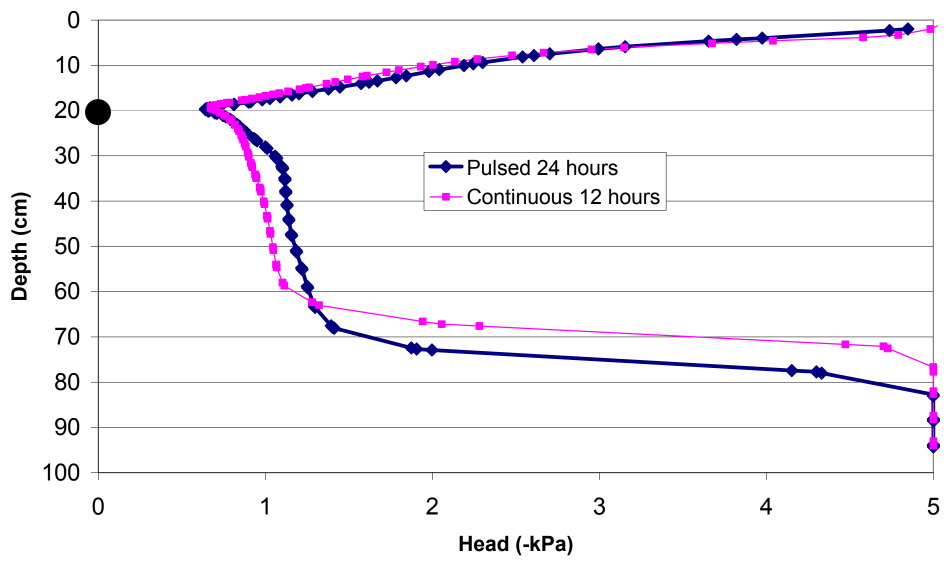


Figure 8.5. Mean difference (Pulsed- Continuous) in wetting pattern parameters between Pulsed and Continuous irrigation. Sand.

For an explanation of the mechanism behind the changes demonstrated by pulsing, we must consider the profile hydraulic head trend and the hydraulic conductivity/head [K(Ψ)] relationship (Figure 8.6). The profile hydraulic head trend follows a depth profile above and below the Drip Tape. Profile results are presented for both pulsed and continuous schedules at the completion of a water application phase. For the continuous schedule, this occurred after 12 hours. For the pulsed schedule, this occurred after 24 hours and had already incorporated 12 hours of redistribution. Figure 8.6 (top) shows that between 0.26 and 0.60 m depth, the head in the continuous schedule profile is slightly higher than in the pulsed schedule profile. At approximately 0.32 m the heads are –0.9 kPa (continuous) and –1.1 kPa (pulsed). Now considering the K(Ψ) relationship (Figure 8.6[bottom]) these heads convert to hydraulic conductivities of 9 and 3 $mmhr^{-1}$ for continuous and pulsed, respectively. Therefore, at the end of the application phase, the continuous schedule had produced a volume of soil with hydraulic head high enough to support a 3-fold increase in hydraulic conductivity. Hence, the wetting pattern from the continuous schedule moved deeper and further laterally in the profile, than the wetting pattern from the pulsed schedule.



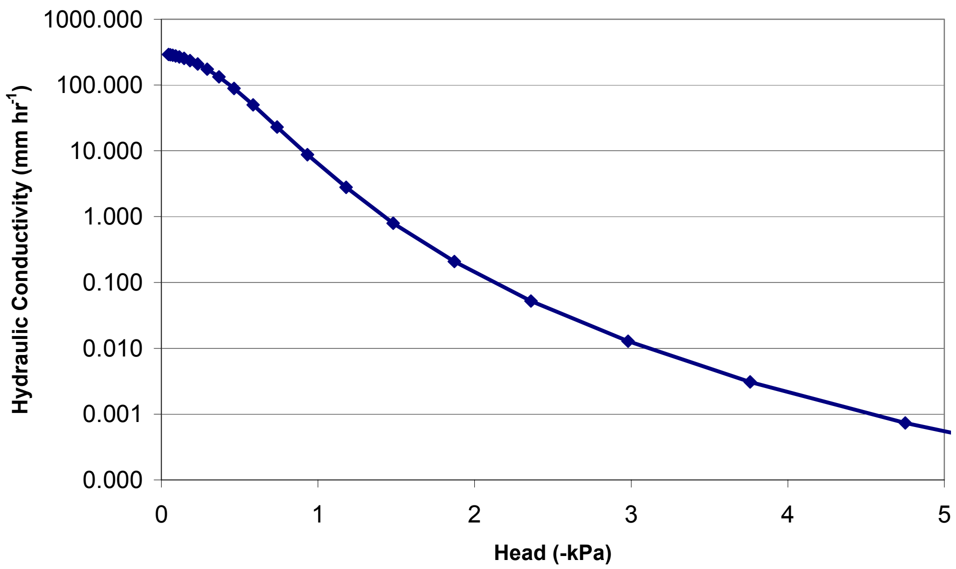


Figure 8.6. Soil water head depth profile for pulsed and continuous irrigation for Sand after the addition of equivalent water amounts (top). Hydraulic conductivity vs head relationship (0 to -5 kPa) (bottom).

As stated, pulsing reduces both the radius (a negative aspect) and depth of wetting (a positive aspect). However, it is quite clear from all simulations, that the radius is reduced at a lesser rate than the wetted depth. The sand simulations produce a quite regular 3:1 reduction ratio ie. for every centimetre the radius is reduced, the depth is reduced by 3 cm.

The Flow Rate~Pulsing Interaction

Figure 8.4 and Figure 8.5 both show that the effects of pulsing on wetting pattern parameters diminished with increasing flow rate and that the changes were more marked with increasing soil texture coarseness. Pulse irrigation may be defined as a series of irrigation time cycles, where each cycle includes two phases, the operating and redistribution phase (Karmeli and Peri, 1974). During the redistribution phase, the water content behind the wetting front will be reduced due to water redistributing according to potential differences. At the same time the wetted volume is expanding with the time of irrigation. The following relationship (Equation 8.1) describes the time taken to refill (T_{refill}) the pulsed wetted volume back to what it would be if continuously applied (Freeman Cook, pers comms) :

$$T_{refill} = \frac{\Delta\theta\, V}{q} \qquad \text{Equation 8.1}$$

where :$\Delta\theta$ = change on water content during redistribution phase.

V = volume of wetted soil if irrigation was continuous

q = emitter flow rate.

From this useful relationship, we can see that the refill time is inversely related to the flow rate ie. the higher the flow rate, the smaller the time to refill the pulsed volume back to the continuous volume. Hence, the effect pulsing has on controlling the wetted volume shape will decrease with increasing flow rate.

Hysteresis Effect on Wetting Pattern

Although not included in the simulations, hysteresis will also play a part in modifying the wetting patterns. The wetting phase of a water retention curve occurs at a higher head than the drying curve and hence supports a higher hydraulic conductivity (Simunek *et al*, 1995). As was explained in Figure 8.6, during the drying phase between irrigation pulses, the mean water content of the wetted zone decreases, resulting in a lower hydraulic conductivity. Therefore, a schedule which incorporates drying phases, will also help maintain lower hydraulic conductivity and reduce the depth of the wetting pattern. The considerable effect on depth of wetting pattern of a small change in hydraulic head in the profile has already been demonstrated.

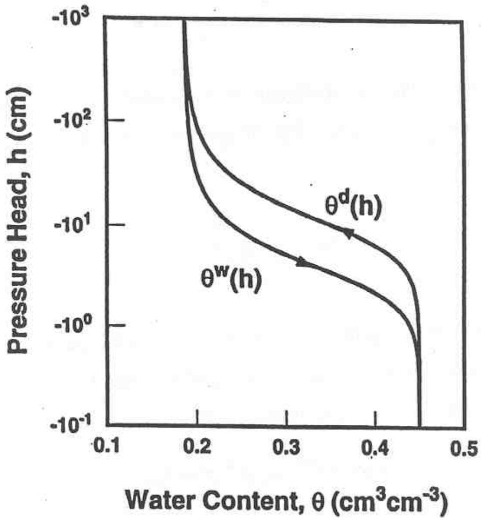


Figure 8.7. Water retention curve with hysteresis. θ^w(h) and θ^d(h) denote the wetting and drying curves respectively (Simunek *et al*, 1995).

8.4.2 CRZI/Drip Tape Effects in Different Soil Types

This section addresses the question of CRZI / Drip Tape performance in soil types other than the Hanwood Loam in which the trials were carried out.

The "Crop Establishment" chapter explored the importance of water reaching the soil surface and so the first data in this section presents the maximum surface wetted radius data (Figure 8.8). The data shows :

i). The surface wetted radius decreased with increasing soil texture coarseness.

ii). On all soil types CRZI produced greater surface wetted radius.

iii). Drip Tape was unable to supply water to the surface in sand.

iv). Surface wetted radius increased with emitter flow rate thus agreeing with the empirical work of Zur (1996). This point is discussed further below.

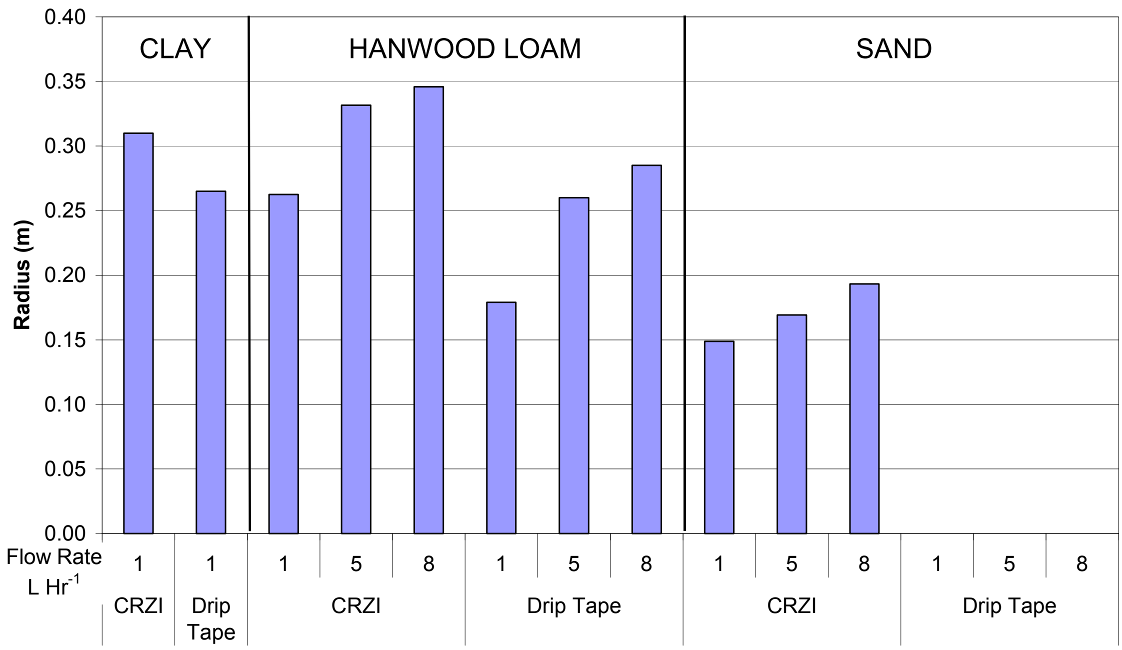


Figure 8.8. Simulated surface wetted radius for CRZI and Drip Tape.

To gain an overall picture of the difference between the two products, the Drip Tape results were subtracted from CRZI results for every simulation performed and these were averaged with respect to soil type.

Results show that for each wetted zone shape parameter on each soil, CRZI shows better performance than Drip Tape ie. CRZI exhibits greater maximum radius, greater surface wetting radius and shallower depth of the wetted zone (Figure 8.9). However, for the clay and loam the differences are minimal. The greatest differences are evident in sand, particularly with the surface wetting radius and depth of wetted zone. Drip Tape must rely more on the soil properties to control water movement whereas, irrespective of soil type, CRZI is able to maintain a small saturated zone in the profile at the installation depth, from which water can move via capillarity.

This is further evidence supporting the hypothesis that performance of the trial in a coarse textured soil would have increased the probability of obtaining significant differences between the two products.

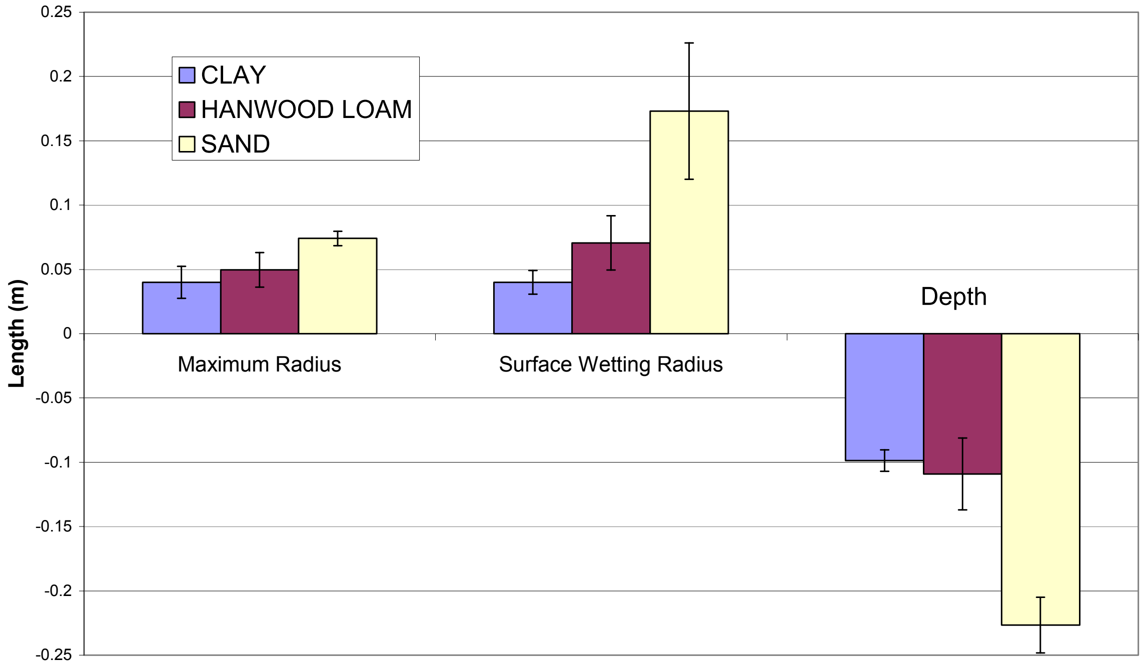


Figure 8.9. Mean difference in measurements between CRZI and Drip Tape (CRZI-Drip Tape) from all simulation results with respect to soil type. Error bars indicate standard deviation.

Flow Rate, Wetted Area Shape and Width

The effect of flow rate on the shape of the wetted area can be explained with reference to Philip (1984). Figure 8.10 presents travel times of a wetting front emanating from a source at point '0'. To enable application to all soil types and flow situations, the values are dimensionless. The spatial coordinates have been scaled with reference to α (the inverse of the capillary length scale). The temporal values have been scaled as follows (Equation 8.2) :

$$T = (\alpha^3 \, q \, t / 16 \pi \Delta\theta) \qquad \text{Equation 8.2}$$

where : T = dimensionless time

α = inverse of the capillary length scale (cm^{-1})

t = dimensioned time (minutes)

Δθ = change in water content of wetted zone (-)

q = flow rate ($L\ hr^{-1}$)

At small time scales, when capillary forces dominate, the figure describes more symmetrical wetting patterns. As time progresses, the capillary/gravity forces ratio declines, leading to elongation.

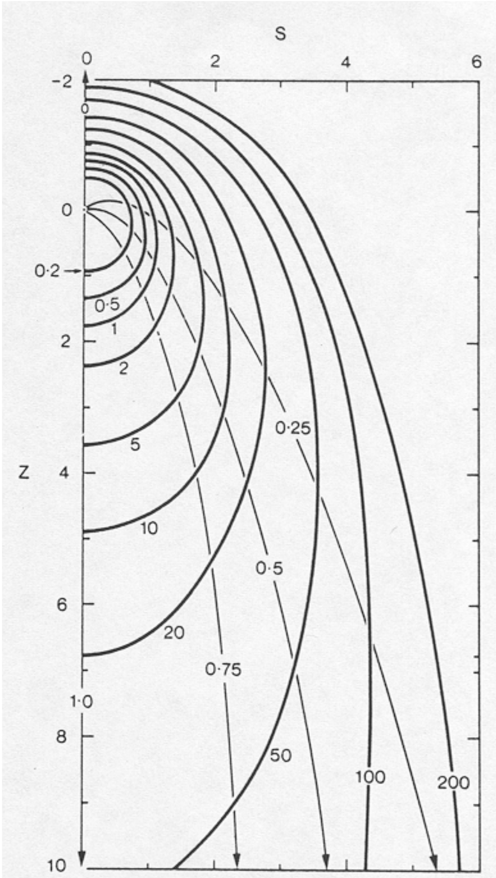


Figure 8.10. Streamlines and isochrones for steady infiltration from buried sources. Horizontal (S) and vertical (Z) axes are dimensionless coordinates. The heavy curves are isochrones, with numerals being the dimensionless travel time T (Philip, 1984).

If T is constrained to values small enough to ensure minimal elongation of the wetting pattern, say ≤ 0.1, then combinations of flow rate *vs* time for different soils can be calculated to meet this target. Using Equation 8.2, *t* was plotted for a range of flow rates from 1-8 L hr^{-1} (Figure 8.11). The α term was varied to produce a range of curves according to soil type. The $\Delta\theta$ term may be viewed as the level of soil water depletion prior to irrigation, or the amount of space available to the incoming water. The time available before elongation occurs will vary directly with this depletion. Depletions of 0.02, 0.04, and 0.06 cm^3cm^{-3} were chosen for the sand, sandy loam and clay respectively.

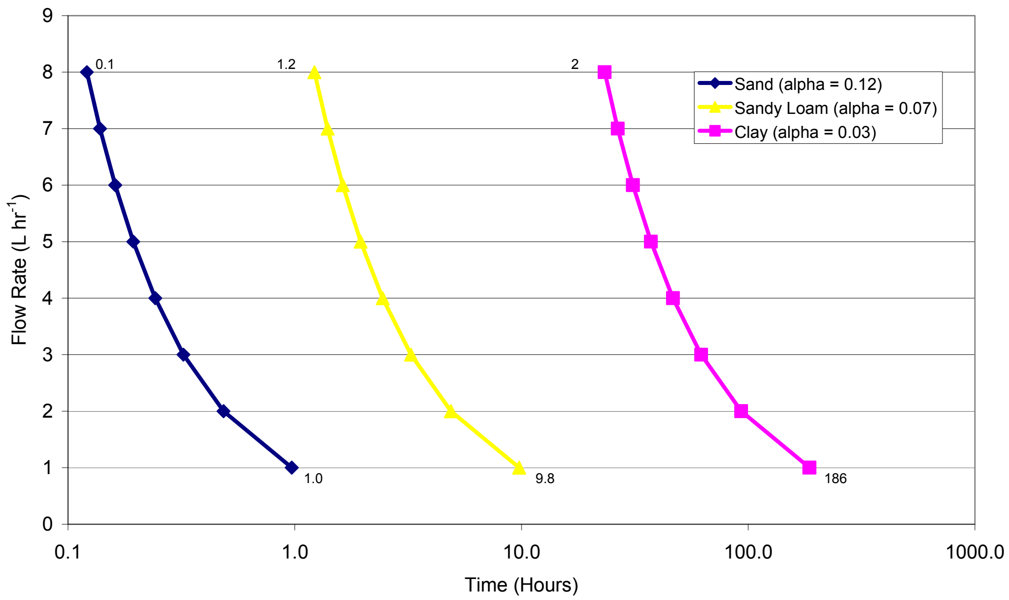


Figure 8.11. Flow rate *vs* application time to minimise vertical elongation of the wetting pattern. Using Philip (1984).

The coarse texture and hence low capillarity of the sand can be seen to elongate past the chosen threshold, after the addition of only 1 litre of water, giving a range of 0.1-1.0 hours, depending on flow rate. This would need to be applied several times a day to satisfy a crops evaporative demand. The aim of the threshold is to maintain the water content at the margins of the wetted zone, low enough to suppress the hydraulic conductivity to below 'rapid drainage' levels. However, the limited available water in a sand makes this a system very sensitive to crop water stress and a high level of management and monitoring would be required. A soil water status monitoring sensor in the root zone would be an essential component of the system. Due to the high saturated hydraulic conductivity of a sand, flow rate will have a greater effect on modifying the shape of the wetted zone. An empirical expression developed by Schwartzman and Zur (1986) predicts that doubling emitter discharge would increase the wetted width by 10% and decrease the wetted depth by 30%. Thus, combining this prediction with Figure 8.9 results in the recommendation that for lighter soils, a high flow rate applied for a short period, will achieve both greater wetted radius and a wetted zone higher in the profile.

In contrast, the fine texture and high capillarity of the clay was able to accept 186 litres, before the elongation threshold was passed. Therefore, a much lower management level is needed as all evaporative demand can be satisfied with one application. With a clay, the rate of water movement away from the wetted zone is the major limitation. This then makes the system sensitive to pressurising of the soil and resultant tunnelling. To avoid this problem, the lowest flow rate emission source should be chosen.

8.5 Conclusions

The final experimental component of the research introduced a simulation tool, HYDRUS-2D, to help address several issues not covered by the field-based program.

The modelling scenarios examined i) the effect of irrigation pulsing on modifying the shape of the wetted volume and ii) the difference between the water distribution patterns of CRZI and Drip Tape in soil types other than that in which the trials were conducted.

Pulsing the irrigation schedule (½ hour on/off) brought the general effect of reducing the wetted width (negative effect) and decreasing the depth of the wetted volume (positive effect). However, in all simulations the wetted depth decrease exceeded the width decrease to give an overall net positive effect. Greatest benefit was seen in coarse textured soil, where the depth reduction exceeded the width reduction by 3:1. The mechanism for this benefit was found to be the maintenance of a lower mean hydraulic conductivity

The simulations indicated that the pulsing effect diminished with flow rate. Examination of this interaction found that the space made available for infiltration following the redistribution phase, was filled quicker with a higher flow rate, bringing it closer to the continuously applied scenario.

CRZI exhibited advantage over Drip Tape in all soil types by producing wetted zones that were wider and higher in the profile. The benefit was far larger in sandy soil. In fact, in no scenario using a sandy soil was Drip Tape able to provide water to the soil surface.

9 General Conclusions

The research has followed an ever-focussing path. The trial commenced with the Irrigation System Experiment (Chapter 4) testing a range of pressurised and non-pressurised subsurface irrigation products. The outcomes of this trial indicated that Drip Tape should be the main comparison to CRZI. The Water Use Efficiency trial (Chapter 5) then compared the products' performance using optimal irrigation control. The final field trial (Establishment - Chapter 6) highlighted differences between the products over just one, very important, growth stage – crop establishment. Developing in parallel with the annual crop experiments was a vineyard, which contributed relevant outcomes (Chapter 7). And finally, being conscious that all experimentation had been performed in the one soil type, a simulation model was introduced in an attempt to gauge expected outcomes in other soils (Chapter 8).

A range of CRZI prototypes were used to address different CRZI/soil/water interactions. The CRZI concept commenced as a simple, 'appropriate technology', capable of being used in developing countries where such systems use minimal filtration and are gravity supplied with heads of less than 2 m (ie CRZI 'Perforated Pipe'). The Irrigation System trial showed that due to a low distribution uniformity, this product could not be used in long rows. The same trial highlighted the excellent performance of Drip Tape. And so it was decided that instead of developing a completely independent system, CRZI would incorporate, exploit and improve on the well researched advantages of Drip Tape. Subsequent versions then focussed on directing as much water as possible through the geotextile, as this was seen as the major benefit over Drip Tape.

If one theme were chosen to represent the whole research, it would be that of *CONTROL*. 'Control' consists of both system design and operational aspects, which unite to produce the potential for greater efficiency in water control, improved crop yield/quality, with less negative environmental consequences.

Design of system hardware controls the efficiency baseline. Drip products were developed to provide greater control over water/nutrient application and are an area where development is ongoing. For instance, current technology cannot control emitter flows to match the rate at which soil can move water away from the source. One of the assumptions of the thesis has been that, an irrigation source which uses a soil's capillarity for water movement, has advantage over a source which pressurises and disrupts soil structure through applying water at rates greater than the soil can move away.

The Irrigation System experiment found the treatments with least control over water flow (SIP and CRZI 'Perforated Pipe') produced poor distribution uniformity (DU) and the least yield. In addition, the large flow rate of the CRZI 'Perforated Pipe' rapidly created tunnels from the emitter to the surface.

Even the lower flow rate of Drip Tape in the vineyard caused tunnelling, albeit in the third season. Tunnelling negates many of the advantages of SDI and is virtually irremediable.

The occurrence of tunnelling and pooling of water on the soil surface, led to the identification of different methods of soil wetting employed by Drip Tape and CRZI. CRZI greatly increased the surface area over which water can infiltrate into the soil, thus decreasing the areal application rate to near that of the soil's hydraulic conductivity. Also contributing to tunnelling/surfacing resistance is the construction of CRZI which stops preferential water flow in the zone of installation disturbance. Thus, if drip tape is described as a *point* source, then CRZI should be referred to as an *area* source.

Operational control

If system design sets the efficiency baseline, then o*perational control* allows for fine-tuning. The project investigated irrigation *pulsing* (Chapter 8) and provided the first explanation of the soil physical processes involved. Simulation modelling (HYDRUS-2D) found that pulsing has potential to hold wetted volumes higher in the profile, particularly in coarse textured soil. It also found that pulsing slightly decreased wetted width, thus both challenging popular thought and supporting experimental work. Given that pulsing reduces the mean flow rate and decreases the time the soil around the emitter is pressurised, it is also a method to protect against tunnelling.

Pulsing was used in the Water Use Efficiency experiment to deliver a well controlled irrigation schedule and produced excellent production and water use efficiency results. This trial also found that an electronic control system is mandatory for extracting optimal performance without large labour costs. The research developed a software/hardware irrigation control system with sensor feedback.

Doubts existed regarding the suitability of Hanwood Loam soil, on which all experiments were performed, for the product comparison. The clay pan situated at 0.3-0.4 m was found to have a marked lower hydraulic conductivity and hence, had potential to be a natural equivalent to the impermeable PE layer of CRZI. A lack of time and budget precluded field-testing in other soil types and so HYDRUS-2D was employed to give a broad indication of how the products may have performed in both coarser and finer soil textures. Simulation found that in all soil types, CRZI produced wetted zones that were wider and higher in the profile than Drip Tape. However, in the finer soil textures the differences were so small that field trial variability would easily result in statistical insignificance. CRZI exhibited far larger benefit in sandy soil. In fact, in no scenario using a sandy soil was Drip Tape able to provide water to the soil surface.

The research introduced the method of using plants as bioassays of water movement and germination in SDI. In particular, the method used in the Establishment experiment, where seed was sown perpendicularly to the irrigation line-source, proved to be very successful. This method allows direct addressing of the main question (crop establishment) without relying on surrogate measurements such as soil water content or soil colour change. Efforts should be made to minimise unintended consequences of this method, such as rolling the soil to prevent ‘microfurrows’, formed from the seeding operation, affecting surface water distribution.

The Establishment trial also introduced the concept of Surface Wetting Efficiency (E_{sw}) to describe the proportion of water moving to the surface from a buried source and hence being available for crop establishment. Drip Tape exhibited the highest E_{sw} through pooling water on the surface. CRZI achieved similar results without saturating the soil surface. The trial also found a constant relationship between maximum wetted width and maximum establishment width.

RECOMMENDATION

The economics of CRZI production have not been investigated. This is the sole responsibility of the developers. Due to the combination of materials, the cost will be in excess of other SDI products. This may limit the use of CRZI to areas where water costs are high, produce return is high, soil is highly permeable, and considerable environmental pressure exists. ‘Market’ garden areas close to cities would fit this need. Given it’s property of increasing the amount of water infiltrated beneath the soil surface, CRZI would also have a place in effluent disposal schemes in both commercial, public parks/gardens and domestic situations.

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12 Appendices

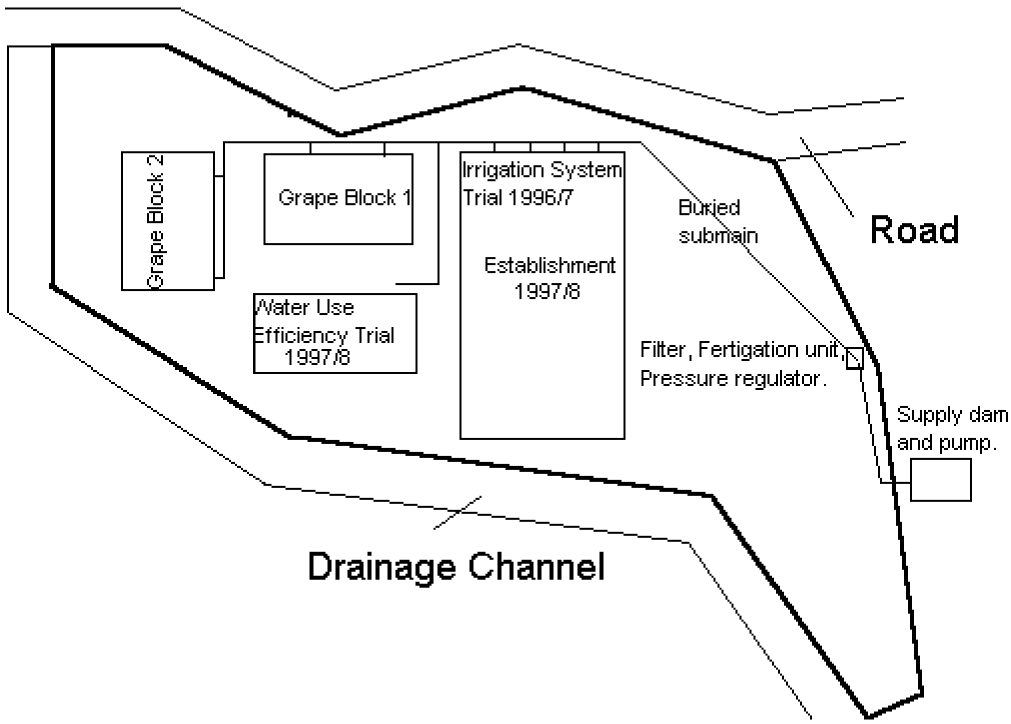

Figure 12.1. CRZI trial site map, Field 1200, CSIRO Land Water, Research Road, Griffith, NSW.

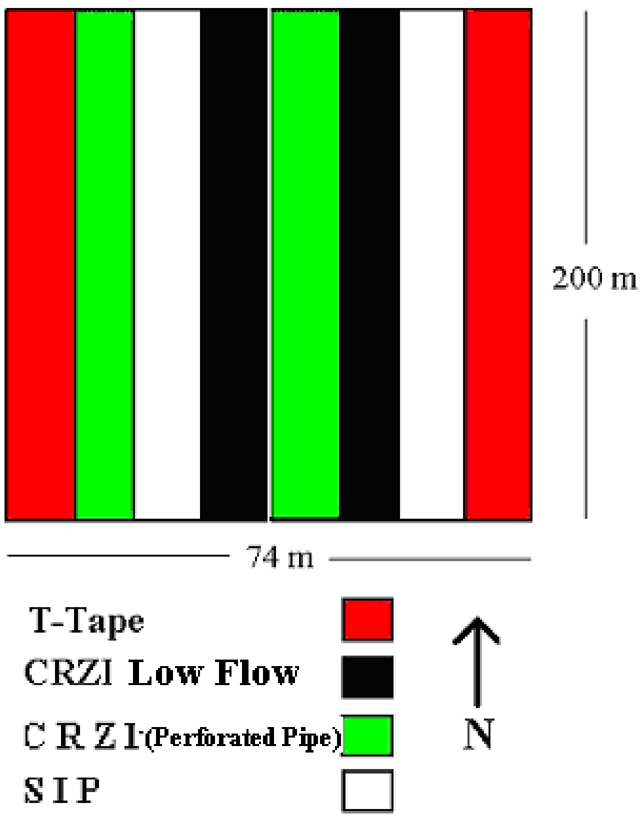

Figure 12.2. Irrigation System trial treatment layout.

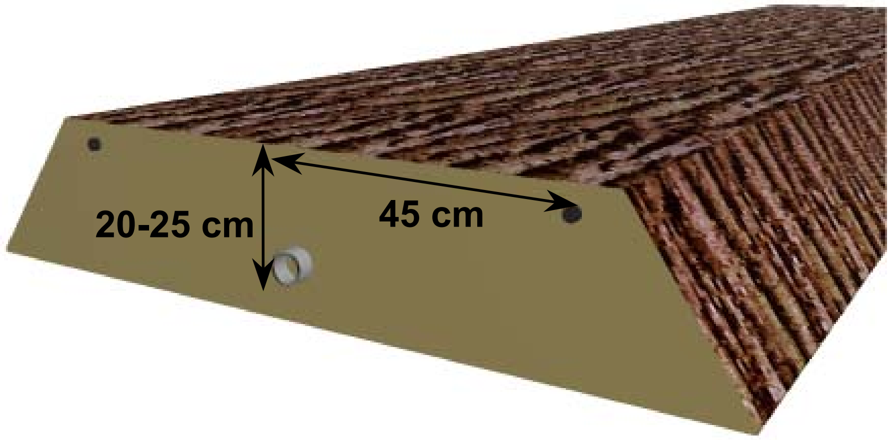

Figure 12.3. Irrigation System bed configuration.

		BLOCK 1				BLOCK 2			
Date	**DAS**	**CRZI 1**	**CRZI 2**	**SIP**	**Drip**	**CRZI 1**	**CRZI 2**	**SIP**	**Drip**
18/01/1997	0	60		59				57	49
19/01/1997	1	26	71	21	60	74	56	29	23
21/01/1997	3	33	11	38	117		8	74	28
22/01/1997	4	38			41	60			
23/01/1997	5								41
24/01/1997	6		99		17	17	95		
25/01/1997	7	37							
26/01/1997	8			152					
4/02/1997	17		55			35	56		21
5/02/1997	18	34		21	51			42	
6/02/1997	19			24				16	
13/02/1997	26	7			50		100		62
14/02/1997	27		76	25		57		29	
15/02/1997	28	79		13				15	
16/02/1997	29	47							
19/02/1997	32		72		42	46	70		
20/02/1997	34	71							55
22/02/1997	36			72				62	
25/02/1997	39	15			14				15
26/02/1997	40		47	22		31	45	17	3
27/02/1997	41		14			15	14		38
28/02/1997	42	46		26	44	15		25	
1/03/1997	43			6				8	
3/03/1997	45							7	
4/03/1997	46	11	15		11	13	19		12
5/03/1997	47		20		8	10	15		9
6/03/1997	48	17	7		10	10	7		10
7/03/1997	49			20					
11/03/1997	53	12	7		11	5	7	22	12
12/03/1997	54	4			4	17			
13/03/1997	55	9	24		14	5	23		5
14/03/1997	56			25				30	
15/03/1997	57								13
24/03/1997	66	7	11		7	8	11		7
25/03/1997	67	12	15		11	10	14		12
26/03/1997	68	5	8		5	12	7		5
27/03/1997	69			26				33	
16/04/1997	88	14	9		12	6	9		13
17/04/1997	89	6	19		5	13	18		6
18/04/1997	90	10			9				9
19/04/1997	91			25				17	
Totals		**600**	**580**	**574**	**542**	**457**	**570**	**482**	**448**

Figure 12.4. Irrigation application for Sweet Corn Crop 2 (1997).

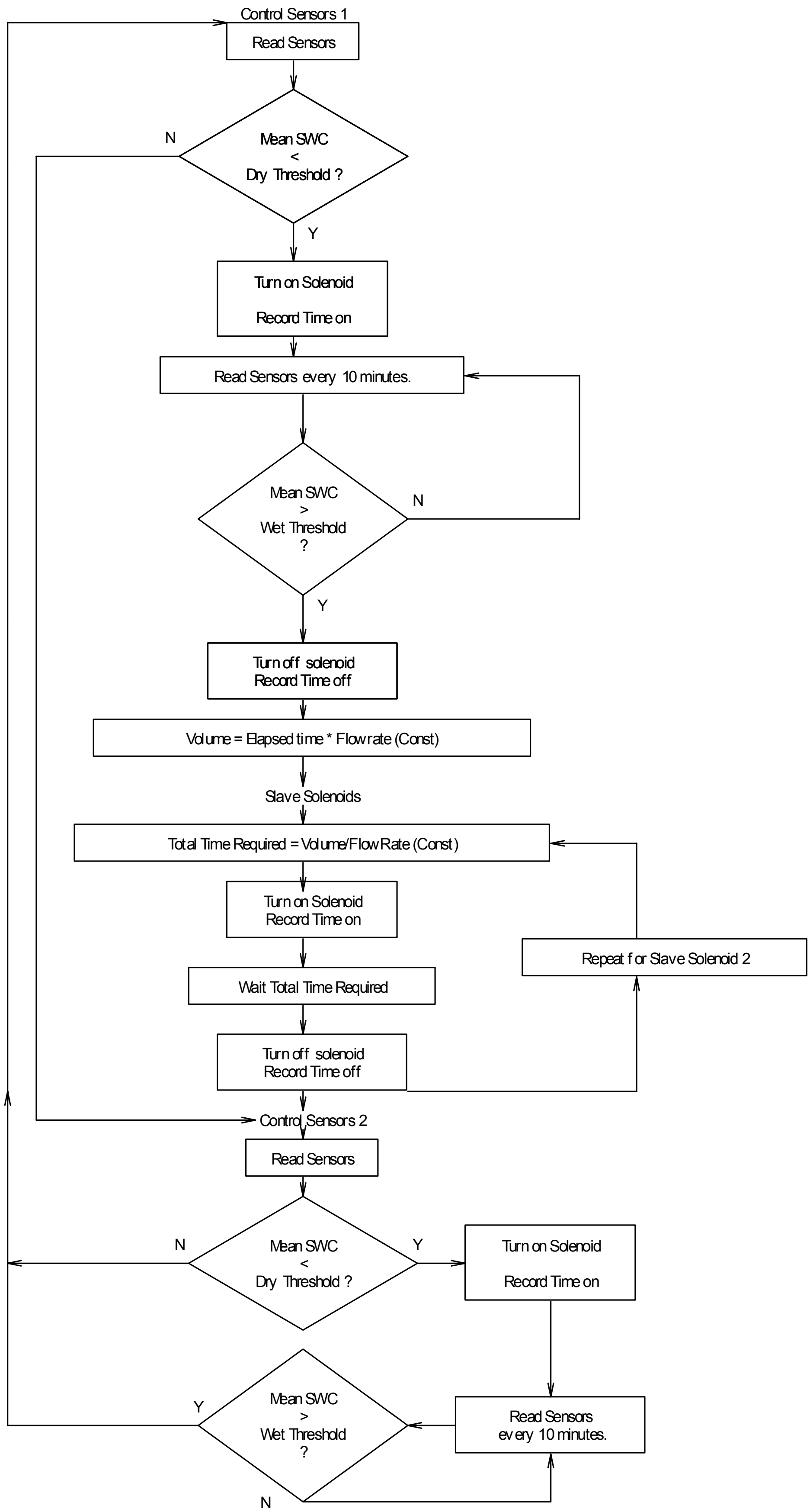

Figure 12.5. WUE experiment (Melon) irrigation control algorithm.

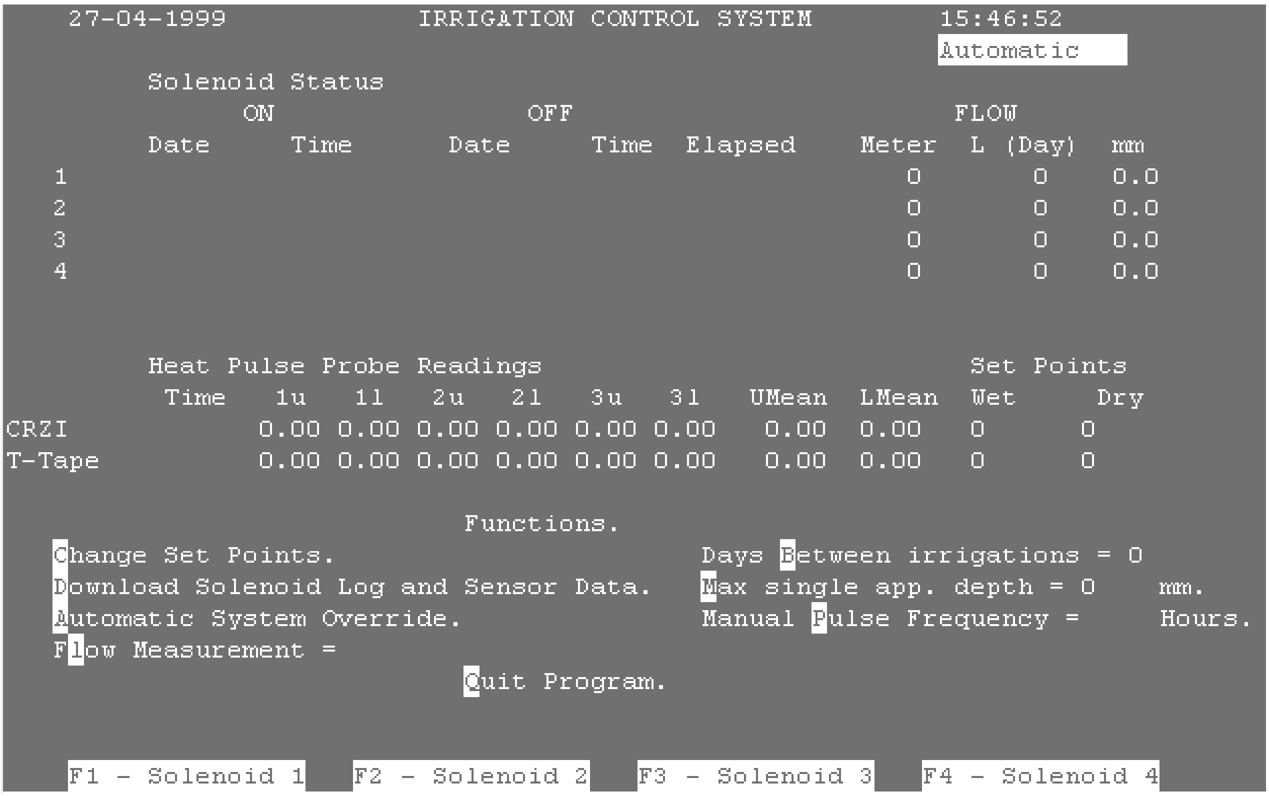

Figure 12.6. Sample input screen from irrigation control system for Melon WUE experiment.

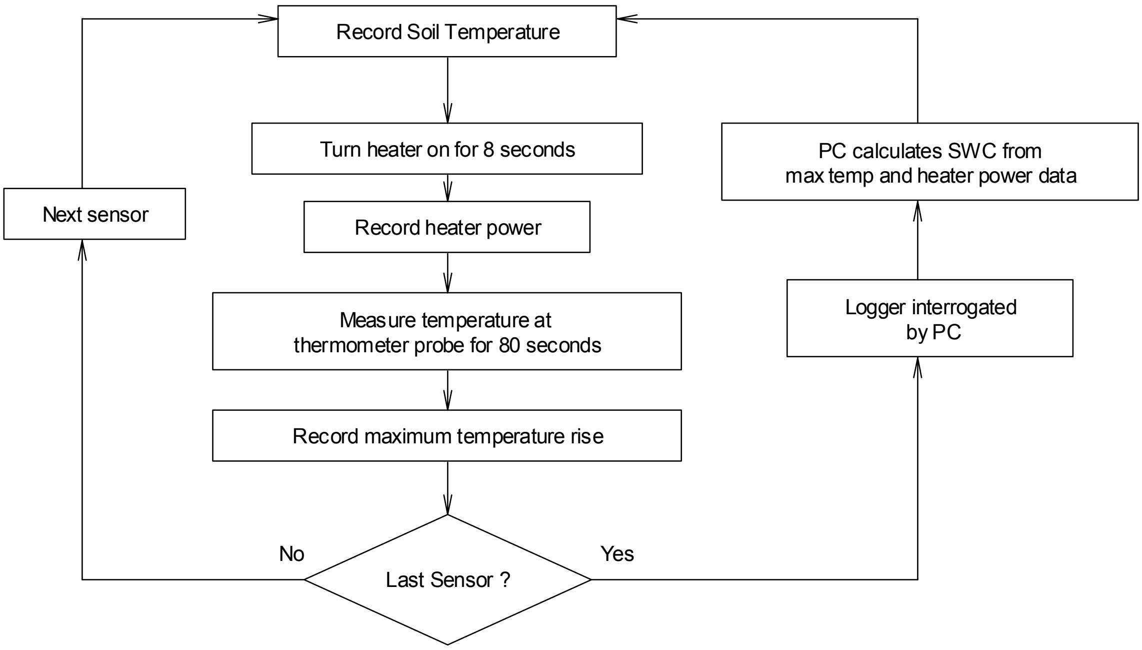

Figure 12.7. Flow chart of heat pulse sensor logging.

Bed No.	Treatment	Depth	Bulk Density (cm^3 cm^{-3})	Organic Matter%	Heater Resistance (Ω)
4	Drip Tape	Upper	1.36	0.011	40
	Drip Tape	Lower	1.62	0.021	40.7
5	CRZI	Upper	1.49	0.019	39.1
	CRZI	Lower	1.6	0.0099	43
12	Drip Tape	Upper	1.46	0.017	39.5
	Drip Tape	Lower	1.71	0.013	38.1
15	CRZI	Upper	1.62	0.013	38.5
	CRZI	Lower	1.64	0.0088	37.8
28	Drip Tape	Upper	1.43	0.013	27.1
	Drip Tape	Lower	1.57	0.0054	42.6
37	CRZI	Upper	1.47	0.0146	47.2
	CRZI	Lower	1.63	0.01162	42.6

Figure 12.8. Constant parameters for SWC calculation using heat pulse probes.

Shallow CRZI		45
Deep CRZI		44
Shallow Drip Tape		43
Shallow CRZI High Flow		42
Deep CRZI High Flow		41
Surface Drip Tape		40
Shallow Drip Tape S2		39
Deep CRZI High Flow		38
Deep CRZI		37
Shallow Drip Tape S2		36
Surface Drip Tape		33
Shallow CRZI High Flow		32
Shallow Drip Tape		31
Shallow CRZI		30
Shallow CRZI		29
Shallow Drip Tape S2		28
Deep CRZI		27
Surface Drip Tape		26
Deep CRZI High Flow		25
Shallow Drip Tape		24
Shallow CRZI High Flow		23
Deep CRZI High Flow		22
Shallow Drip Tape		21
Shallow Drip Tape S2		20
Shallow CRZI High Flow		19
Deep CRZI		18
Surface Drip Tape		17
Shallow CRZI		16
Deep CRZI High Flow		15
Shallow CRZI High Flow		14
Surface Drip Tape		13
Shallow Drip Tape S2		12
Shallow CRZI		11
Deep CRZI		10
Shallow Drip Tape		9
Surface Drip Tape		8
Shallow Drip Tape		7
Deep CRZI		6
Deep CRZI High Flow		5
Shallow Drip Tape S2		4
Shallow CRZI High Flow		3
Shallow CRZI		2

Figure 12.9. 1997/8 CRZI Melon Trial - Colour Key to Block and Replicate Layout.

RANDOMISED COMPLETE BLOCK DESIGN FOR ESTABLISHMENT EXPERIMENT			
		Gypsum Placement	
Bed	**Treatment**	**N**	**S**
1	Shallow CRZI		X
2	Shallow CRZI	X	
3	Deep CRZI High Flow	X	
4	Deep Drip Tape	X	
5	Deep CRZI	X	
6	Shallow Drip Tape		X
7	Shallow CRZI		X
8	Deep CRZI High Flow	X	
9	Deep CRZI		X
10	Deep Drip Tape		X
11	Shallow CRZI	X	
12	Shallow Drip Tape	X	
13	Shallow CRZI	X	
14	Shallow CRZI		X
15	Deep Drip Tape	X	
16	Deep CRZI		X
17	Shallow Drip Tape		X
18	Deep CRZI High Flow		X
19	Shallow Drip Tape	X	
20	Deep Drip Tape	X	
21	Deep CRZI High Flow		X
22	Shallow CRZI	X	
23	Shallow CRZI		X
24	Deep CRZI		X
25	Shallow CRZI	X	
26	Shallow CRZI	X	
27	Deep CRZI	X	
28	Shallow Drip Tape	X	
29	Deep Drip Tape		X
30	Deep CRZI High Flow		X
31	Deep CRZI		X
32	Shallow Drip Tape	X	
33	Shallow CRZI		X
34	Deep CRZI High Flow		X
35	Shallow CRZI		X
36	Deep Drip Tape	X	

Figure 12.10. Randomised Complete Block Design and surface gypsum placement for Establishment Trial.

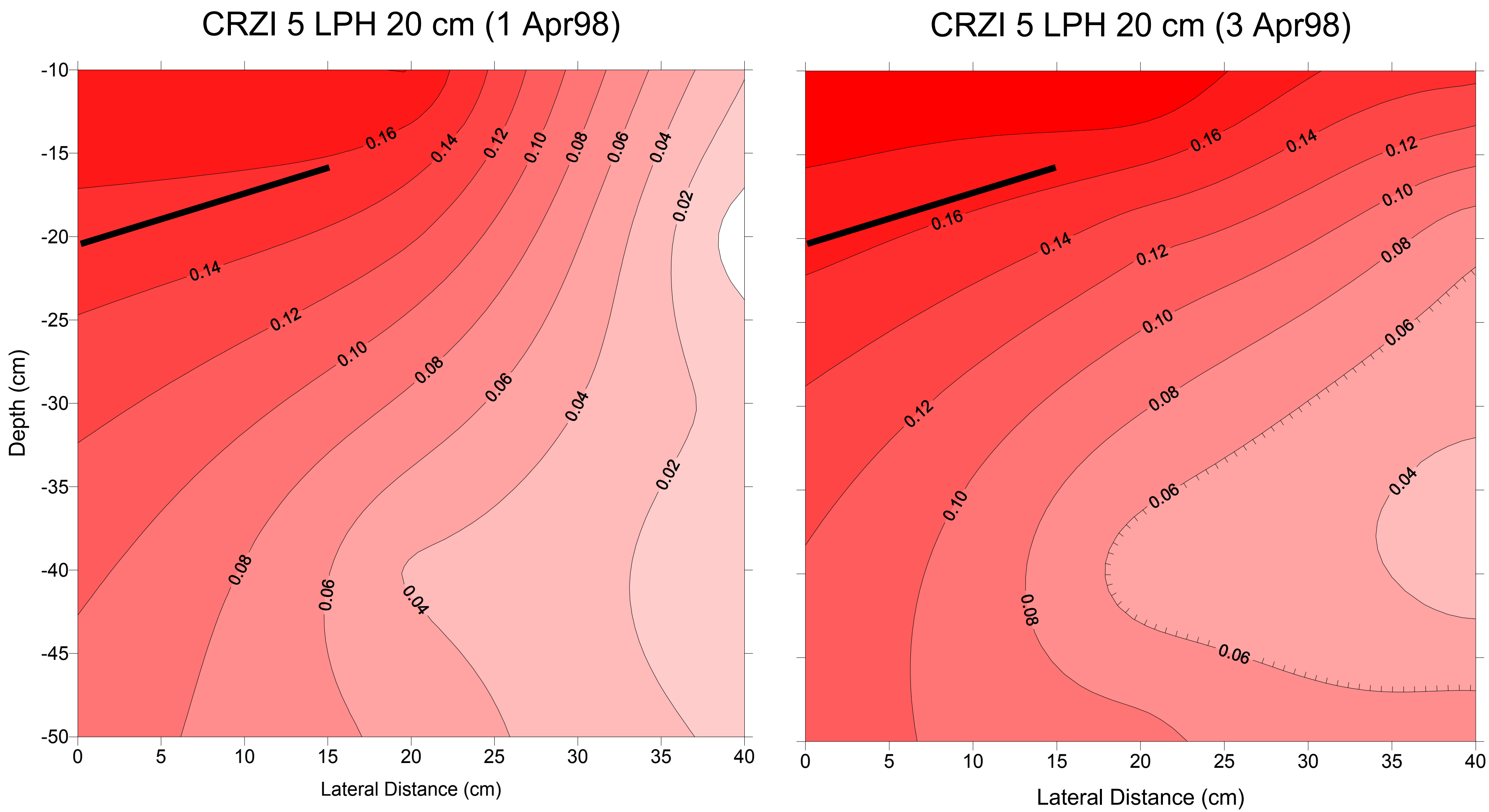

Figure 12.11. Profile wetting patterns at 2 (left) and 4 (right) days after irrigation commenced (SWC change, cm^3cm^{-3}) - Shallow CRZI.

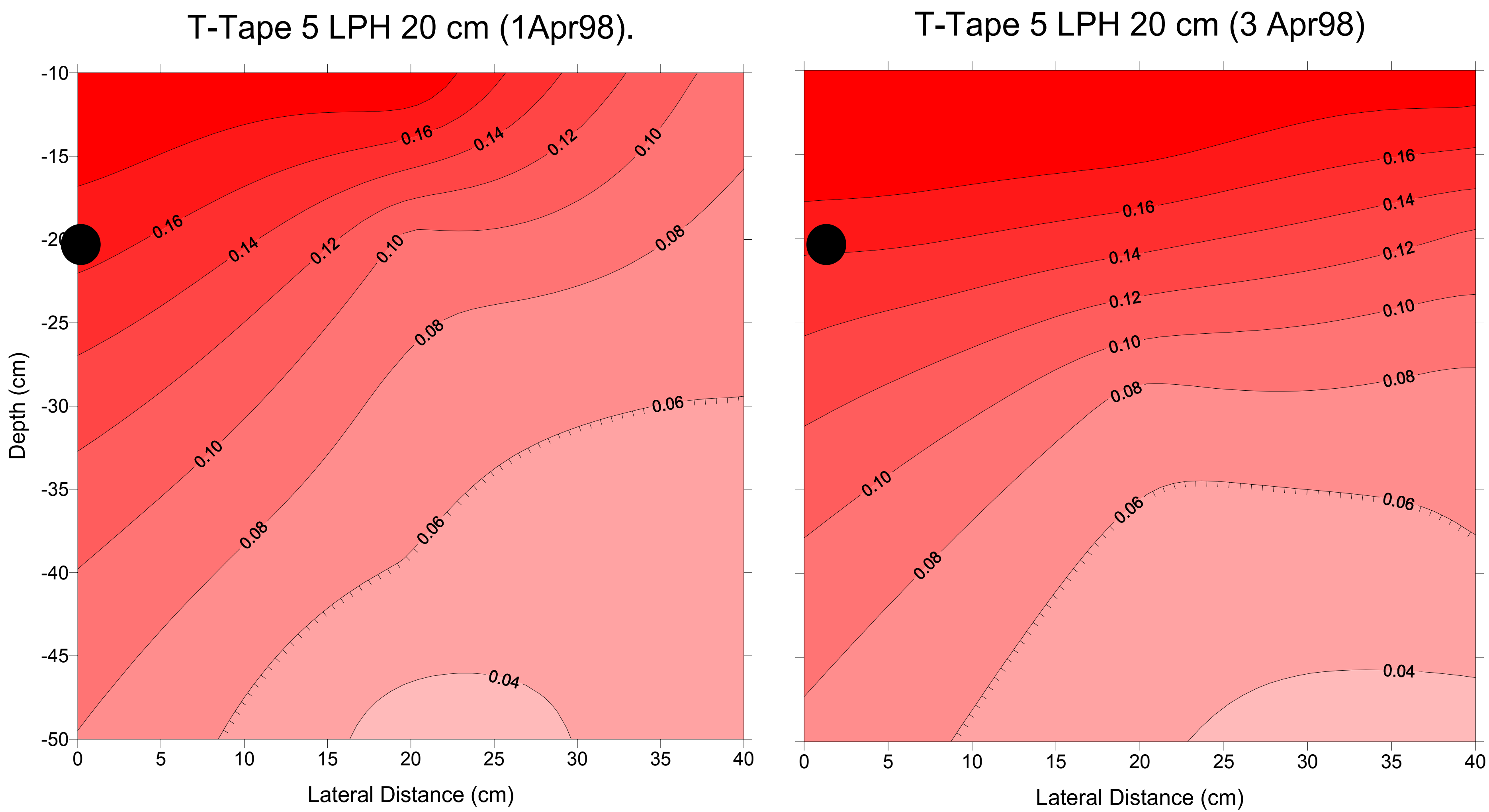

Figure 12.12. Profile wetting patterns at 2 (left) and 4 (right) days after irrigation commenced (SWC change, cm^3cm^{-3}) - Shallow Drip Tape.

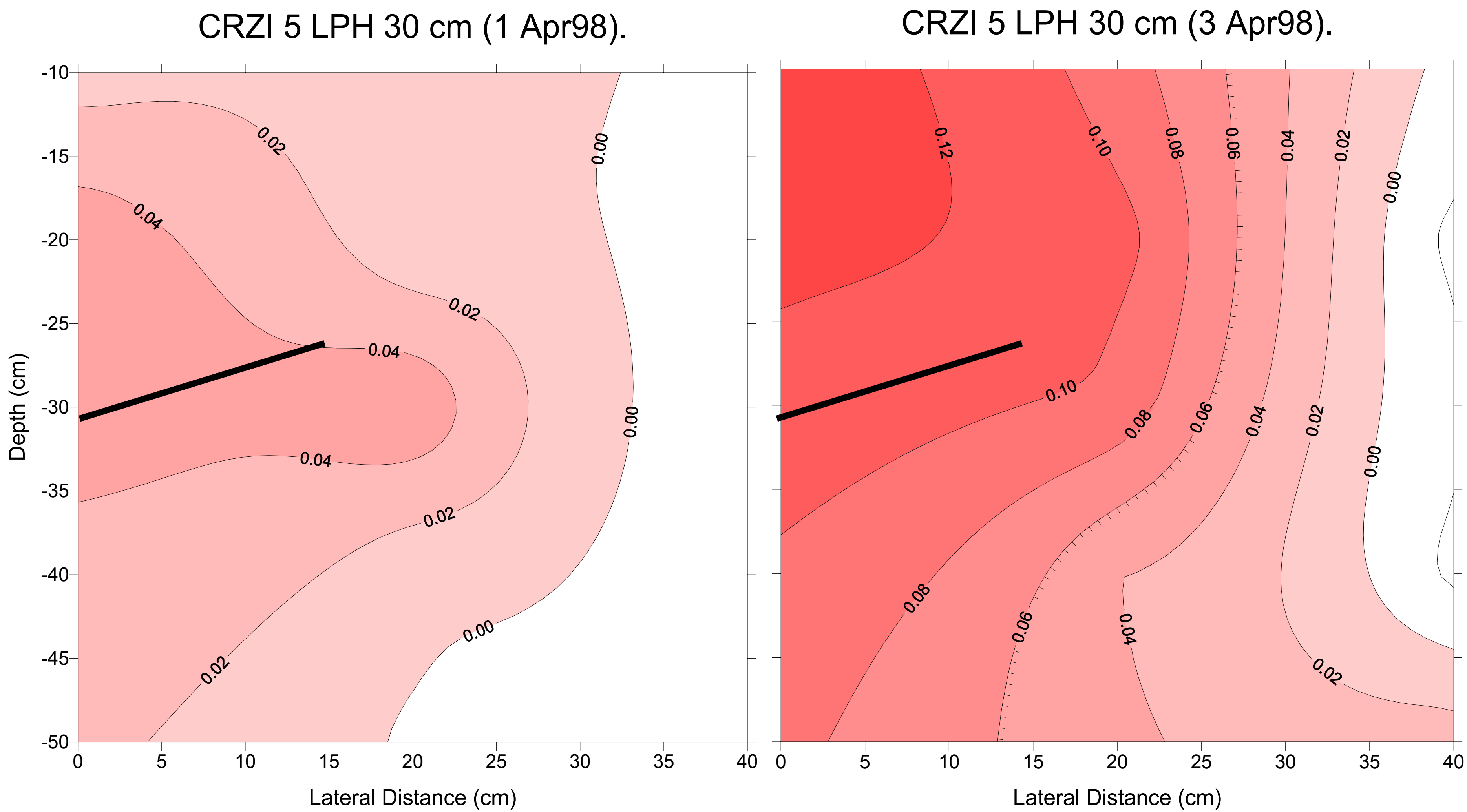

Figure 12.13. Profile wetting patterns at 2 (left) and 4 (right) days after irrigation commenced (SWC change, cm^3cm^{-3}) – Deep CRZI.

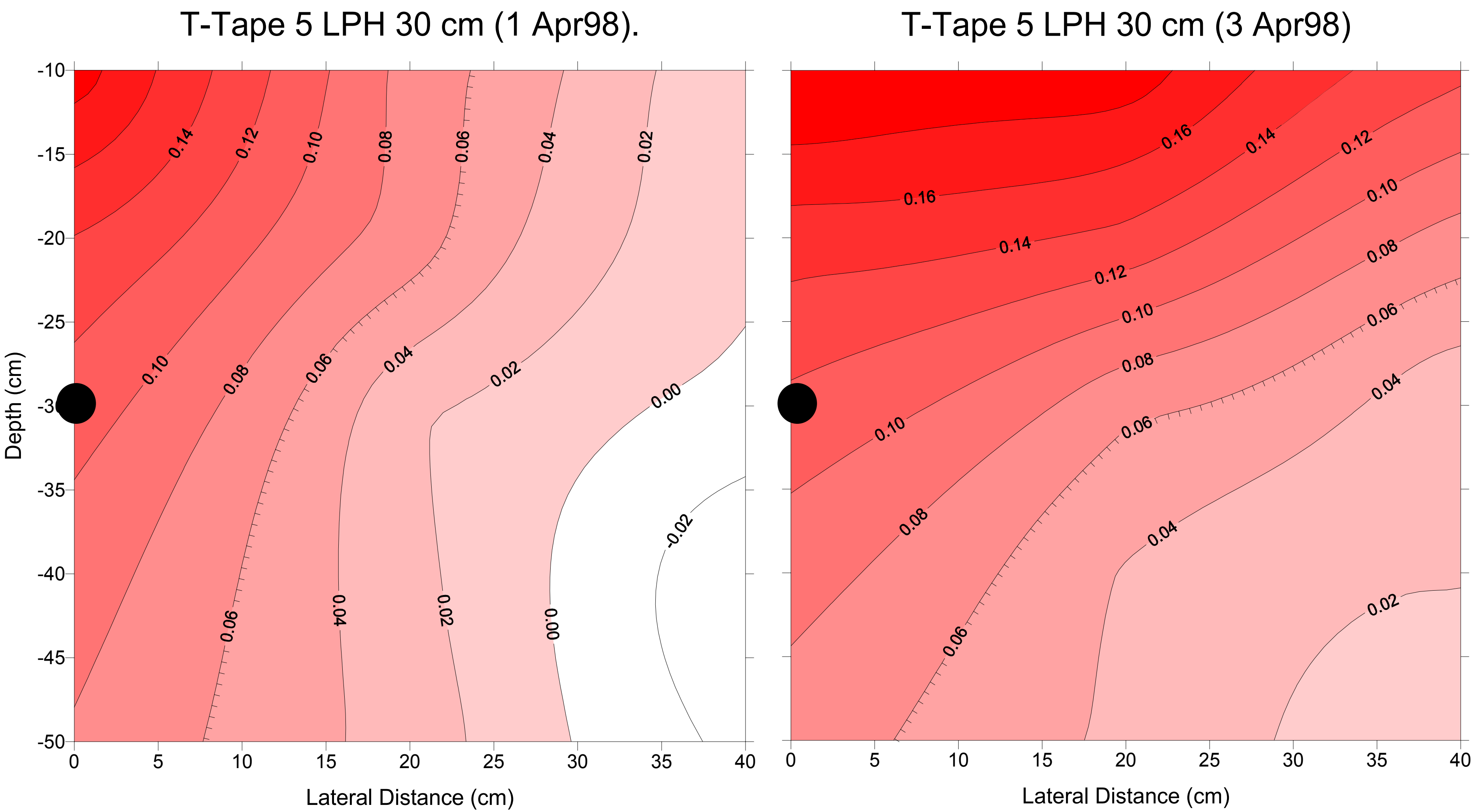

Figure 12.14. Profile wetting patterns at 2 (left) and 4 (right) days after irrigation commenced (SWC change, cm^3cm^{-3}) - Deep Drip Tape

Moisture characteristic of cores; vol. water contents at end

eSample	K@-3cm(cm/hr)	t @	t @	core wt @ 100 cm	core wt @ 330 cm	core wt @ 600 cm	length	sleevewt	O.D. soil	Bulk Dens
10/1	0.676	1444.3	1414.4	1393	1371.7	1363	7.5	319.2	930.4	1.63
10/2	0.393	1469.8	1454.5	1432.8	1412.1	1404.1	7.5	315.9	969.7	1.70
10/3	0.866	1402.5	1371.7	1349.7	1329.9	1321.1	7.45	299.1	911.3	1.61
10/4	0.537	1430	1410.3	1386.1	1359.8	1351.2	7.5	310.9	927.7	1.62
30/1	0.026	1415.8	1405.3	1395.4	1373.7	1359.9	7.5	302.3	884.7	1.55
30/2	0.085	1393.7	1382	1373.4	1352.9	1338.7	7.45	308.9	857.8	1.51
30/3	0.091	1316.4	1306.6	1295.6	1272.8	1258.5	6.9	313.6	784.3	1.49
30/4	0.114	1393.2	1377.8	1367.4	1346.8	1334.6	7.5	304.2	864.1	1.51
60/1	0.571	1376.7	1354.5	1339	1316.5	1306.9	7	319.4	888.2	1.66
60/2	0.430	1423.7	1406.7	1385.3	1356.2	1346.5	7.5	316.9	929.1	1.63
60/3	0.299	1378.3	1359.4	1343.1	1320.2	1311.2	7.45	316.8	889.2	1.57
60/4	0.361	1333.4	1315.2	1296.2	1267.8	1258.5	7	295.4	871.6	1.63

vol water@ 10	Vol water@ 50	vol water@ 100	vol water@ 330	vol water@ 600	vol water@ 1000	vol water@ 5000	Vol water@ 15000
1	1.7	2	2.518	2.778	3	3.7.00	4.176
0.341	0.288	0.251	0.214	0.198	0.174	0.155	0.140
0.322	0.295	0.258	0.221	0.207	0.182	0.161	0.146
0.338	0.284	0.245	0.210	0.195	0.172	0.152	0.138
0.335	0.300	0.258	0.212	0.197	0.174	0.154	0.140
0.400	0.382	0.365	0.327	0.302	0.240	0.204	0.183
0.400	0.379	0.364	0.328	0.303	0.234	0.199	0.178
0.416	0.397	0.376	0.333	0.305	0.231	0.197	0.176
0.393	0.367	0.348	0.312	0.291	0.234	0.200	0.178
0.317	0.275	0.246	0.204	0.186	0.161	0.150	0.132
0.311	0.281	0.244	0.193	0.176	0.158	0.146	0.128
0.303	0.270	0.241	0.201	0.185	0.152	0.141	0.124
0.312	0.278	0.242	0.189	0.172	0.158	0.147	0.129

Figure 12.15. - Hydraulic conductivity and bulk density (above), water retention data for site (below). Three layers presented (10, 30, 60cm).